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SUSTAINABLE BIOFUELS – CRITICAL REVIEW OF CURRENT VIEWS AND CASE STUDIED USING EXTENDED SYSTEMS ANALYSIS PROVIDING NEW PERSPECTIVES AND POSITIVE EXAMPLES

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 40774-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

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This project has benefitted from association with activities within IEA Bioenergy, European Forest Institute and other international networks that address issues of relevance for the project. In-kind contributions of associated experts have strengthened the project considerably, which is gratefully acknowledged. Additional financing within Chalmers University of Technology has made it possible to engage two PhD students in the project: Oskar Englund, who defended his PhD thesis in March 2016, and Olivia Cintas, who defended her PhD thesis in spring 2018.

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EXECUTIVE SUMMARY

The sustainability performance of bioenergy and biofuels is debated, both within the scientific community and in society. Sometimes conflicting views are put forward even though similar bioenergy and biofuel production are discussed. One reason for current conflicting views is differences in basic assumptions and methodological approaches applied in the underlying environmental assessments. Thus, the overall aim with this study is to improve the knowledge about how underlying assumptions may affect the results regarding biofuels sustainability performance. This is important to inform the current debate and to make appropriate interpretations of the various studies presented within the biofuel sustainability field. Furthermore, policy tools based on inadequate environmental assessment methods, for example employing too narrow system boundaries, may not be effective in supporting those bioenergy systems that have more favorable performance concerning net greenhouse gas (GHG) emissions reduction, land-use efficiency and other environmental aspects.

This report contains three different examples that concern important aspects of assessing the environmental performance of bioenergy and biofuel systems: (i) the impact of system boundaries on biogas GHG performance and land use efficiency; (ii) methodology approaches in assessments of forest bioenergy systems and associated carbon balances; and (iii) assessment and mapping of ecosystem services in a landscape perspective. The reports ends with a discussion of findings and policy implications.

The first example (chapter 2), represented by biogas production systems, include aspects such as alternative use of residual biomass, indirect effects of changed handling systems of residual biomass, and direct effects of changed cropping systems. A purpose with this example is to illustrate how the use of narrow systems perspectives in life cycle assessment (LCA) can result in misleading results concerning biofuels' GHG performance. Today, the GHG calculation methodology in the EU Renewable Energy Directive (RED) determines which biofuel systems that are "good" or "bad" from a GHG perspective. As illustrated in this example, today's RED calculation methodology represents an approach which has narrow systems boundaries and limited possibility to capture spatial variations in conditions which also change over time.

The biogas example includes three different categories of feedstocks, namely (i) liquid manure, representing a residue with no alternative use (except as fertilizer which will be similar as for digested manure); (ii) whey (from dairy), representing a residue or co-product which may have an alternative use as protein feed in animal production; and (iii) ley crops, representing a primary energy crop cultivated on arable land. The overall finding is that the ranking of the three different biogas systems regarding their GHG performance and net demand for arable land are completely changed when the RED calculation methodology is replaced by the system expansion approach. From being one of the best biogas system, the food industry residue-based systems will be the system with worst performance, whereas the opposite is the case for perennial crop-based systems.

The following conclusions and recommendations are made:

- A strict division between (i) residual biomass, determined to be burden-free, (ii) co-products, partly accountable for upstream emissions, and (iii) primary biomass crops, only including direct emissions, is often counterproductive and will in many cases not lead to a real increase in environmental sustainability

- Policy tools based on LCA methodologies must comprise a dynamic perspective allowing temporal and spatial changes and differences
- Unwanted environmental effects related to specific biomass feedstocks and resources, irrespectively if they consist of residual biomass or primary energy crops, must be resolved by other, direct and dedicated policy tools
- Policy tools developed to stimulate a circular economy must be harmonized with corresponding policy tools developed in a biomass-based economy
- Thus, policy tools promoting biofuels should be as general as possible and based on technology- as well as feedstock-neutrality, and focus on the specific biofuel systems real GHG performance and on diminishing unwanted fossil vehicle fuels

Chapter 3 gives a description of how analyses of forest bioenergy systems provide varying results depending on method approach, such as the definition of reference scenarios, the spatial scale that is considered and how temporal system boundaries are set.

An illustrative example is when GHG balances are quantified at stand level to estimate the climate change mitigation benefit of residue harvest for bioenergy in association with final felling and/or thinning. This approach prescribes a strict sequence of events (site preparation, planting or natural regeneration, thinning and other silvicultural operations, final felling) that in reality occur simultaneously across the forest landscape. The assessment outcome can therefore vary drastically depending on how the temporal GHG balance accounting window is defined. If stand-level GHG accounting is started at the time of the first biomass extraction and use for bioenergy, i.e., commencing with a pulse emission followed by a phase of sequestration, there will – by design – be an initial net GHG emission, except for the cases where the bioenergy system displaces more GHG emissions than those associated with the bioenergy system itself). This initial net GHG emission is commonly referred to as a “carbon debt” and it follows that net emissions savings are delayed until this debt has been repaid.

Landscape-scale studies can provide a more complete representation of the dynamics of forest systems, as they can integrate the effects of all changes in forest management and harvesting that take place in response to – experienced or anticipated – bioenergy demand. They can therefore help to clarify how total forest carbon stocks are affected by specific changes in forest management. A conclusion from such studies is that the impact of bioenergy initiatives on forest carbon stocks is more complex and geographically varying than what might be captured in stand-level studies. The landscape-scale studies do not support the conclusion that is sometimes presented based on stand-level studies: that bioenergy incentives will inevitably result in increasing initial CO2 emissions (compared to a reference without those incentives) due to decreasing forest carbon stocks.

In general, information and knowledge from many scientific disciplines, applying a range of different methodologies, are needed to inform policy making for forest based bioenergy.

Main conclusions and recommendations in Chapter 3:

- The net climate change effects of bioenergy should be assessed in the specific context where bioenergy policies are developed and bioenergy is produced. For forest bioenergy, this often means that studies should analyse bioenergy systems as components in value chains or production processes that also produce material products, such as sawn wood, pulp, paper and chemicals.

- Important insights can be gained from energy systems modelling, integrated assessment modelling, and landscape level bioeconomic modelling that use location-specific biophysical and socio-economic data, and consider management responses and market effects in parallel sectors. These modelling studies should employ several alternative scenarios for critical factors, including policy options and energy technologies.

- Bioenergy based on by-products from forest industry processes (sawdust, bark, black liquor, etc.) is typically found to contribute positively to climate change mitigation also in the short-term. Tops and branches and biomass from some silviculture operations such as fire prevention and salvage logging are often found to support short-term mitigation.

- Studies that do not consider dynamic factors (e.g., forest management responses to bioenergy demand) may find that the use of small diameter trees and slowly decaying residues (e.g., stumps) does not contribute to net GHG savings in the short- or even medium-term (several decades). The use of larger diameter roundwood for bioenergy is sometimes found to not even deliver net GHG savings on multi-decade to century timescales

- Studies that include parallel sectors and employ biophysical-economic modelling for larger landscapes report mixed results. Results are more favorable if the increased forest biomass demand also triggers investments that increase forest area and productivity, which in turn result in carbon gains on the landscape level.

- Most current studies focus on greenhouse gases, despite that the effect of other climate forcers can be significant. The effects of all climate forcers influenced by vegetation cover and forest management should ideally be included (e.g., surface reflectivity, or albedo).

Chapter 4 presents an analysis of methods for assessing and mapping ecosystem services in landscape and we also review the associated terminology. This is an important area of system analysis, such as LCA, which currently sees a development of methodologies for quantifying geographically located ecosystem effects. The chapter is based on the results of a systematic review published in a scientific journal. We found a significant diversity in methodological approaches and inconsistent terminology, but also harmonization initiatives, such as the new International Classification of Ecosystem Services (CICES) classification system, developed by the European Environment Agency (www.cices.eu). In summary, we found that:

- Proxy-based methods may be appealing since they are much less complex than, for example, direct mapping with survey and census approaches, or empirical production function models. But there are disadvantages, such as the risk of generalization error, which makes them unsuitable for landscape scale studies.

- Given the importance of high resolution and need for more complex methods and validation, most ecosystem services assessments with a landscape scope will need to limit the number of ecosystem services included in the study. To ensure that the most relevant ecosystem services are included, it is essential to involve stakeholders in the selection process.

- Practitioners with advanced GIS skills may benefit from creating their own models. However, some existing models, e.g., the InVEST model, have been applied many times, in several cases with validated and acceptably accurate results. When using third-party models, it is imperative that these are properly evaluated on their suitability for the specific project beforehand, and also calibrated and validated using empirical data.

- Translation of ecosystem services into the CICES classification system is in most cases relatively straight-forward. Further development of CICES should consider whether to only include direct ecosystem services associated with benefits to humans.

- The comprehensiveness and use of more technical terms in CICES may create a barrier for communication and interaction with those that lack in-depth understanding of ecosystem services. Given the importance of stakeholder involvement in assessments of ecosystem services, this is a clear disadvantage.

- It may therefore be beneficial to review the wording or to complement the typology with alternative, less technical, descriptions. This can preferably be coordinated with other initiatives that aim to inform policies and everyday practices, such as the Nature’s contributions to people (NCP) concept within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

An overall conclusion in this study is that the development of more and more complex bioenergy systems – motivated by the need for more efficient utilization of biomass resources, improved GHG performance and additional environmental benefits (e.g., ecosystem services) – must be accompanied by parallel development of assessment methodologies and policy tools that can support these sustainability improvements.

SAMMANFATTNING

Bioenergiutvecklingen har skapat en omfattande debatt. Biodrivmedel och andra biobränslen har ifrågasatts med hänvisning till studier som pekar på ökad konkurrens om åkermark och direkta/indirekta negativa miljöeffekter p.g.a. förändrad markanvändning. Andra studier visar i stället att samproduktion av t.ex. livsmedel och biobränslen kan stödja jordbruksutveckling samt skapa mer effektiva och resilienta produktionssystem. Likaså finns skilda meningar om skoglig bioenergi. Å enda sidan anförs att satsningar på skoglig bioenergi driver upp råvarupriser, skadar den biologiska mångfalden och förvärrar snarare än minskar vår klimatpåverkan. Å andra sidan anförs att skoglig bioenergi ger god klimatnytta, en stärkt konkurrenskraft för den traditionella skogsnäringen tack vare en diversifierad produktportfölj, samt att hållbarhetskrav kopplade till bioenergi kan förstärka skydd och hänsynstagande gentemot biologisk mångfald inom skogsbruket.

Detta projekt inom samverkansprogrammet Förnybara drivmedel och system har syftat till att bredda och vidareutveckla systemforskningen kring biodrivmedel och tillföra nya perspektiv, samt att kritiskt granska och föreslå alternativ till de synsätt, analyser och styrmedel som format bioenergiutvecklingen de senaste åren. Projektet har haft hög ambition gällande vetenskaplig publicering men också gällande kommunikation riktad mot näringsliv, myndigheter och den politiska sfären i Sverige och internationellt.

Slutrapporten beskriver resultat och insikter relaterat till projektets centrala frågeställning: Hur kan metodval och antaganden om kritiska parametrar påverka resultat och slutsatser i studier av markeffektivitet och växthusgasbalanser för biobränslen (kapitel 2-3)? Rapporten innehåller också en översikt gällande metoder för att kartlägga och bedöma markanvändningens påverkan på ekosystemtjänster i ett landskapsperspektiv (kapitel 4).

Studiens första exempel (kapitel 2) innefattar biogassystem baserat på tre olika kategorier av biomassaråvara, nämligen flytgödsel, restprodukter från livsmedelsindustri (vassle) samt energigröda (gräs). Syftet med exemplet är att illustrera hur alltför snäva systemgränser kan leda till resultat angående biodrivmedels växthusgasprestanda och markanvändningseffektivitet som stödjer slutsatser som avviker från de som erhålls utifrån ett brett livscykelperspektiv. Den beräkningsmetod som används idag inom EU:s förnybarhetsdirektiv (RED) för att fastställa biodrivmedels växthusgasprestanda representerar en sådan metod med alltför snäva systemgränser och som saknar möjligheter att beakta förändringar i tidsmässiga och rumsliga förutsättningar.

När växthusgasprestanda för biogas baserat på de tre kategorierna av råvara beräknas utifrån ett utvidgat systemperspektiv istället för enligt RED-metodologin, blir rankingen mellan de olika systemen helt annorlunda. Från att vara ett av de bästa biogassystemen utifrån ett växthusgas- och markanvändningsperspektiv (baserat på RED-metodologin), blir systemet baserat på restprodukter från livsmedelsindustri ett av de sämsta när systemgränserna utvidgas. För biogassystem baserat fleråriga energigrödor blir situationen den omvända. Baserat på slutsatser som genereras i detta exempel kan följande rekommendationer ges för utvecklingen av policy-verktyg inom biodrivmedelsområdet:

- En strikt uppdelning mellan (i) restprodukter som inte belastas med uppströms utsläpp, (ii) biprodukter som är delvis belastade med uppströms utsläpp och (iii) primära energigrödor som enbart belastas med direkta utsläpp är oftast kontraproduktivt eftersom det i många fall inte leder till att de bästa biodrivmedelssystemen ur hållbarhetssynpunkt premieras.

- Policy-verktyg som baseras på LCA måste vara dynamiska och kunna hantera och inkludera skillnader och förändringar i tidsmässiga och rumsliga förutsättningar.
- Oönskade miljöeffekter från användning av specifika biomassaresurser, både i form av restprodukter och primära energigrödor, måste styras med riktade policy-verktyg och inte via styrmedel som fokuserar på växthusgasprestanda.
- Policy-verktyg för att stimulera en ökad cirkulär ekonomi måste harmoniseras med de styrmedel som införs för att stimulera en biobaserad ekonomi.
- Policy-verktyg för att stimulera utvecklingen av hållbara biodrivmedel måste därför vara så generella som möjligt och vara teknik- och råvaruneutrala samt fokusera på de specifika biodrivmedelssystemens faktiska klimatnytta ur ett brett systemperspektiv.

Kapitel 3 ger en beskrivning av hur systemanalyser av skogliga system ger varierande resultat beroende på metodansats, exempelvis definition av referensscenario, vilken rumslig skala som beaktas och hur temporala systemgränser sätts.

Ett illustrativt exempel är när växthusgasbalanser kvantifieras för ett fall där biomassa tas ut för energiändamål i samband med slutavverkning eller gallring på en begränsad yta. Med denna ansats karakteriseras bioenergisystemet som en strikt sekvens av aktiviteter/händelser (t.ex. markbearbetning, plantering, gallringar, slutavverkning) som i realiteten sker parallellt och kontinuerligt i ett skogslandskap. Resultatet kan i sådana ansatser variera drastiskt beroende på hur man placerar tidsfönstret för beräkning av växthusgasbalanser. Om tidsfönstret placeras så att det i startögonblicket sker ett uttag av biomassa för energi så erhålls oundvikligen en initial utsläppspuls följt av en period av CO_2-inbindning, om inte bioenergisystemet ersätter annan energitillförsel som skulle ha orsakat större växthusgasutsläpp än vad som är associerat med själva bioenergisystemet. Denna initiala utsläppspuls betraktas ofta som en "koldioxidskuld" vilken fördröjer bidraget till minskande växthusgasutsläpp.

Studier på landskapsnivå kan ge en mer fullständig representation av skogssystemets dynamik, eftersom de kan integrera effekterna av alla förändringar inom skogsförvaltning och skörd som sker p.g.a. upplevd eller förväntad efterfrågan på bioenergi. De kan därför bidra till att förtydliga hur totala skogliga kollager påverkas av specifika förändringar av skogsförvaltningen. Av sådana studier ser man att påverkan av bioenergisatsningar på de skogliga kollagren är komplexa och varierar geografiskt. De ger inte stöd för den slutsats som emellanåt förs fram med hänvisning till beståndsnivåstudier: att satsning på bioenergi oundvikligen kommer resultera i ökande initiala CO_2-utsläpp (jämfört med ett scenario utan bioenergisatsningar) p.g.a. minskande skogliga kollager. Generellt behövs information och kunskap från många vetenskapliga discipliner, med tillämpning av en rad olika metoder, för att informera beslutsfattandet för skogsbaserad bioenergi. Ett antal slutsatser och rekommendationer presenteras i kapitel 3:

- Bioenergins klimatpåverkan bör bedömas i det specifika sammanhang där bioenergipolitiken utvecklas och bioenergi produceras. För skoglig bioenergi innebär det ofta att studier ska analysera bioenergisystem som utgör komponenter i värdekedjor eller produktionsprocesser som också producerar materialprodukter, såsom sågat trä, massa, papper och kemikalier.

- Viktiga insikter kan erhållas genom energisystemmodellering, s.k. integrated assessment modelling, och modellering på landskapsnivå som använder platsspecifika biofysiska och socioekonomiska data och beaktar bioenergimarknadens påverkan på skoglig förvaltning och marknadseffekter i parallella sektorer. Sådana modelleringsstudier bör använda flera alternativa scenarier för kritiska faktorer, inklusive policyalternativ och energiteknik.

- Bioenergi baserad på skogsindustrins restprodukter (sågspån, bark, svartlut etc.) bedöms vanligtvis bidra positivt till att minska klimatförändringen även på kort sikt. Detsamma gäller ofta för uttag av toppar och grenar, och uttag av biomassa i samband med brandförebyggande åtgärder.

- Studier som inte beaktar dynamiska faktorer (t.ex. hur skoglig planering svarar på förväntad marknadsutveckling) finner ibland att uttag av gallringsvirke och avverkningsrester som bryts ned långsamt inte bidrar till minskade GHG-utsläpp på kort eller ens medellång sikt (flera decennier). Ännu sämre utfall fås i sådana studier för stamved av virkeskvalitet där man ibland inte ser GHG-besparingar på många decennier (ibland närmare ett sekel).

- Studier som omfattar parallella sektorer och använder biofysisk-ekonomisk modellering för större landskap rapporterar varierande resultat. Ett skäl till detta är att man förmår fånga upp ekonomiska aspekter och aktörsbeteenden, vilket innebär att man kan få en bild av hur ökad efterfrågan på skogsbiomassa kan stimulera satsningar för att öka den skogliga produktionen som resulterar i ökad kolinbindning i skogen.

- Huvuddelen av de studier av klimateffekter av skogliga system som har gjorts fokuserar på växthusgaser, trots att effekten av andra klimatpåverkande faktorer kan vara betydande. Det finns därför ett behov av studier som beaktar hur skogsbruk påverkar fler faktorer än växthusgaser, t.ex. markens reflektivitet (albedo).

I kapitel 4 presenteras en analys av metoder för att analysera och kartlägga ekosystemtjänster i landskap och en genomgång av den associerade terminologin. Detta är ett angeläget område inom systemanalys, t.ex. i LCA, där man för närvarande kan se en utveckling av metodansatser för att kvantifiera geografisk lokaliserade ekosystemeffekter. Kapitlet bygger på resultaten av en systematisk review som har publicerats i en vetenskaplig tidskrift. Vi fann en betydande diversitet i metodansatser och inkonsistent terminologi, men också försök till att harmoniera dessa, t.ex. klassificeringssystemet Common International Classification of Ecosystem Services (CICES), som utvecklas av Europeiska miljöbyrån (www.cices.eu). I sammandrag:

- Proxybaserade metoder har fördelen att de är mindre komplexa än t.ex. direkt kartläggning eller empiriska produktionsfunktionsmodeller. Men det finns nackdelar vilket gör proxybaserade metoder olämpliga för studier på landskapsnivå, som t.ex. risken för felaktiga generaliseringar.

- Eftersom hög upplösning och mer komplexa metoder och validering är nödvändigt kommer de flesta studier av ekosystemtjänster på landskapsnivå behöva begränsas till att hantera ett fåtal ekosystemtjänster. För att säkerställa att de mest relevanta ekosystemtjänsterna ingår är det viktigt att involvera intressenter i urvalsprocessen.

- Analytiker med avancerade GIS-färdigheter kan med fördel skapa egna modeller, men vissa befintliga modeller har använts i ett flertal fall med validerade och acceptabla resultat för användaren. Vid användning av tredjepartsmodeller är det dock nödvändigt att de utvärderas i förväg om lämpligheten för det specifika projektet, samt att de kalibreras och valideras med hjälp av empiriska data.

- Användning av klassificeringssystemet CICES verkar i de flesta fall vara relativt problemfritt. Vidareutveckling av CICES kan överväga att endast omfatta direkta ekosystemtjänster som associeras med nytta för människan.
- Omfattningen och användning av mer tekniska termer i CICES kan försvåra kommunikation och interaktion med dem som har begränsad erfarenhet av begreppet ekosystemtjänster. Med tanke på betydelsen av intressenters medverkan i bedömningar av ekosystemtjänster är detta en tydlig nackdel.
- Det kan därför vara till nytta att granska formuleringen eller komplettera typologin med alternativa, mindre tekniska, beskrivningar. Detta skulle kunna samordnas med andra initiativ som syftar till att informera politiken, myndigheter och andra relevanta verksamheter. Ett exempel är konceptet Nature’s Contributions to People (NCP) inom den mellanstatliga science-to-policy plattformen om biologisk mångfald och ekosystemtjänster (IPBES).

En övergripande slutsats i denna studie är att utvecklingen av mer och mer komplexa bioenergisystem – som motiveras av behovet av ett mer effektivt utnyttjande av biomassaresurser, förbättrad växthusgasprestanda och ytterligare miljöfördelar (t.ex. ekosystemtjänster) – måste åtföljas av en parallell utveckling av politiska verktyg som kan stödja dessa hållbarhetsförbättringar.

CONTENTS

1 INTRODUCTION

The sustainability performance of bioenergy and biofuels is debated, both within the scientific community and society. Sometimes conflicting views are presented even though similar production systems and energy carries are in focus. This can reflect differences in specific design and conditions of the biofuel system, including technical performance, geographical location and surrounding support systems. But divergence in views can also be due to differences in basic assumptions and methodological approaches applied in the underlying environmental assessments. Here, critical aspects include the definition of spatial and temporal systems boundaries, definition of reference systems, selection of environmental impact categories, and methods for allocating impacts between biofuels and by-products.

Better knowledge in how methodology approaches and assumptions about critical parameters may affect assessment outcomes regarding biofuels sustainability performance can facilitate appropriate interpretations of the various studies presented within the biofuel sustainability field. This is important to inform the current debate and policy development.

Policy tools based on inadequate environmental assessment methods, for example employing too narrow system boundaries, may not be effective in supporting those bioenergy systems that have more favorable performance concerning net greenhouse gas (GHG) emissions reduction, land-use efficiency and other environmental aspects. The development of more and more complex biofuel systems, driven by a more efficient utilisation of biomass resources, improved GHG performance and additional environmental benefits, need to be accompanied by a parallel development of policy tools which can embrace these sustainability improvements.

The overall aim with this study is to improve the knowledge in how underlying assumptions may affect the results regarding biofuels sustainability performance. This is done by presenting three different examples of methodological assessment approaches in studying the environmental performance of bioenergy and biofuel production systems. The three different examples, presented in individual chapters, comprise (i) the impact of system boundaries on biogas greenhouse gas performance and land use efficiency, (ii) forest bioenergy systems and carbon balances, and (iii) ecosystem services generated in terrestrial landscapes from biomass production. A final chapter, provides general conclusions and recommendations drawing on the three different examples.

This report is intended to be a readable popular summary of the project output. For further reading, we refer to the lists of recommended readings as well as publications associated with this project (listed in the end of the report).

The general methodological approach applied in this study is a review and compilation of relevant literature and selection of applicable studies illustrating the consequences of methodological choices and assumptions.

2 THE IMPACT OF SYSTEM BOUNDARIES ON BIOFUELS GHG PERFORMANCE AND LAND-USE EFFICIENCY – CONSEQUENCES FOR DIFFERENT TYPES OF BIOMASS FEEDSTOCK

2.1 INTRODUCTION

This chapter start with a general description of how life cycle assessment (LCA) is applied in the evaluation of biofuels environmental performance today and in relation to biofuel policies. Special focus is on the types of biomass feedstock utilised. Thereafter, three different examples are presented showing how varying system boundaries in the environmental assessment of biogas production systems will affect the results of GHG performance and land use efficiency. These examples include aspects such as alternative use of residual biomass, indirect effects of changed handling systems of residual biomass, and direct effects of changed cropping systems. Based on the quantitative results presented in the three examples regarding specific key issues related to expansion of systems perspectives, additional calculations are presented in a separate section. Finally, based on the three examples and the additional calculations, the findings are concluded and discussed from a policy implication perspective.

The overall purpose with this chapter is to illustrate how the definition of biomass feedstock resources and system boundaries will affect the GHG performance and land-use efficiency for biofuels. An additional objective is to discuss the relevance of different approaches and related policy implications. The selection of the three cases is grounded on a mix of studies which highlight specific critical aspects, and the need of expanded and adapted perspectives in the use of LCA in research and as a policy tool regarding the sustainability evaluation of biofuels.

Biogas as vehicle fuel has been chosen as a case in the three examples since this category of biofuels include a high variety of potential biomass feedstocks and generated by-products and residues, thus represent a biofuel system with high complexity. The GHG calculation methodology stated in the EU RED is used as a reference and starting point for comparisons in the final section. This methodology utilizes allocation based on lower heating value when dividing emissions between the produced biofuel and potential co-products. The GHG performance of the feedstocks depends on the predetermined definition; residues (burden-free) or co-products (partly accountable for upstream emissions), whereas crop-based feedstock need to include the total amount of the upstream emissions (European Commission, 2009)[1]. The complementary calculation methodology is based on the system expansion approach, recommended by the ISO standard of LCA (ISO, 2006)[2].

2.2 LIFE CYCLE ASSESSMENT OF BIOFUELS – A SHORT OVERVIEW

Life cycle assessment (LCA) is commonly used in the evaluation of climate and environmental effects of biofuels, and is also used in policies. The EU Renewable Energy Directive (RED) uses an LCA approach to calculate of the greenhouse gas (GHG) balances for specific biofuel production

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[1] European Commission (2009a). Directive 2009/28/EC, Brussels

[2] ISO (2006). ISO 140 44 – Environmental management – Life Cycle Assessment – Requirements and Guidelines. International Standardisation Organisation

pathways. A critical aspect in LCA is the definition of system boundaries which can affect the results significantly. The definition of system boundaries and allocation of environmental impacts becomes increasingly important as integrated and complex biofuel production systems are developed that use different kinds of organic waste, residues and by-products as feedstock. This development aligns with political ambitions to promote a bio-based and circular economy, and is driven by policies that promote the utilization of organic waste and residues, e.g., the RED.

According to the ISO standardization of LCA, the handling of residues and by-products should, when possible, be based on the expansion of system boundaries. If this is not possible, allocation should be used dividing the environmental impact between the main product and the by-products based on their physical or economic properties. At least two prerequisites for applying system expansion exist; (i) that the alternative use of the by-product/residue could be identified, and (ii) that life cycle inventory data exist so that the alternative use can be characterized. It is in this context important to consider that alternative uses of by-products/residues may vary over time and space. One reason is that markets supporting alternative uses may become saturated.

A common definition of waste is that this is an output that does not displace any other product and does not provide economic value or even has a negative value. This definition is in line with the ISO standardization of LCA. When waste and residues are defined based on economics and markets, instead of their physical properties, a specific biomass resource may be considered a waste or residue in one context and a by-product or co-product in another context. The promotion of the utilization of organic waste streams, residues and by-products, in line with a bio-based and circular economy, leads to an increased economic value of residual biomass resources, which in turn affects the definition of these resources.

The RED contains a list of specific biomass resources. These are defined as either residues or co-products, where residues are considered burden-free feedstocks whereas co-products are accountable for some part of the upstream emissions. Such a list is problematic from an LCA perspective, considering that the definition of residue and co-products may change over time and space. In fact, the definition of a biomass resource as a waste or residue within the RED may be what makes it a co-product or by-product in the sense that it gains an economic value as a biofuel feedstock. The definition of biofuel feedstocks as residues or co-products influences the calculated GHG performance of the biofuel produced. It also indirectly influences the estimated land-use efficiency if the alternative product is based on cultivated crops.

Furthermore, the GHG performance of crop-based biofuels varies significantly depending on cropping system (e.g., annual crops or perennial crops) and whether LUC is included in the calculations. For example, analyses of the GHG performance of ley crop-based biogas show that the introduction of ley crops in cereal-based crop rotations can reverse a negative trend of declining soil carbon content and gradually transform the arable lands into carbon sinks. The increase in soil carbon also improves soil fertility and hence crop yields, reducing the demand for arable land for food production.

The RED limits the use of arable crops for biofuel production and suggestions exist that crop-based biofuels should be phased out completely. The motivation is that promotion of these biofuels increases the risk of arable land competition and displacement of food crops, which in turn may lead to direct and indirect land use change (LUC) causing GHG emissions. However, studies of LUC emissions associated with biofuels report widely different results, and especially the inclusion of indirect LUC adds greatly to the uncertainty in quantifications of LUC effects. The causes behind LUC are multiple, complex, interlinked, and change over time. This makes quantification inherently uncertain since it is sensitive to many factors that can develop in different directions, including land-use productivity, trade patterns, prices and elasticities, and use of by-products associated with biofuels production.

For example, if the introduction of biofuel cropping systems leads to improved soil fertility, such as when ley crops are included in cereal crop rotations, less land is needed to produce a given amount of food. This example shows that a system expansion approach is needed when LCA is used to evaluate crop-based biofuels, including direct land-use effects and long-term changes in soil carbon storage, productivity and crop yields.

2.3 ANALYSIS OF CRITICAL FACTORS AND METHODOLOGICAL CHOICES

2.3.1 Alternative use of residual biomass

Figure 2:1 presents the results in a study[3] that assesses the GHG performance of biogas vehicle fuel depending on (i) how the residual biomass is defined and (ii) which calculation methodology that are used. The industrial residual biomass feedstocks included were (i) distiller's waste, (ii) rapeseed cake, (iii) whey permeate, (iv) fodder milk, and (v) bakery residues. Two calculation methodologies were utilised; the EU RED and ISO 140 44 applying system expansion. As a reference, calculations were also performed where no allocation was made (all emissions were allocated to the biogas). The alternative use of the residual biomass was assumed to be animal feed based on the current practices in Sweden. The feed that the residual biomass was assumed to replace was protein feed based on imported soy meal from Brazil and barley cultivated in Sweden. The mix of soy meal and barley represent the protein quality of the respective residual biomass.

All the biomass feedstocks are, according to the EU RED and corresponding interpretation by the Swedish Energy Agency guidelines, classified as residues except for rapeseed cake which is classified as a co-product. Distiller's waste will, however, be reclassified as a co-product if dried. A conclusion from Figure 2:1 is that the GHG reduction, compared with fossil liquid fuels, will be around 85% for all feedstocks according to the RED calculation methodology. One exception is for rapeseed cake where the reduction only amount to some 50%. However, if also the potential alternative use of the feedstocks is included, or as protein feed replacing soy meal and barley, then the reduction will be significantly lower, varying from 20-60%. Biogas from rapeseed cake which will give similar GHG reduction independently of calculation methodology. Thus, if there exists an alternative market as feed for the considered residual feedstocks in Figure 2:1, then the RED calculation methodology will considerably overestimate the GHG benefits of these biogas vehicle fuel systems.

[3] Tufvesson L., Lantz M., Börjesson P. (2013). Environmental performance of biogas produced from industrial residues including competition with animal feed – life-cycle calculations according to different methodological standards. Journal of Cleaner Production, 53, 214-223.

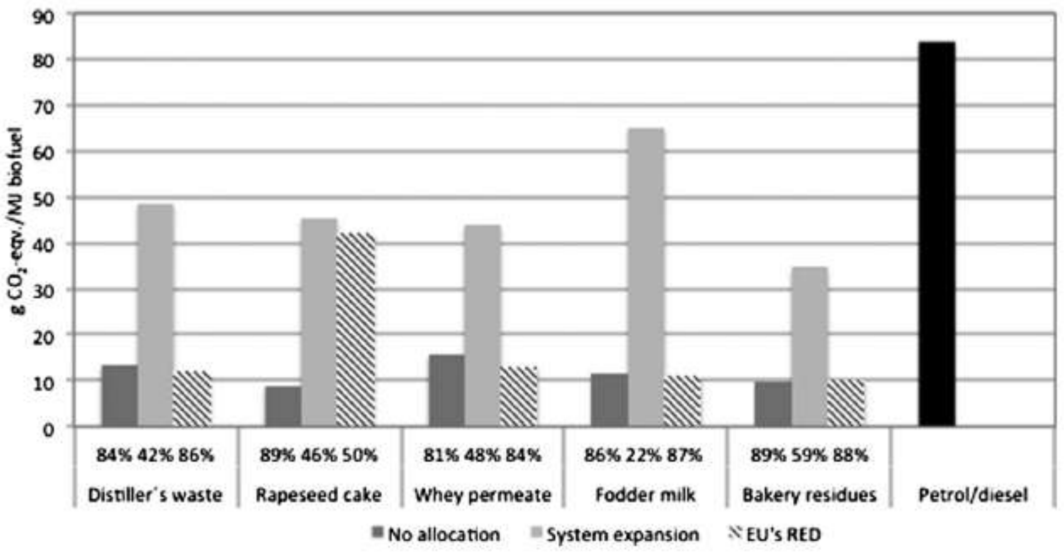

Figure 2:1. GHG performance of biogas vehicle fuel systems depending on feedstock and calculation methodology, and compared with petrol/diesel[4].

2.3.2 Indirect effects of changed handling systems of residual biomass

When residues without any obvious alternative usage as co-products (such as animal feed) are used for biogas production, no indirect benefits from such alternative use by substituting will occur. However, benefits may arise from changes in the handling of the residual feedstocks. For example, when manure, municipal food waste, some food industry waste etc., are collected and utilised for biogas production, the recirculation of nutrients will be improved by the generation of digestate, or biofertilizer, leading to indirect benefits from the replacement of mineral fertilizers. The benefits regarding biogas from liquid manure mainly consist of improved quality of the fertiliser after anaerobic digestion where a larger share of the nutrients (primarily nitrogen) is plant available. Independently of anaerobic digestion or not, the liquid manure will always be used as fertilizer. Regarding other residual biomass feedstocks, existing handling systems are normally not designed to recirculate nutrients back to arable land (like manure), thus the potential of replacing mineral fertilizers will be more substantial for these biogas systems. An additional GHG benefit, together with the benefit of nutrient recirculation, is that also organic matter is recirculated back to arable land through the use of biofertilizer leading to increased soil carbon content. The use of biofertilizers, instead of mineral fertilizers, may also cause some increased emissions of GHG, particularly during spreading operations, but these are rather small and outweighed by the GHG reductions described above, leading to significant net GHG benefits.

Biogas from liquid manure will lead to a specific and potential significant indirect GHG benefit by the reduction of methane emissions from conventional storage of the manure. This indirect benefit may be in the same order of magnitude as the GHG reduction when the biogas is used to replace fossil liquid fuels. As a result, the life cycle GHG emission from manure-based biogas can become negative, expressed per MJ biogas. Based on this specific GHG benefit regarding manure-based

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[4] Tufvesson L., Lantz M., Börjesson P. (2013). Environmental performance of biogas produced from industrial residues including competition with animal feed – life-cycle calculations according to different methodological standards. Journal of Cleaner Production, 53, 214-223

biogas, a dedicated economic incentive (in the form of a production subsidy) has been introduced in Sweden.

Figure 2:2 shows results from a study[5] of the direct and indirect GHG effects (as well as the effects on the primary energy input) for a co-digestion biogas plant that uses a mix of substrates including food industry waste, sludge, manure etc., when the system boundaries are expanded. The study also includes increased soil compaction when biofertilizer is used instead of mineral fertilizers, requiring more heavy field machinery equipment. A conclusion from Figure 2:2 is that the direct GHG emissions from the production of biogas amount to some 17 g CO_2-eq/MJ, including transport of substrates, biogas production, upgrading, distribution and handling of digestate. This system boundary corresponds to the EU RED calculation methodology; thus, this biogas production system leads to some 80% GHG reduction compared with fossil liquid fuels.

When the system boundaries are expanded to also include the benefits of avoiding methane emission from traditional handling and storage of manure and sludge, the GHG emissions will be reduced (Figure 2:2). The increased recirculation of nutrient from the use of biofertilizer, instead of mineral fertilizer, will give further GHG reductions, as well as the increased input of soil organic matter. On the other hand, the use of food industry residues for biogas production, instead of as animal feed, and biofertilizers instead of mineral fertilizer, leading to somewhat increased soil compaction, will lead to somewhat increases in the GHG emissions.

The overall GHG net effect of these indirect benefits and disadvantages will, however, be positive leading to net GHG emissions equivalent to approximately 8 g CO2-eq/MJ (see Figure 2:2). Applying a system expansion perspective, instead of the RED calculation methodology, will thus result in improved GHG performance of the biogas system and the GHG reduction, resulting from substitution of fossil liquid fuels, increases from 80% to 90%. Another conclusion in the study is that the substitution of mineral fertilizers leads to a significant GHG benefit. However, the size of this benefits depends on, for example, the GHG performance of the mineral fertilizer replaced which may vary due to production technologies. Newer studies also conclude that the choice of mineral fertilizer substitution principle strongly influences LCA environmental benefits of nutrient cycling in the agri-food system.

[5] Lantz M., Börjesson P. (2014). Greenhouse gas and energy assessment of the biogas from co-digestion injected into the natural gas grid - A Swedish case-study including effects on soil properties. Renewable Energy, 71, 387-395.

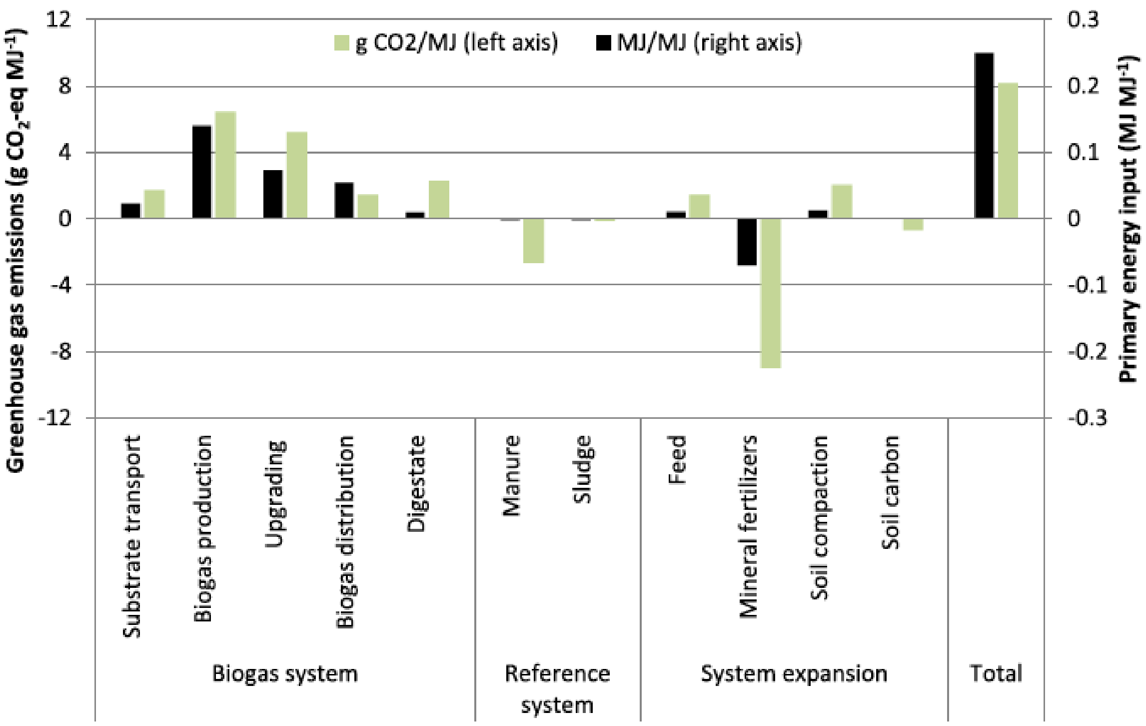

Figure 2:2. GHG emissions and primary energy input for biogas from co-digestion (Lantz and Börjesson, 2014)[6].

2.3.3 Direct effects of changed cropping systems

In a study[7] that investigates how an introduction of ley crops in cereal-based crop rotations will affect the soil carbon balances, two intensive agriculture regions in Sweden were included; Cereal 1, representing the south part of Sweden, and Cereal 2, representing the southwest part of Sweden. The current crop rotations include 6 years of cereal crop production (also including sugar beet and rape seed), whereas the modified crop rotations include 4 years of cereal crops and 2 years of ley crops for biogas production. Figure 2:3 shows the effects on the soil organic carbon (SOC) also including two fertilization strategies in the modified crop rotation, one using only mineral fertilizer and one using digestate (biofertilizer) from the biogas production (complemented with some mineral fertilizer). The difference in the SOC between the current and modified crop rotation both using mineral fertilizer is the increased soil carbon input from the cultivation of ley crops instead of cereal crops. In the modified crop rotation using digestate, also the additional soil carbon input from the biofertilizer, compared with the mineral fertilizer, is included.

The overall conclusion from Figure 2:3 is that the introduction of ley crops as biogas feedstock in intensive agriculture regions with cereal-based crop rotations may give a significant positive impact on the SOC storage, and that the input of SOC will be almost equivalent between the changed crop

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[6] Lantz M., Börjesson P. (2014). Greenhouse gas and energy assessment of the biogas from co-digestion injected into the natural gas grid - A Swedish case-study including effects on soil properties. Renewable Energy, 71, 387-395.

[7] Björnsson L., Prade T. and Lantz M. (2016). Grass for biogas – Arable land as a carbon sink. Report 2016:280, Transportation and Fuels, Energiforsk, Stockholm.

rotation (from annual crops to perennial ley crops) and the use of digestate instead of mineral fertilizer. The soils in the south of Sweden, C1, will be transform from a carbon source into a carbon sink. This will almost be the case in southwest of Sweden too, C2, but here the starting point was somewhat different with higher initial soil carbon losses in the current crop-rotation system.

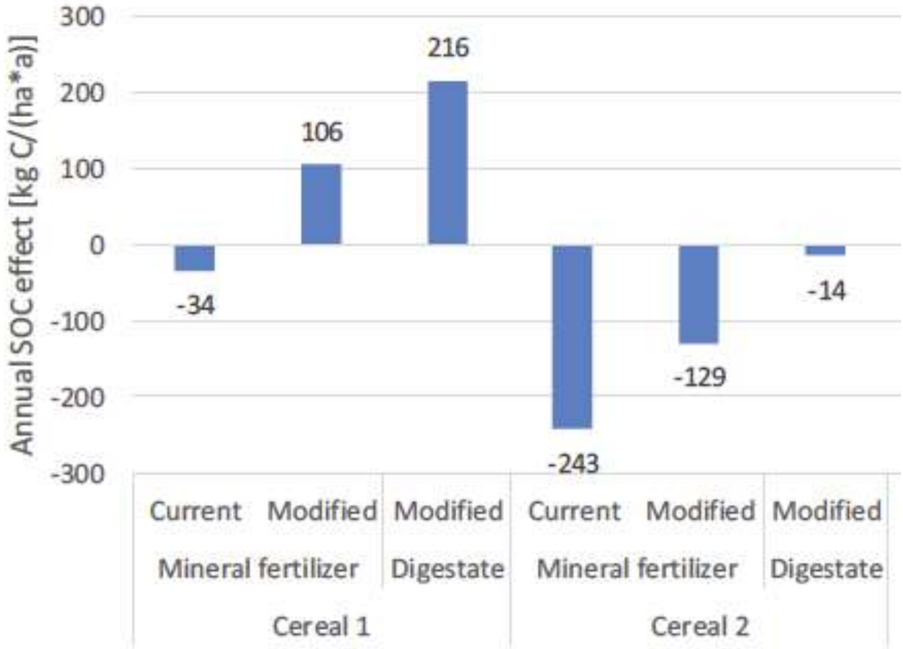

Figure 2:3. Annual soil organic carbon (SOC) effect in the soils of the study regions under current and modified crop rotations (Björnsson et al., 2016)[8].

An additional benefit of increased content of SOC will be increased soil productivity, especially in soils having an initial low SOC. It has been estimated[9][10] that the yields of cereal crops may increase by 10-20% in a 20- to 30-year perspective, when ley crops are introduced in cereal-based crop rotations, equivalent to 20-25% of the cropping land area. This means that when the temporal system boundaries are expanded in LCA's of ley crop-based biofuels, and when the alternative land use is cereal-crop cultivation, the net demand of arable land for biofuel production may be reduced. Thus, this indicates the importance of not only taking into account the long-term perspective in soil carbon sequestration from direct land-use changes but also the effects in form of improved soil productivity, higher crop yields and reduced net demand of arable land for food production.

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[8] Björnsson L., Prade T. and Lantz M. (2016). Grass for biogas – Arable land as a carbon sink. Report 2016:280, Transportation and Fuels, Energiforsk, Stockholm.

[9] Björnsson, L. et al., (2013) Impact of biogas crop production on greenhouse gas emissions, soil organic matter and food crop production–A case study on farm level. Report No 2013:27, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

[10] Prade, T., Kätterer, T., Björnsson, L. (2017) Including a one-year grass ley increases soil organic carbon and decreases greenhouse gas emissions from cereal-dominated rotations - a Swedish farm case study. Accepted for publication in Biosystems Engineering.

2.3.4 Combining methodological key issues and expanding system boundaries

The following calculations are based on the quantitative results presented in the studies described above regarding specific key issues related to expansion of systems perspectives. Thus, the additional and new calculations presented here should be seen as illustrative examples which, from a scientific point of view, contain uncertainties regarding the exactness in GHG emissions per MJ of biogas due to different methodological approaches, assumptions regarding input data, etc., in the reviewed studies.

Three different biogas feedstocks have been selected for the calculations, representing the following distinctive categories: (i) Liquid manure, representing a residue with no alternative use (except as fertilizer which will be similar as for digested manure), (ii) Whey (from dairy), representing a residue or co-product which may have an alternative use as protein feed in animal production, and (iii) Ley crops, representing a primary energy crop cultivated on arable land. The calculations have been done stepwise including one critical key issue at the time. The results of the GHG and land-use efficiency calculations are shown in Figure 2:4 and Figure 2:5.

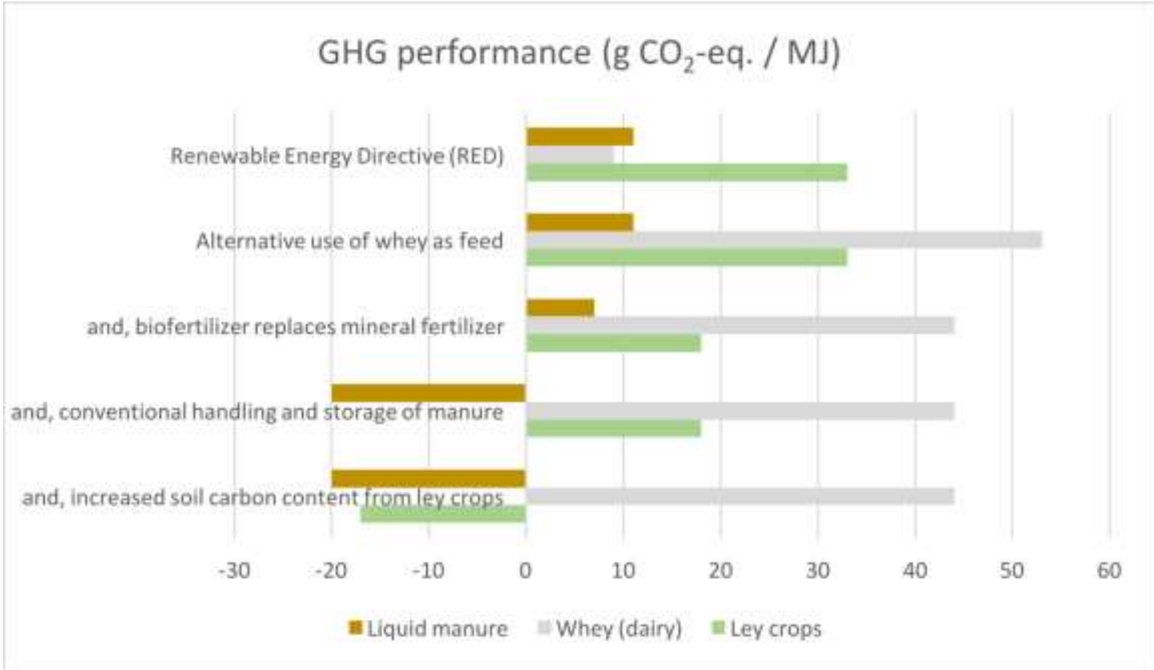

Figure 2:4. The GHG performance of biogas vehicle fuel depending on feedstock and calculation methodology including expansion of systems boundaries.

As shown in Figure 2:4, the biogas produced from whey and manure will have similar GHG emissions when the RED calculation methodology is applied, whereas the GHG emissions from ley crop-based biogas will be more than three times as high. When the systems boundaries are expanded taking into account the alternative use of whey as protein feed, then the GHG emissions from whey-based biogas will increase more than six times now representing the biogas systems with the highest GHG emissions. An additional system expansion including the GHG benefits of using digestate as fertilizer (biofertilizer), instead of mineral fertilizer, will improve the GHG performance of all the systems. The reduction of GHG emissions will be somewhat lower for liquid manure since this reduction is only due to improved quality of the fertilizer, and not increased recirculation of nutrients (as for whey and ley crops), since manure is used as fertiliser anyway.

When the system boundaries are expanded further for manure-based biogas, also including the reduction of methane emissions from conventional storage of the liquid manure, then the GHG emissions turns negative. Finally, when the direct land-use changes are included in the systems boundaries in the ley crop-based biogas systems, and when the alternative land use is annual crop cultivation, then the GHG emissions turn negative also for this biogas system. This is due to the increased sequestration of soil organic carbon.

An overall conclusion from the results presented in Figure 2:5 is that the ranking of the three different biogas systems based on their GHG performance are completely changed when the RED calculation methodology is replaced by the system expansion approach. Furthermore, the GHG performance, expressed as g CO_2-equivalents per MJ biogas, is drastically different depending on the calculation approach applied.

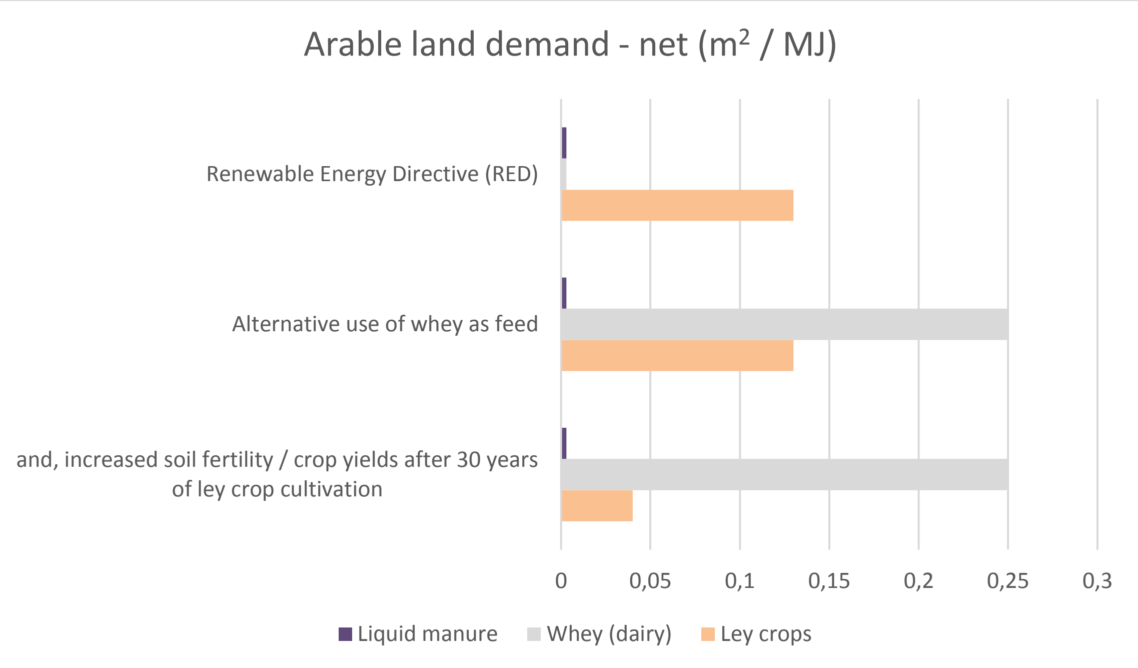

Figure 2:5. The need of arable land for the production of biogas vehicle fuel depending on feedstock and calculation methodology including expansion of systems boundaries.

As can be seen in Figure 2:5, the demand of arable land for producing 1 MJ of biogas is approximately 0.13 m^2 per MJ for ley crop-based systems, but zero for systems based on liquid manure and whey, according to the RED calculation methodology. However, when the system boundaries are expanded to also include the alternative use of whey as protein animal feed, the demand of arable land for this system will be twice as high as for the ley crop system. The reason is that the “protein yield” per hectare from feed crops needed to compensate for the loss of whey as protein feed (soy bean and barley) is significantly lower than the “biogas yield” per hectare for ley crops. Thus, a conclusion is that it is much more land-use efficient to grow dedicated biogas crops with high energy yields than to start to use residual biomass containing protein with suitable quality which could be used as animal feed.

If also the temporal system boundaries are expanded (equivalent to roughly a 30-year perspective), taking into account the increased soil fertility and food crop yields when ley crops are introduced in a cereal-based crop rotation, then the net arable land demand will be significantly reduced for ley crop-based biogas. In a longer term, the net arable land demand could even become negligible. The overall conclusion from the results presented in Figure 2:5 will be similar as for Figure 2:4, the ranking of the three different biogas systems based on their net demand of arable land are completely changed when the RED calculation methodology is replaced by the system expansion approach. From being one of the best biogas system from a land-use efficiency perspective, whey-based biogas systems will be the system which will require the highest demand, whereas the opposite will be the case for ley crop-based systems.

2.4 POLICY IMPLICATIONS AND DISCUSSION

A purpose with this chapter was to illustrate how a too narrow systems perspective in LCA can give misleading results regarding biofuels GHG performance. Today, the GHG calculation methodology stated in the RED determines which biofuel systems that are “good” or “bad” from a GHG perspective. As illustrated in this study, today’s RED calculation methodology represents an approach which has too narrow systems boundaries and limited possibility to capture spatial variations in conditions which also change over time. As a consequence of this, the RED may not promote those biofuel systems that have more favourable performance concerning net greenhouse gas (GHG) emissions reduction, land-use efficiency and other environmental aspects.

Based on the key methodological issues discussed in this chapter, and corresponding conclusions regarding the need of expanded systems perspectives, the following recommendations for policy makers can be drawn:

- A strict division between (i) residual biomass, determined to be burden-free, (ii) co-products, partly accountable for upstream emissions, and (iii) primary biomass crops, only including direct emissions, is counterproductive and will in many cases not lead to a real increase in environmental sustainability
- Policy tools based on LCA methodologies must comprise a dynamic perspective allowing temporal and spatial changes and differences
- Unwanted environmental effects related to specific biomass feedstocks and resources, irrespectively if they consist of residual biomass or primary energy crops, must be resolved by other, direct and dedicated policy tools
- Policy tools developed to stimulate a circular economy must be harmonized with corresponding policy tools developed in a biomass-based economy
- Thus, policy tools promoting biofuels should be as general as possible and based on technology- as well as feedstock-neutrality, and focus on the specific biofuel systems real GHG performance and on diminishing unwanted fossil vehicle fuels

The development of more and more complex biofuel systems – driven by requirements for more efficient utilisation of biomass resources, improved GHG performance and additional environmental benefits – need to be accompanied by a parallel development of policy tools which can embrace these sustainability improvements. For example, regarding forest-based bioenergy systems and related carbon balances, expanded spatial and temporal systems boundaries are crucial (see chapter 3). Considering multifunctional bioenergy systems, a landscape perspective is often needed to be applied for assessments to appropriately consider environmental impact categories other than GHG performance (see chapter 4).

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3 CLIMATE EFFECTS OF FOREST BASED BIOFUELS

3.1 INTRODUCTION

In recent years, there has been considerable debate about climate effects of bioenergy products that are produced from forest biomass. There is no clear consensus among scientists on the issue and their messages may even appear contradictory to decision-makers and citizens. Some scientists, for example, signal that the use of forest biomass for energy enhances global warming, while others maintain that forest bioenergy can play a key role in climate change mitigation. The divergence in views arises because scientists address the issue from different points of view, which can all be valid. The varying context of the analysis and policy objectives have a strong influence on the formulation of research questions, as well as the methods and assumptions about critical parameters that are then applied, which in turn have a strong impact on the results and conclusions.

This chapter presents an overview of current scientific debate on forest biomass and climate change mitigation. It is a shortened version of a report published by the European Forest Institute[11] with some extensions based on other literature produced within this project. More extensive information and supporting references can be found in the recommended reading listed in the end of this chapter. The chapter emphasizes that the issue of concern is the net climate change effects of bioenergy implementation, assessed in the specific context where policies to promote bioenergy are developed and bioenergy products are produced. The so-called "carbon neutrality debate" concerns an ambiguous concept and distracts from the broader and much more important question: *how can forests and the forest product industry serve a range of functions while contributing to climate change mitigation – through carbon sequestration, storage, and substitution of fossil fuels and other products that cause high GHG emissions?*

3.2 FOREST BIOENERGY SYSTEMS AND CARBON BALANCES

In industrialized countries, forest biomass for bioenergy is typically obtained from a forest managed for multiple purposes, including the production of pulp and saw logs, and provision of other ecosystem services. Thus, forest bioenergy is not a single entity, but includes a large variety of sources and qualities, conversion technologies, end-products and markets. Forest bioenergy systems are often components in value chains or production processes that also produce material products, such as sawn wood, pulp, paper and chemicals. Bioenergy feedstocks mainly consist of by-products from sawn wood and pulp and paper production, and small diameter trees and residues from silvicultural treatments (e.g., thinning, fire prevention, salvage logging) and final felling. A large fraction of this biomass is used to supply energy within the forest industry. Energy co-products (electricity and fuels) from the forest industry are also used in other sectors. Consequently, the technological and economic efficiencies, as well as the climate mitigation value, will vary.

The fossil fuel used for harvesting, chipping and truck transport typically corresponds to a few percent of the energy content in the supplied biomass. Thus, the fossil carbon emissions are typically small for forest-based bioenergy systems and the climate impacts are therefore mainly related to

[11] Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., Yeh, S. (2016). Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3. European Forest Institute.

how the forest carbon cycle is affected by management changes to provide biomass for bioenergy in addition to other forest products. The key issue is the change (if any) in average carbon stock across the whole forest landscape. Scientists have reported that bioenergy systems can have positive, neutral or negative effects on biospheric carbon stocks, depending on the characteristics of the bioenergy system, soil and climate factors, and the vegetation cover and land-use history in the locations where the bioenergy systems are established.

Thus, the promotion of forest bioenergy needs to reflect the variety of ways that forests and forest-related sectors contribute to climate change mitigation. The impact of bioenergy implementation on net GHG emission savings is both context- and feedstock-specific due to that many important factors vary across regions and time. Changes in forest management that take place due to bioenergy demand depend on factors such as forest product markets, forest type, forest ownership and the character and product portfolio of the associated forest industry. How the forest carbon stock and biomass output are affected by these changes in turn, depends on the characteristics of the forest ecosystem. There can be trade-offs between carbon sequestration, storage, and biomass production.

Studies that estimate the GHG emissions and savings associated with bioenergy systems have often focused on supply chain emissions and have adopted the assumption that the bioenergy systems under study do not have any impact on the carbon that is stored in the biosphere. This “carbon neutrality” of bioenergy is claimed on the basis that the bioenergy system is integrated in the carbon cycle (Figure 3:1) and that carbon sequestration and emissions balance over a full growth-to-harvest cycle.

While the reasoning behind the carbon neutrality claim is valid on a conceptual level, it is well-established that bioenergy systems – like all other systems that rely on the use of biomass – can influence the cycling of carbon between the biosphere and the atmosphere. This is recognized in the United Nations Framework Convention on Climate Change (UNFCCC) reporting: biogenic carbon emissions associated with bioenergy are not included in the reporting of energy sector emissions, not because bioenergy is assumed to be carbon neutral but simply as a matter of reporting procedure. Countries report their emissions from energy use and from land use, land use change and forestry (LULUCF) separately. Because biogenic carbon emissions are included in the LULUCF reporting, they are not included in the energy sector as this would lead to double-counting.

When biomass from existing managed forests is used for bioenergy, the critical question is how this biomass use influences the balance and timing of carbon sequestration and emissions in the forest, and hence, the timing and the overall magnitude of net GHG emission savings. The fossil fuel (GHG) displacement efficiency – how much fossil fuels or GHG emissions are displaced by a given unit of bioenergy – is another critical factor. The diverging standpoints on bioenergy can be explained to a significant degree by the fact that scientists address these critical factors from different points of view. The conclusions vary because the systems under study differ, as do the methodology approaches and assumptions about critical parameters. This is discussed further in section 3.3 below.

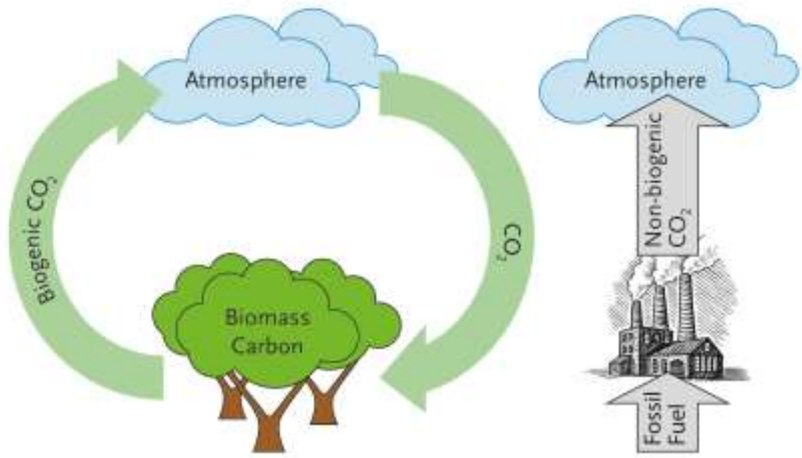

Figure 3:1. The Intergovernmental Panel on Climate Change (IPCC) distinguishes between the slow domain of the carbon cycle, where turnover times exceed 10,000 years, and the fast domain (the atmosphere, ocean, vegetation and soil), where vegetation and soil carbon have turnover times of 1-100 and 10-500 years, respectively. Fossil fuel use transfers carbon from the slow domain to the fast domain, while bioenergy systems operate within the fast domain Figure: National Council for Air and Stream Improvement.

3.3 EVALUATING CARBON BALANCES AND CLIMATE CHANGE IMPACTS

Forest carbon balances are assessed differently due to the different objectives of studies. For instance, the objective might be to determine the climate effect of specific forest operations (e.g. thinning, fertilization, harvest); or determine the carbon footprint of a bioenergy product; or investigate how different forest management alternatives contribute to GHG savings over varying timescales.

The IPCC concludes that cumulative emissions of CO_2 largely determine global warming by the late 21st century and beyond. The exact timing of CO_2 emissions is much less important than how much carbon is emitted in total in the long run. Thus, in relation to temperature targets, the critical question is how forest management and biomass harvest for energy influences forest carbon stocks over the longer term, since this in turn influences cumulative net CO_2 emissions. The influence of bioenergy expansion on investments into technologies and infrastructure that rely on fossil fuels is also critical, since this has strong implications for future GHG emissions. A long-term view is also needed to align assessments with timescales suitable for forest ecosystems and forest management planning.

Short-term GHG emissions reduction targets have been adopted to drive progress towards the cuts necessary to meet the global temperature target. Short-term GHG targets can also be due to concerns over ocean acidification, and a desire to slow the rate of warming, which has important consequences for the capacity of ecosystems to adapt to climate change, and avoid transgressing possible climate tipping points. It is important to clarify how forest bioenergy and forest management in general can serve both these short-term and long-term objectives.

Major methodological choices which can have large influence on outcomes include:

- **Definition of a counterfactual no-bioenergy (reference) scenario**: How do forest markets, forest management, and forest carbon stocks evolve in the absence of bioenergy demand and production? Which energy alternatives are used instead of bioenergy?
- **Spatial system boundary:** Are carbon balances assessed at the forest stand level or at the forest landscape (system) level?
- **Temporal system boundary:** What is the time period of assessment and how does it compare with the forest rotation period? When is the accounting begun in relation to the first harvest for bioenergy?
- **Scope:** Are economic and social aspects included and are market-mediated effects considered? Is the bioenergy system assessed in isolation or does the study examine how forest management as a whole responds to bioenergy incentives and how this in turn affects the state of the forests and forest product outputs? Does the study investigate the role of bioenergy within the integrated energy-land use-natural carbon cycle?

3.3.1 Reference scenarios

The range of reference (counterfactual) scenarios in the literature represents the differences in the scope and objectives of studies, and the context of the bioenergy system being evaluated. It can also reflect aspects such as access to data and models, and the principles associated with the chosen assessment method.

Studies that quantify GHG balances for bioenergy systems either focus on absolute GHG emissions and carbon sequestration, or consider net GHG balances by comparing a bioenergy scenario with a reference scenario where the assessed bioenergy system is absent. This reference scenario must include a specification of a reference forest system and a reference energy system. For the latter, a straight-forward and transparent approach is to specify the GHG displacement efficiency based on the characteristics of the chosen reference energy system. The parameter can be held constant or set to change over time, to reflect the fact that the reference energy system may change over time.

Studies that assess the emissions reduction due to a specific bioenergy product often consider forest bioenergy as a marginal activity. Additional harvest for bioenergy is compared with a "business as usual" (BAU) situation with forest management producing the same mix of forest products, besides the bioenergy product. For example, a bioenergy scenario where residues from forest felling are harvested for bioenergy may be compared with a reference scenario where these residues are left to decompose on the ground.

Studies that model economic and market reactions include economic equilibrium modelling where the reference is represented by a state in equilibrium. The GHG and other impacts associated with the bioenergy system are investigated by applying a bioenergy demand shock to this market equilibrium state. The impacts are quantified by comparing the old and new state of market equilibrium.

Studies that use integrated systems modelling commonly include reference scenarios. Rather than providing a basis for calculating net effects, these reference scenarios are usually presented and analysed together with several alternative scenarios that may include more or less bioenergy supply. The definition of the reference scenario has a strong influence on the outcome of assessments. It is essential that reference scenarios are explicitly presented and justified.

3.3.2 Assessment scales in time and space

The appropriate spatial and temporal scales for assessment are key when assessing forest carbon balances. In countries where forestry is based on rotation-forestry systems with even-aged forest stands and a balanced stand age distribution on the landscape level (e.g. Sweden), one spatial scale considered in assessments is the forest stand, i.e., the typical scale for final felling operations. Studies then often focus on assessing the carbon balance associated with distinct operations, such as salvage harvest and residue collection for bioenergy at final felling. They also consider changes in forest management practices, such as when thinning intensity increases and some volume of biomass is extracted for energy, in addition to the wood that is extracted for the production of sawn wood, paper and other forest products. The bioenergy system is often evaluated in isolation, i.e., it is not considered whether the forest management and output of other forest products is affected by the presence of the bioenergy system.

Studies may consider forest carbon balances over one or several rotation periods for the stand, i.e., longer than a 100-year time horizon. If the policy objective is short-term emission reductions, studies may evaluate bioenergy options by calculating carbon balances for a shorter time than a forest rotation.

One drawback of stand-level assessments is that they prescribe a strict sequence of events (site preparation, planting or natural regeneration, thinning and other silvicultural operations, final felling) that in reality occur simultaneously across the forest landscape. The assessment outcome can therefore vary drastically depending on how the temporal carbon balance accounting window is defined. If the carbon accounting starts at the time of the first biomass extraction and use for bioenergy, i.e., commencing with a pulse emission followed by a phase of sequestration, there will be – by design – often an initial net GHG emission. This initial net GHG emission is commonly referred to as a “carbon debt” and it follows that net emissions savings are delayed until this debt has been repaid. The exception occurs when the bioenergy system displaces more GHG emissions than those associated with the bioenergy system itself.

If the purpose is to investigate the effects of introducing biomass extraction for energy as a new component in the management of an existing forest, it might be appropriate to start the accounting at the time of the first biomass extraction for bioenergy. However, if the purpose is to investigate the climate effects of incentivizing bioenergy, the definition of the time period for accounting is less clear. Landowners and other actors in the forest sector can respond to bioenergy incentives in many different ways, and forest management might be adapted to anticipated bioenergy demand in advance of the first biomass extraction and its use for bioenergy. Due to this, it might be considered appropriate to start the carbon balance accounting clock earlier, e.g., at the time of a change in forest management. Figure 3:2 illustrates the possible developments for carbon stocks in managed forests when management changes to include biomass extraction for bioenergy.

As the outcome of stand-level assessments is very sensitive to these types of methodological decisions, this may at least partly explain strongly divergent views on the climate effects of forest bioenergy. Statements such as: "it can take many decades until a regrowing forest has captured the carbon that was released when trees were harvested and burned for energy", and "theories on carbon debt and payback time of biomass are not credible, because they are based on the unrealistic assumption that trees are burned before they have grown", implicitly reflect positions on the proper time period for accounting, which are left undeclared in the debate.

Studies intending to inform policy development need to consider how bioenergy incentives can affect the state of forests and the forest sector's contribution to climate change mitigation through carbon sequestration, carbon storage and fossil fuel displacement, and how this in turn affects the GHG impacts of bioenergy implementation over time.

Landscape-scale assessment can provide a more complete representation of the dynamics of forest systems, as it can integrate the effects of all changes in forest management and harvesting that take place in response to – experienced or anticipated – bioenergy demand. It can therefore help to clarify how total forest carbon stocks are affected by specific changes in forest management. For example, stand-level assessments show that carbon stored in logging residues is emitted earlier to the atmosphere when the residues are used for energy instead of being left to decay in the forest. In such studies, the assessment outcome is simply determined by the decay time of residues in the forest, and the GHG displacement efficiency of bioenergy use. Assuming the same GHG displacement efficiency, slash tends to score better than stumps in the same location, because stumps decay slower, and each type of residues scores worse in boreal biomes than in temperate and tropical biomes where it decays faster. Landscape-level assessments provide another perspective. They show that the gradual implementation of residue collection at logging sites will have a relatively small influence on the development of the carbon stock in the forest as a whole, which is affected by many other factors that can change in response to bioenergy incentives.

A forest landscape can simply be represented by a series of time-shifted stands. Such theoretical landscapes can be used to illustrate how forest carbon stocks are affected by specific changes in forest management, such as an altered average rotation period or the establishment of new practices such as stump harvesting at final felling.

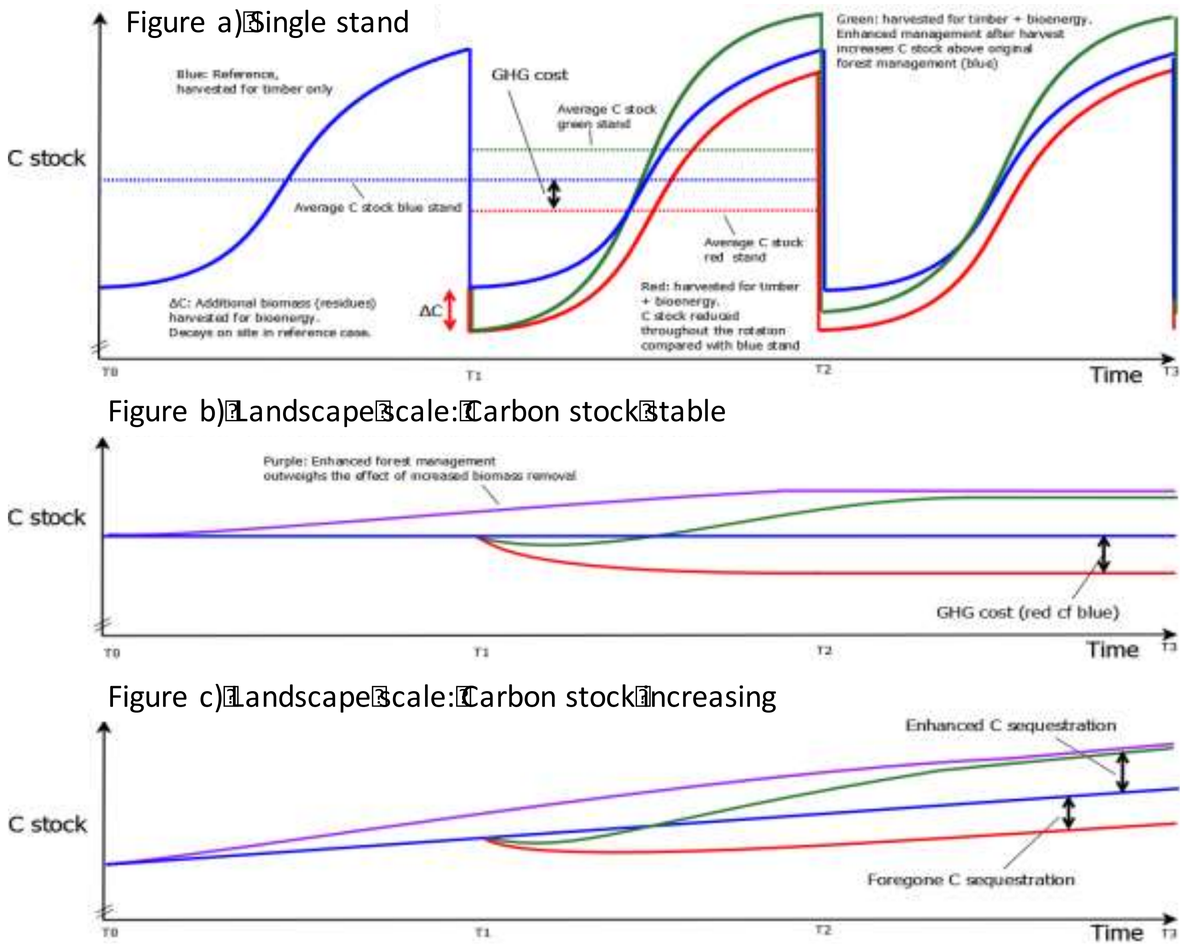

Figure 3:2. Simplified representations of the carbon stocks in a managed forest. The diagrams do not show changes in rotation period or the carbon stock fluctuations around these simplified curves caused by climate variation and forest operations such as thinning. Figure a shows the carbon stock (sum of carbon in trees, soil and litter) of an individual stand, over successive rotations. The blue curve shows the reference scenario, a forest harvested for timber only. The other curves show two alternative scenarios, in which harvest residues (branches and tops), usually left in the forest, are removed for bioenergy at harvest, at time T1 and each successive harvest. The concept of "GHG cost" is illustrated in the red curve: the average carbon stocks are lower compared with the blue stand, due to removal of harvest residues, and, possibly, flow-on effects on soil carbon stocks and forest growth rate. The green curve illustrates how enhanced forest management can reduce the GHG cost. Figures b and c show the total carbon stocks summed across a landscape of multiple stands at different stages in the rotation cycle, assuming that all stands follow either the blue, red or green curves from Figure a. In reality, the forest carbon stock on the landscape level will reflect a mix of different management approaches applied to different stands, which may include adjustment to the rotation period. An additional curve, in purple, shows a scenario where changes in forest management across the forest landscape outweigh the effect of increased biomass removal for bioenergy, so that the forest carbon stock increases on landscape level. Figure c shows a situation where the carbon stocks across the landscape are increasing, such as where the national estate is dominated by young stands; over time, the total carbon stocks increase as these stands mature. Although the total stocks continue to increase in all scenarios in Figure c, biomass removal can lead to "foregone sequestration" (red curve), though this can be reduced or avoided through enhanced forest management (green and purple curves). Be reminded that the net GHG mitigation of associated bioenergy systems also depends on the GHG displacement efficiency; i.e., a bioenergy system that is associated with declining forest carbon stocks (red curve) can deliver higher GHG mitigation than another bioenergy system that is associated with increasing forest carbon stocks (green or purple curves) if the latter has much lower GHG displacement efficiency. Source: IEA Bioenergy: ExCo:2013:04

3.3.3 Integrated modelling of forest systems and associated markets

Forest management is linked to the economic incentives and market expectations of forest owners for different forest products. Bioenergy is typically only one of the many forest products that are supplied to markets. Although in many European countries sawn wood currently generates the major income for forest owners, an anticipated increase in demand for bioenergy can incentivize investments in measures to increase forest production and biomass output. For example, forest owners may implement measures to protect their forests against disturbances, replanting and tending the forest and introducing more productive tree species and provenances.

An integrated modelling approach that captures economic and biophysical dynamics and interactions (bioeconomic modelling) can be used to study how forest management will vary depending on the characteristics of demand, forest structure, climate, forest industry profile, forest owners' views about emerging bioenergy markets, and the outlook for other forest product markets. Such studies can reveal how adjustments across affected systems (including the forest, product uses, markets and processing technologies) combine into a positive, negative, or neutral influence on the development of forest carbon stocks and GHG emissions.

One important finding from studies that apply bioeconomic modelling is that the effects of bioenergy on atmospheric carbon are more variable than suggested by studies which exclude economic factors and fail to consider the diversity and dynamic characteristics of forests and the forest sector.

As an illustration of the variation of outcomes, incentivizing wood-based energy markets could potentially increase the price of small-diameter logs used for pulp, board, round timber and other products. In some regions, this might encourage forest owners to opt for shorter rotation ages, and the pulp and paper industry could face increased raw material competition. In other regions, forest management aimed at an economically optimal output of forest products might instead result in longer average rotation periods, reduced sawn wood output, and increased pulpwood and forest fuel output due to increased thinning frequency. The effects on forest carbon storage can vary from positive to negative depending on the character of the forests and conditions for its management.

Insights from integrated modelling approaches give strong reason to object to generalizing statements about the climate effects of forest bioenergy. Evidence suggests that incentives to promote forest bioenergy can result in decreases as well as increases in forest carbon stocks in the landscape. The longer-term climate benefit of different forest management scenarios depends on the structure of the forest and associated industry and markets.

3.3.4 Integrated modelling of bioenergy in global climate scenarios

Energy system modelling and integrated assessment (IA) modelling frameworks cover all major energy sectors, and for IA models also the agriculture, forestry, and climate and ocean carbon pools. They integrate questions about energy infrastructure turnover, energy substitutions and counterfactuals, and are suited to examining the evolution of the modelled systems in a holistic and consistent fashion.

The IA models analyse the spatial and temporal trade-offs among land-use and land cover changes, deforestation and reforestation, investments in fossil, renewable, and other technologies. Any solutions from the models must be understood in the context of the emissions trade-offs made in the models. For example, the slower adoption of low-carbon technologies in one sector or time period often implies more rapid reductions elsewhere in the system.

This type of systems modelling studies show the relative cost-effectiveness of bioenergy options in different sectors in the context of climate targets, other policy objectives, and alternative energy options. They can reveal competitive and also synergistic interaction with other energy technologies. They can also provide insights into the long-term benefits of investments in R&D and technological change, and the influence of bioenergy incentives on investments in industry, energy and transport systems with implications for future GHG emissions commitments. As shown in Figure 3:3, the last decade has seen a significant rise in global investments in renewable energy sources. However, so far these investments have not brought about the rate of decline in fossil energy use which is judged to be needed for reaching ambitious climate targets. Besides the immediate GHG savings associated with their use, bioenergy and other mitigation options need to be evaluated for their contribution to phasing out technologies and infrastructure that rely on fossil fuels, so that fossil carbon is left in the ground permanently.

Conclusions from systems modelling studies may appear counter-intuitive and difficult to reconcile with simple stand/landscape-level assessments. The dominant bioenergy options in scenarios that meet stringent climate targets may not be the ones that are assessed as having the highest GHG reduction capacity per unit of biomass. For example, assessments of GHG balances may indicate that using bioenergy to displace fossil fuels in heat and electricity generation provides a larger GHG emissions reduction per unit of biomass (or land) than displacing petrol or diesel used in transport. But systems modelling shows that the attractiveness of different bioenergy options depends on – among other things – the availability and cost of other carbon-free options than biofuels in the transport sector, and how the carbon emission reduction targets are implemented. To take another example, bioenergy options that cause relatively higher upfront emissions (due to biospheric carbon losses) may be among the preferred ones in scenarios that meet stringent climate targets.

The consensus view expressed in the IPCC is that there is no agreed vision about where biomass could be cost-effectively deployed within the energy system, due in large part to uncertainties about technological developments and costs over time. But it has been consistently shown that bioenergy contributes significantly to the energy supply in most scenarios that meet ambitious climate targets (this result is also summarised by the IPCC 5th Assessment Report, AR5). The studies reviewed by the IPCC indicate a high risk of failing to meet long-term climate targets without bioenergy. Results show that, with existing technologies, it would be very difficult to meet the temperature target set out in the Paris Agreement, unless bioenergy contributes a significant share of energy needs.

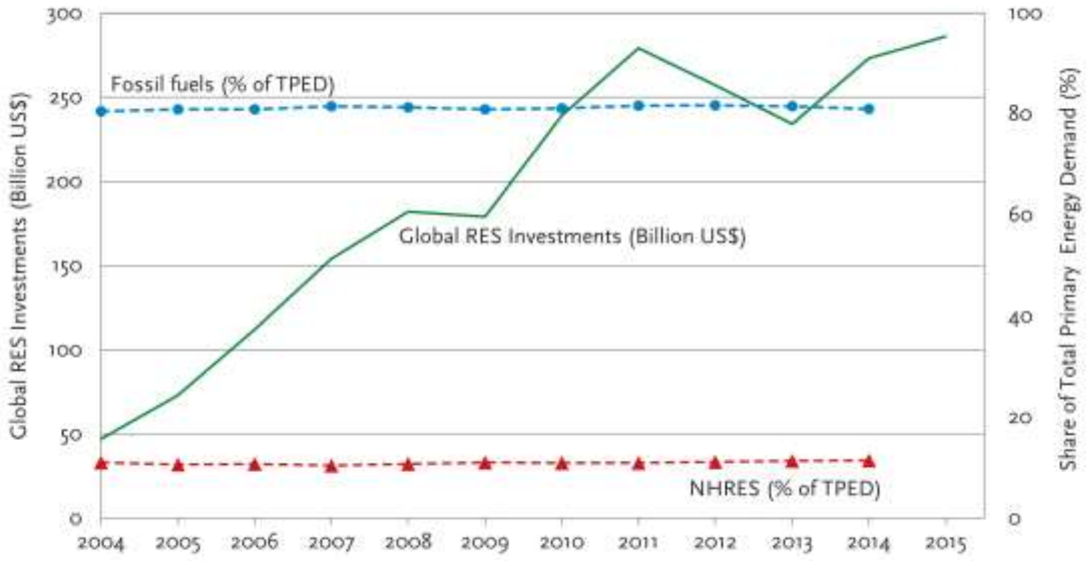

Figure 3:3. Global investments in renewable energy sources (RES in diagram). TPED: total primary energy demand. NHRES: non-hydro RES. Source: Filip Johnsson, Jan Kjaerstad and Johan Rootzén, Chalmers University of Technology, Sweden.

3.3.5 Impact metrics and policy targets

A metric is a measure used to quantify or assess a variable of interest. The usual metric for quantifying the climate effects of different GHGs, applied in GHG accounting such as for reporting to the UNFCCC, is Global Warming Potential (GWP). GWP expresses the integrated radiative forcing (warming impact) of a greenhouse gas relative to that of CO_2, over a fixed period, usually 100 years (GWP100). Using the relevant GWP for each different greenhouse gas, the aggregated value is then expressed as "CO_2-equivalents" (CO_2-eq).

Global Temperature change Potential (GTP) has been proposed as an alternative metric. The IPCC's Fifth Assessment Report (2014) provides GTP as well as GWP values for the greenhouse gases, with time horizons of 20 and 100 years. GTP is more closely related than GWP to the ultimate impacts of climate change: specifically, it refers to the impact on temperature reached at a defined future date. GTP100 emphasises the greenhouse gases with longer-term effects, reducing the contribution for gases with short atmospheric lifetimes such as methane.

To inform policy development, it is recommended that both GWP and GTP are applied, to gain a full understanding of the likely range of outcomes.

Recently several new metrics have been proposed that incorporate additional climate change effects that are relevant to bioenergy, including methods to (i) incorporate the effects of timing of emissions; (ii) equate albedo effects with CO_2 emissions; (iii) quantify the marginal impact on forest carbon stock due to marginal changes in forest management; (iv) integrate several aspects of temperature effects (absolute temperature reached, relative change and rate of change).

These metrics have been devised for application in life cycle analysis (LCA) studies. They are 'characterisation factors', which are multiplied by the emissions and removals quantified in the life cycle inventory to calculate climate change impact. None of these more nuanced metrics are currently applied under any carbon offset or renewable energy.

The net GHG emissions of a bioenergy product may be expressed as CO_2-equivalent per energy unit (MJ, per kWh) or per unit of "service" provided by the bioenergy product (e.g., heat generated or km driven). It is also relevant to consider the emissions saved per hectare of forest or per unit weight of biomass, or per euro spent. Different factors may define the extent to which land management and biomass-derived fuels can contribute to climate change mitigation, making the following indicators relevant in different contexts:

- The **displacement factor** describes the reduction in GHG emissions from the displaced energy system per unit of biomass used (e.g. tonne of CO_2-e avoided per tonne of carbon contained in the biomass that generated the reduction). This indicator does not discourage fossil inputs in the bioenergy chain if these inputs increase the displacement efficiency. It does not consider costs.

- The **relative GHG savings** describes the percentage emissions reduction with respect to the fossil alternative for a specific biomass use. GHG savings favour biomass options with low supply chain GHG emissions. However, this indicator alone cannot distinguish between different biomass uses, such as transport fuel, heat, electricity or combined heat and power, to determine which use reduces emissions more. It ignores the amount of biomass, land or money required, and it can be distorted as each use can have different reference systems.

- The indicator **GHG savings per ha** (or m^2 or km^2) of land favours high biomass yield and conversion efficiency but ignores costs. Intensified land use that increases the associated GHG emissions (e.g. due to higher fertilizer input) can still improve the indicator value if the biomass yield increases sufficiently.

- The indicator **GHG savings per euro spent** input tends to favour the lowest cost, commercially available bioenergy options. Prioritisation based on monetary indicators can lock in current technologies and delay (or preclude) future, more cost-effective or GHG reduction-efficient bioenergy options because their near-term costs are higher.

The choice of metric should be governed by the objective of the study, but is partly a subjective choice.

3.3.6 The role of bioenergy in climate change mitigation: synthesis

The science literature provides different views and conclusions on the climate impacts of forest bioenergy. This divergence appears to arise from different points of view on the context of the analysis and policy objectives. These have a strong influence on the formulation of research questions, as well as the methods and assumptions about critical parameters that are then applied in analyses, which in turn have a strong impact on the results.

- The net climate change effects of bioenergy should be assessed in the specific context where bioenergy policies are developed and bioenergy is produced. For forest bioenergy, this often means that studies should analyse bioenergy systems as components in value chains or production processes that also produce material products, such as sawn wood, pulp, paper and chemicals.

- Studies analysing carbon flows in individual forest stands can provide useful information with- in the limited boundaries of the studies, e.g., allowing benchmarking of different pathways on a common scale. However, the definition of the time period for carbon balance accounting (i.e., when to start the clock) has a strong impact on the outcome. The studies can even be misleading as a model for the forest sector and its overall impact on climate. Their limited scope reduces their usefulness for informing policymaking.

- The definition of reference scenarios (counterfactual) has a strong influence on the outcome of assessments. These scenarios should be clearly defined and justified in relation to the objectives of the study. It is essential that the results are carefully explained and interpreted correctly.

Information and knowledge from many scientific disciplines, applying a range of different methodologies, is needed to inform policy making for forest bioenergy. Important results and insights can be gained from energy systems modelling, IA modelling, and landscape level bioeconomic modelling that use location-specific biophysical and socio-economic data, and consider management responses and market effects in parallel sectors. These modelling studies should employ several alternative scenarios for critical factors, including policy options and energy technologies.

Some findings are intuitive and have implications for policy:

- The efficiency of biomass conversion and the GHG displacement associated with the use of bioenergy and other forest products are very influential on the assessed mitigation value of forest bioenergy, regardless of feedstock.

- The mitigation value grows over time as the quantity of displaced GHG emissions accumulates. In this sense, bioenergy is more favourable when long time horizons are applied, although uncertainty concerning GHG displacement efficiency of bioenergy also grows with longer time horizons.

Bioenergy contributes significantly to the energy supply in most scenarios that meet ambitious climate targets (summarized in IPCC AR5), indicating a high risk of failing to meet long-term climate targets without bioenergy. The IPCC did not find any convergence between modelling studies regarding the most cost-effective bioenergy deployment within the energy system, but lignocellulosic feedstocks dominate.

Some conclusions can be drawn from other types of studies about feedstocks from forests:

- The bioenergy based on by-products from forest industry processes (sawdust, bark, black liquor, etc.) is typically found to contribute positively to climate change mitigation also in the short-term.

- Tops and branches and biomass from some silviculture operations such as fire prevention and salvage logging are often found to support short-term mitigation.

The study results differ from each other the most concerning the GHG balance and mitigation value of using slowly decaying residues and roundwood as a feedstock for bioenergy.

- Studies that do not consider dynamic factors (e.g. forest management responses to bioenergy demand) may find that the use of small diameter trees and slowly decaying residues (e.g. stumps) does not contribute to net GHG savings in the short- or even medium-term (several decades). The use of larger diameter roundwood for bioenergy is sometimes found to not even deliver net GHG savings on multi-decade to century timescales.

- Studies that include parallel sectors and employ biophysical-economic modelling for larger landscapes report mixed results. Results are more favourable if the increased forest biomass demand also triggers investments that increase forest area and productivity, which in turn result in carbon gains on the landscape level.

- Certain parameter assumptions have a large influence on the outcome, for example, the GHG displacement efficiency.

Forest bioenergy is not a single entity, but includes a large variety of sources and qualities, conversion technologies, end-products and markets. Consequently, its technological and economic efficiencies as well as climate mitigation value will vary. Forest bioenergy should be considered as one of several products in a value chain or production process that also includes material products, such as sawn wood, pulp, paper and chemicals. The forest product portfolio may include bioenergy products that, according to some studies, do not provide near/medium-term GHG savings. But it is not certain that excluding these feedstocks from bioenergy markets will result in a new product portfolio with a higher contribution to climate change mitigation in the short and longer-term.

Regarding the need to balance short-term GHG targets with strategies that pursue long-term temperature stabilization goals, we caution that a strong focus on short-term GHG targets may result in decisions that make the longer-term objectives more difficult to meet. For example, a decision to prioritize carbon sequestration and storage in forests managed for wood production may help in meeting near-term GHG targets. However, this could mean an end-point where forests store more carbon but have a lower capacity for producing bioenergy and other forest products. The lack of viable alternatives and strategies towards long-term emissions targets implies a prolonged lock-in and continuous investments in fossil technologies. Events such as storms, insect infestations and fires can cause forest damage and losses of some of the carbon that was sequestered into forests as compensation for GHG emissions, which can further hamper the fulfilment of longer-term objectives.

There are aspects which science needs to address:

- Most current studies focus on greenhouse gases, despite the fact that the effect of other climate forcers can be significant. The effects of all climate forcers influenced by vegetation cover and forest management should ideally be included.

- The coupling of energy systems and land use, in particular the terrestrial carbon sink (dominated by forests remaining forest), can be further improved. For example, when developing a new generation of global climate scenarios, a better reflection of the effects of forest management should be a priority, especially for scenarios with a high share of bioenergy in the energy mix.

- The effects of climate change on forest growth and soil carbon are uncertain. Climate change is associated with risks, such as fires, storms, diseases and insect outbreaks that could greatly affect the carbon stock in the forest. Capacity for risk management and salvage logging, following events such as storm fellings, depends on whether forests are managed for wood production. These aspects need to be further addressed in future studies since they have strong implications for the attractiveness of different forest management strategies.

3.4 RECOMMENDED READING

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4 HOW TO ANALYSE ECOSYSTEM SERVICES IN LANDSCAPES

4.1 INTRODUCTION

Society benefits in a multitude of ways from ecosystem services (ES) that are delivered by natural and managed ecosystems. Some ES are recognized as essential (e.g., food and wood supply), but several ES may not be valued unless diminishing; the provisioning of clean drinking water and the decomposition of wastes are today commonly recognized as essential, but at the same time may be taken for granted when available. It can also be difficult to identify causes behind diminishing ES, the pollination by insects being one example.

The Millennium Ecosystem Assessment (MA) in 2003 brought global attention to the importance of ES and grouped these into four broad categories: provisioning, such as the production of food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefits. Since the MA was published, it has been shown that many ES are diminishing due to degradation and/or depletion of resources such as productive soils and fresh water. Human land use has been identified a major cause. Biodiversity loss is an additional concern since the variety of life at genetic, species and ecosystem level is a prerequisite for many ES. A great challenge for society's path towards a biobased economy is to develop sustainable landscape management systems that provide biomass, support biodiversity and ensure conditions for a multitude of ES. This requires methods to assess impacts on the conditions for ES and biodiversity, and stakeholder involvement in land use decisions.

Life Cycle Assessment (LCA) is often used to assess the environmental performance of bioenergy options and biomass production systems. Whilst LCA is very useful for comparing the environmental impacts of food and bioenergy supply chains, it has so far been of limited use to evaluate and inform spatially-explicit strategies for sustainable bioenergy deployment. LCA is, traditionally, not a tool that examines local impacts and thus has crucial gaps in this respect. There is a need for geographically explicit assessment methods that can incorporate site-specific characteristics and differentiate between management regimes in agriculture and forestry. In the latest UNEP/SETAC LCA guidelines (Koellner et al. 2013), further research was encouraged on how existing methods for quantifying and assessing ES (as well as impacts on these) can be adapted and incorporated into the life cycle impact assessment (LCIA) framework. As an alternative, other methodological approaches can be used in parallel with LCA and provide complementary information about impacts on ES.

This chapter presents a review of methods for analysing and mapping[12] ES in terrestrial landscapes, and attempts to clarify the associated terminology. More extensive information and supporting references can be found in the recommended reading listed in the end of this chapter.

Research on ecosystem services is a rapidly growing area. A systematic literature review identified 170 papers that mapped ES at a landscape scale, and 121 of these mapped ES at a relatively fine

[12] Mapping refers to the organization of spatially explicit quantitative information. It is used here as a collective term for all kinds of geo-explicit analysis.

resolution across landscapes. The remaining papers mapped ES at a coarser resolution (approximately 1 km or higher) or in monetary terms only. Almost half of the papers were published in 2015 and 2016, while only 14% of the papers were published before 2010. This is in line with observations in previously published reviews and confirms that ES research—also at the landscape scale—is a relatively recent and rapidly growing area.

Most studies were carried out in Europe (87), followed by North America (31), Asia (15), Africa and Australia (12 each), and South America (11). At a country level, most studies were carried out in the USA (26), followed by Germany (15), Australia (12), United Kingdom (11), the Netherlands (11), and Spain (10). Two studies did not focus on any specific country (Figure 4:1).

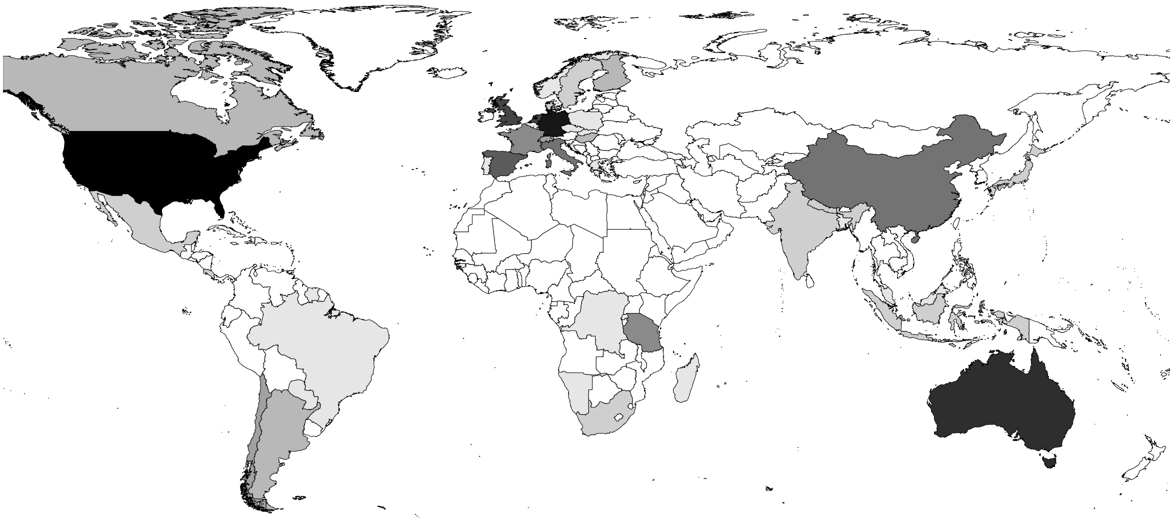

Figure 4:1. Geographical distribution of reviewed studies (n=170). The number of studies performed in each country ranges from 1 (light grey) to 26 (black). White = zero.

4.2 TYPOLOGY AND TERMINOLOGY

Several ES classification systems have been proposed. There are many useful ways to classify ecosystem goods and services, and a pluralism of typologies that can be useful for different purposes may be preferred to a single, consistent system. A drawback is that the use of multiple classification systems makes comparisons and integration of assessments with other data difficult. The Common International Classification of Ecosystem Services (CICES), is developed from the work on environmental accounting undertaken by the European Environment Agency (EEA). The aim of CICES is to propose a universal classification of ES that is both consistent with accepted categorizations and allows easy translation of statistical information between different applications.

The terminology in ES research remains inconsistent. For example, studies that use the MA typology include supporting services. The same "services" are in other studies considered to be ecological (or ecosystem) processes, following, e.g., The Economics of Ecosystems and Biodiversity (TEEB) typology. These are also sometimes referred to as intermediate ES. Furthermore, some consider ecosystem functions to be synonymous with ecosystem processes, while others do not. While terms are often used arbitrarily, inconsistency is also due to an ongoing scientific discourse. It has been argued that definitions of ES are purpose-dependent and should be judged on their usefulness for a specific purpose. However, co-existence of different terminologies and definitions could impede on-the-ground use of the concept. Diversity is important for advancing science and knowledge, but can create difficulties in situations where governance agreements are to be made—particularly where multiple goals need to be considered. At present, work is in progress to establish working definitions of commonly used terms. This may, along with the advancement of the CICES classification, help to harmonize the terminology and make studies more consistent and comparable. Definitions of commonly used terms are presented in Table 4:1.

Table 4:1. Definition of commonly used terms.

Term	Definition
Ecosystem structure	Static ecosystem characteristics: spatial and non-spatial structure, composition and distribution of biophysical elements. Examples: land use, standing crop, leaf area, % ground cover, species composition
Ecosystem processes	Dynamic ecosystem characteristics: Complex interactions among biotic and abiotic elements of ecosystems causing physical, chemical, or biological changes or reactions. Examples: decomposition, photosynthesis, nutrient cycling and energy fluxes.
Ecosystem functions	The subset of *processes* and *structures* that, if benefiting to human well-being, provide *ES*. Can be defined as the capacity of ecosystems to provide *ES*. Example: carbon sequestration
Ecosystem properties	Refers collectively to *ecosystem structure* and *processes*.
Ecosystem services	Direct and indirect contributions of *ecosystem functions* to human well-being. Example: climate regulation, provision of food
Intermediate ecosystem service	*Ecosystem functions* that do not directly benefit to human well-being, but that support other functions that do. Synonymous with 'supporting services'
Ecosystem service providers	The ecosystems, component populations, communities, functional groups, etc. as well as abiotic components such as habitat type that are the main contributors to specific *ES*. Example: Forest tree communities are ES providers for global climate regulation.
Human well-being	A state that is intrinsically or instrumentally valuable for a person or society. Example: The MA classifies components of human well-being into: basic material for a good life, freedom and choice, health and bodily wellbeing, good social relations, security, peace of mind, and spiritual experience.
Ecosystem service supply	ES provisioned by a specific area over a given time period.
Ecosystem service demand	ES demanded in a specific area over a given time period.
Ecosystem service providing units/areas	Spatial units that are the source of *ES*. Commensurate with *ecosystem service supply*.
Ecosystem service benefiting areas	The complement to ES providing areas. *ES benefiting areas* may be far distant from respective *providing areas*. Commensurate with *ES demand*.
Landscape	An area viewed at a scale determined by ecological, cultural-historical, social and/or economic considerations.
Landscape services	The contributions of landscapes and landscape elements to human well-being.
Landscape multifunctionality	The capacity of a landscape to simultaneously support multiple benefits to society.

4.3 THE CONCEPT OF LANDSCAPE

In the year 2000, the European Landscape Convention (ELC) defined landscape as 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors'. The ELC, as well as the Convention for the Safeguarding of the Intangible Cultural Heritage and the Framework Convention on the Value of Cultural Heritage for Society, formally recognized and highlighted the landscape concept as central to matters of sustainability and the management of public spaces. It received a higher status in spatial planning and the meaning of 'landscape' – what it is and what it does – is subject to on-going discussions in relation to legislation, policy, planning, and management.

There are diverging views on the meaning of landscape, and landscape scale, as well as the spatial extent of a landscape as a spatial unit. Landscape scale has been defined as an intermediate integration level between the field and the physiographic region, but with an extent depending on the spatial range of the biophysical and anthropogenic processes driving the processes (or services) under study. Landscape units can be aggregated at various levels of abstraction, allowing – in principle – to build a hierarchical system of different landscape levels. Landscapes can therefore have very different character and size, and studies that relate to very different kinds of study areas may still claim to be performed at a landscape scale.

Amongst the reviewed papers, 94 areas referred to as "landscape" were identified (Figure 4:2). Their sizes range from 24 hectares (ha) to 122 million ha (roughly the size of South Africa). The extent of a landscape has been suggested to range from 100 to 10,000 ha, but only 23 out of the 94 areas were within this range. It is thus obvious that there are diverging views on the spatial extent of landscapes in the ES literature. The term is also sometimes used rather arbitrarily. To avoid this, areas referred to as landscapes should be described in a way that explains why they are considered landscapes.

Given the diverging views on the spatial extent of a landscape, there are also diverging views on the meaning of landscape scale. The view that landscape scale is referred to as having a landscape as a study area is common in the ES literature, although while some attempt to map ES across the landscape, others aggregate the ES under study to one value for the entire landscape. A study area can also be described as containing several "landscapes", each assigned an aggregated ES value. In such cases, some also refer to the entire study area as a landscape. Two studies may thus focus on the same area, refer to it as a landscape, but have widely varying views on what is meant by landscape scale.

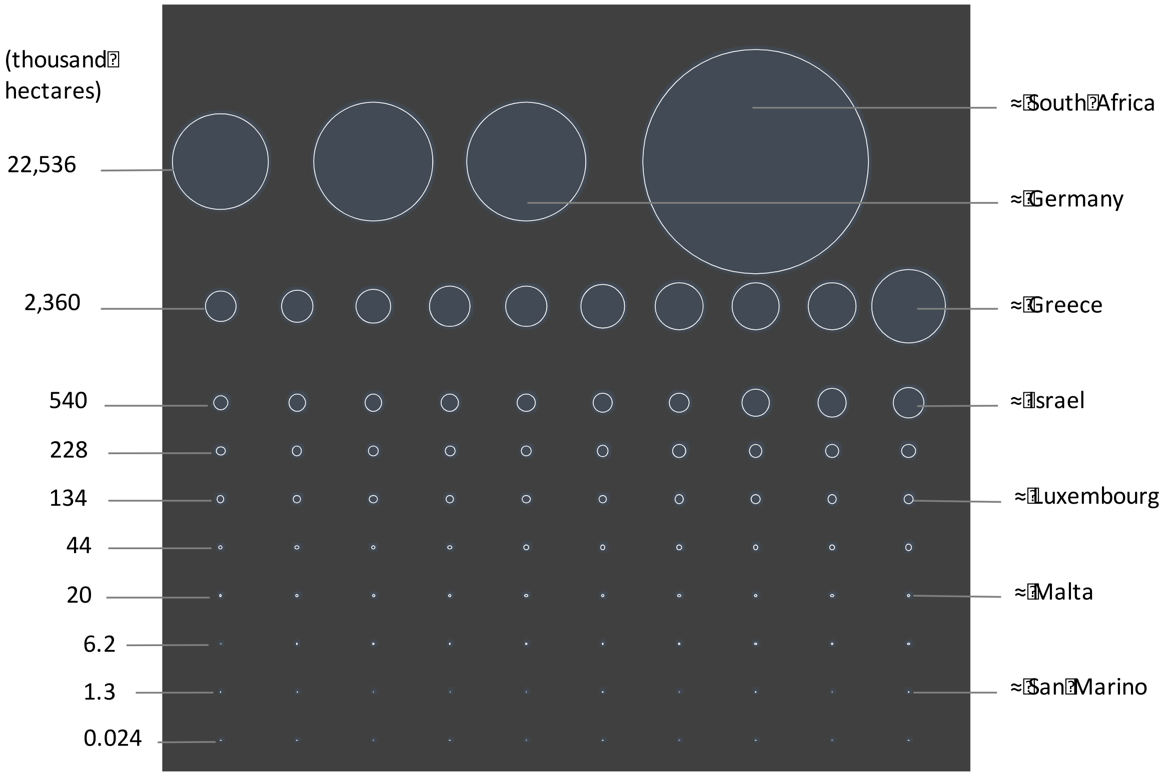

Figure 4:2. Size of the 94 areas referred to as "landscape" in the reviewed papers. Size is specified using absolute numbers for the areas at the far left of the figure, and using countries of an approximately equivalent size for the areas at the far right, to aid comprehension. Due to the large differences, the smallest 15 areas would not be visible in this figure without their outline. Hence, they appear similar in size.

4.4 METHODS FOR ANALYSING ES IN LANDSCAPES

There are a multitude of methods and tools available for mapping and analysing ES at different scales. This, along with inconsistencies in the terminology, creates uncertainties about appropriateness of methods. The inconsistent terminology can even cause uncertainty about what is being analysed. Most ES assessment studies so far use proxy methods, i.e., assigning ES values to an area based on simple characteristics, such as land cover type. Proxy-based methods may be appealing since they are much less complex than, for example, direct mapping with survey and census approaches, or empirical production function models. But there are disadvantages, such as the risk of generalization error, which makes them unsuitable for landscape scale studies. As landscapes are typically not mere combinations of ecosystems, but shaped by the interactions between ecosystem structures/processes and humans, the use of proxies at the landscape level is particularly sensitive to local conditions. Careful calibration and validation is therefore necessary, but this has typically not been done. Proxies may be suitable for identifying broad-scale trends in ES, or for global level and rapid assessments. But they are likely unsuitable for identifying, e.g., hotspots of single or multiple ES values, areas where ES are at risk, and how interventions to enhance ES could be designed. Additional data beyond land cover observation are therefore often necessary for an adequate assessment of ecosystem functions or services, especially at the landscape scale.

Figure 4:3 shows how many times different ES were mapped at a landscape scale in a selection of 347 cases where geo-explicit ES values were estimated. Regulating and maintenance services were most commonly mapped, followed by cultural, and provisioning services. An additional 24 “services” were mapped, that were either a combination (bundle) of individual ES or not covered by the CICES classification system. This includes “landscape services” where landscapes or specific landscape elements, rather than ecosystems, provide benefits to human well-being. A comparison with previous reviews indicates that mapping of cultural services is relatively more common in studies claimed to be done at the landscape scale. Concerning methodology approaches, Logical models and Empirical models were most commonly used, followed by Extrapolation, Simulation/Process models, Data integration, and Direct mapping. In ten cases, a combination of several method types was used.

The large variation shown in Figure 4:3 may reflect the perceived importance of different ES, but it may also reflect that some ES are easier to map than others. For example, the two most frequently mapped ES, global climate regulation and biomass production, are indisputably high priority in society and they are also easily mapped with adequate accuracy using proxies and statistics. Other ES that are also high priority, e.g., surface water and flow mediation, are much less frequently mapped. This may be explained by the more complicated methods required to map such ES with adequate accuracy. Furthermore, the supply of ES is much more commonly mapped than the demand, and few studies attempt to analyse or discuss spatial links between providing and benefiting areas.

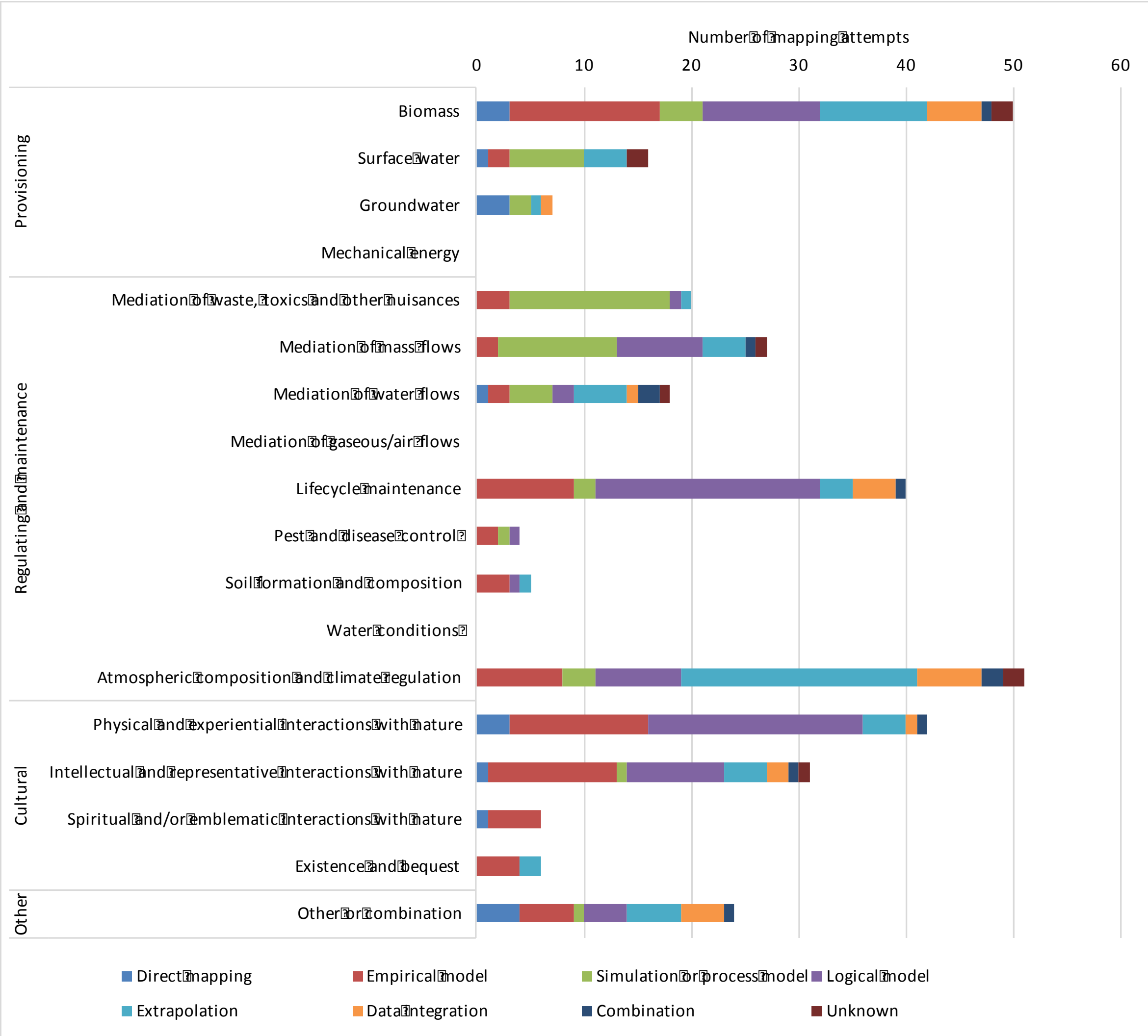

Figure 4:3. Number of times different ecosystem services have been mapped at a landscape scale, in 347 cases identified in our systematic review of the scientific literature (Englund et al. (2017). Methods (identified via colours in the diagram) were in many cases difficult to assess and categorize due to very brief or otherwise insufficient method description. In nine cases, it was not possible to determine which type of method had been used. This should serve as a reminder that method descriptions in scientific literature should not only facilitate understanding, but also reproduction. Several of the reviewed papers failed to facilitate the latter.

4.5 VALIDATION OF RESULTS

Excluding the cases that used direct mapping (that does not require validation), only 12% of all reviewed ES mapping cases were validated with empirical data. No difference was found between recent and older articles in this regard. Validation was almost exclusively applied in studies employing empirical models, simulation and process models, or logical models (Figure 4:4). It was most common for biomass, lifecycle maintenance, and physical and experiential interactions with nature, followed by mediation of waste, and mediation of mass flows. For all mapped ES, at least one study included validation (Figure 4:5).

The common lack of validation is noteworthy and the widespread use of non-validated proxy-based methods is a reason for concern. Collection of empirical data is time consuming and this probably explains why validation is most commonly made in studies that map ES using empirical models, or simulation and process models (fed with empirical data), where empirical data must be collected anyway. However, results that are not validated can be difficult to evaluate and thus be of limited use for both academia and society in, e.g., landscape planning. Validation should therefore be prioritised in ES mapping studies.

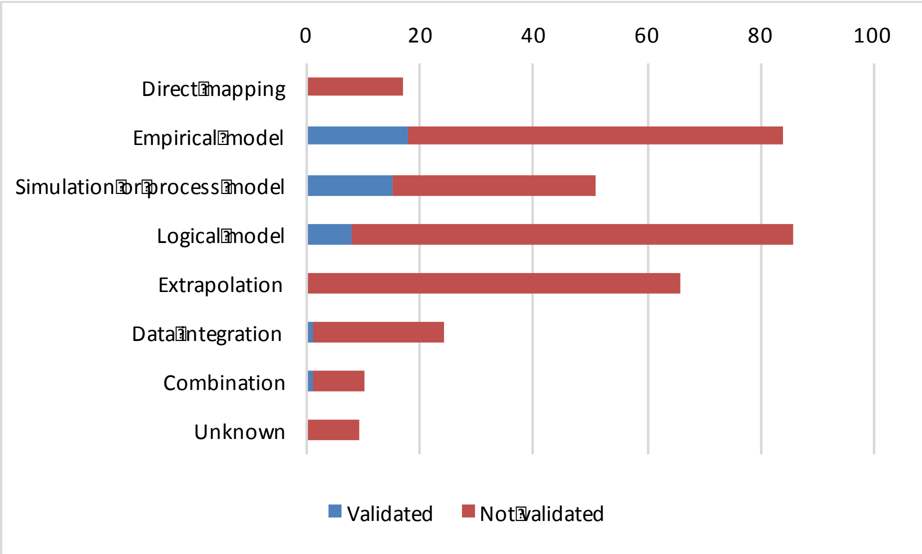

Figure 4:4. Number of cases where mapping results were validated (blue) and not validated (red) with empirical data, for the different method types.

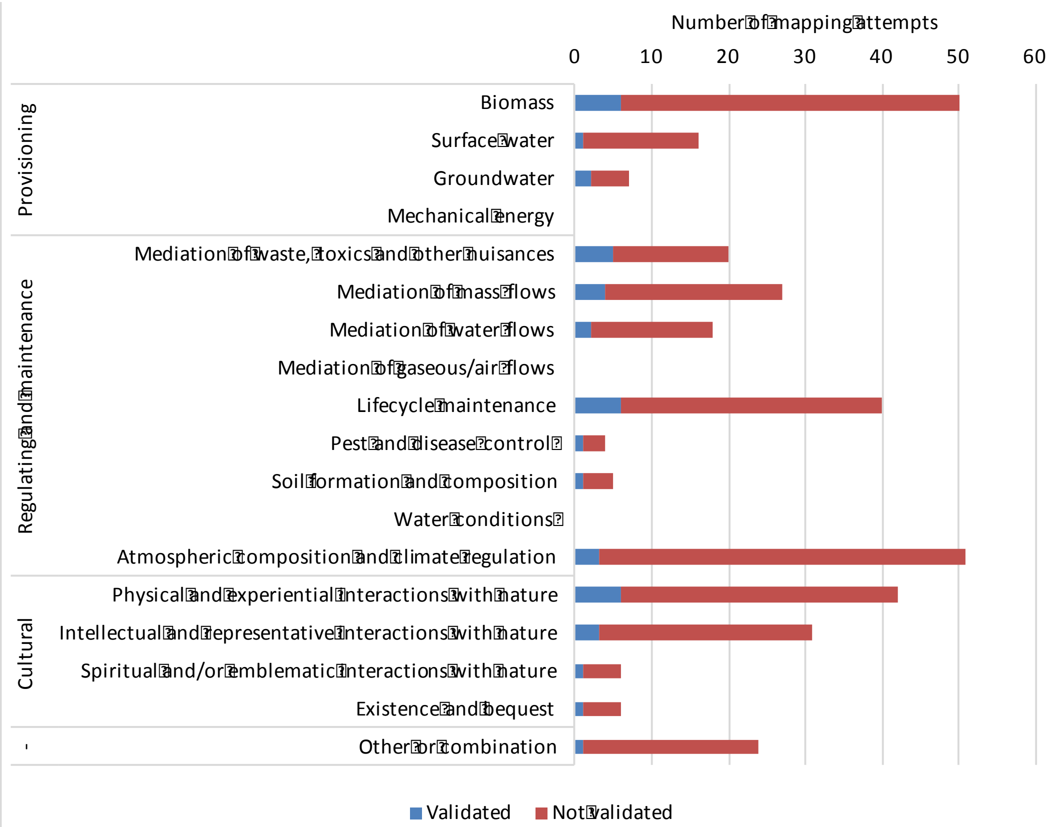

Figure 4:5. Number of cases where mapping results were validated (blue) and not validated (red) with empirical data, for the different ecosystem services.

4.6 DISCUSSION

Landscapes are commonly heterogeneous and the ES supply is unequally distributed across space. To support spatial planning and decision-making, ES assessments therefore need to be carried out in spatially explicit ways. A high level of detail and accuracy is necessary at varying spatial and temporal scales. Given the importance of high resolution and need for more complex methods and validation, most ES assessments with a landscape scope will need to limit the number of ES included in the study. To ensure that the most relevant ES are included, it is essential to involve stakeholders in the selection process. Furthermore, the capacity of the research group and available resources for the project may determine which ES can be included. In some cases (e.g., for global climate regulation or biomass production), proxy-based methods can provide ES values with acceptable accuracy, especially if they can be combined with empirical data, e.g., production statistics. But in general, ES that cannot be studied in other ways than with simple proxies, or be sufficiently validated, should preferably be omitted.

The suitability of methods depends on context as well as practitioners' competence, data availability, time frame, etc. Carefully calibrated empirical or process based models, validated against empirical data, can provide accurate and easily evaluated results, but they might not be relevant for certain ES, study areas, or research groups. The use of simple proxies in landscape level studies may generate misleading results. Practitioners with advanced GIS skills may benefit from creating their own models. However, some existing models, e.g., the InVEST model, have been applied many times, in several cases with validated and acceptably accurate results. When using third-party models, it is imperative that these are properly evaluated on their suitability for the specific project beforehand, and also calibrated and validated using empirical data.

Studies use different classification systems, but experience indicates that translation of ES into the CICES classification system is in most cases relatively straight-forward. Most of the ES that could not be fitted into CICES were either bundles of ES mapped together or examples of ecosystem processes rather than ES. Further development of CICES should consider whether to only include direct ES and thus exclude ecosystem processes and functions. For example, it can be argued that soil formation and composition is not a direct ES, but rather an intermediate ES, or an ecosystem function. The direct ES should rather be associated with what benefits to humans the soils facilitate; e.g., production of crops, or—indirectly, since soils facilitate vegetation growth—mediation of water and nutrient flows. Furthermore, "water conditions" was found to be redundant, as it refers to ensuring favourable living conditions for biota, which is similar to "lifecycle maintenance". Possible additions to CICES could be mediation of UV radiation, i.e., shade, which is an ES commonly used by humans and animals that is rarely described in the literature.

Finally, the comprehensiveness and use of more technical terms in CICES may create a barrier for communication and interaction with those that lack in-depth understanding of ES. Given the importance of stakeholder involvement in ES assessments, this is a clear disadvantage. It may therefore be beneficial to review the wording or to complement the typology with alternative, less technical, descriptions. This can preferably be coordinated with other initiatives that aim to inform policies and everyday practices, such as the Nature's contributions to people (NCP) concept within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

This chapter highlights the diversity of approaches to assess how land use influences ES, as well as the ICES initiative to harmonize the terminology and make studies more consistent and comparable. The systematic literature review, that provided the basis for this chapter, can serve as a starting point for further work to identify the methods and tools that appear to be most suited for adaptation and incorporation into the LCIA framework – and to clarify the direction for such an endeavour, including key data and knowledge gaps that need to be filled. Harmonization initiatives such as the ICES are naturally highly relevant in relation to such an ambition. One conclusion of further work may be that it is preferable to complement LCA studies with separate assessments of ES that are based on other methodology frameworks.

4.7 RECOMMENDED READING

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5 DISCUSSION AND GENERAL CONCLUSIONS FROM THE PROJECT

An overall conclusion in this study is that the development of more and more complex bioenergy systems - motivated by the need for more efficient utilization of biomass resources, improved greenhouse gas performance and additional environmental benefits (e.g. ecosystem services) - must be accompanied by parallel development of policy tools that can support these sustainability improvements.

As illustrated in the first example in this study (chapter 2), represented by biogas production systems using different categories of feedstock, the ranking based on their GHG performance and net demand of arable land are completely changed when the RED calculation methodology is replaced by the system expansion approach. From being one of the best biogas system, food industry residue-based biogas systems will be the system with lowest performance, whereas the opposite will be the case for perennial crop-based systems. Thus, today's RED calculation methodology represents an approach which clearly has too narrow systems boundaries and a lack of a dynamic approach taking into account temporal and spatial changeable conditions.

A number of conclusions and recommendations are made. A strict division between (i) residual biomass, determined to be burden-free, (ii) co-products, partly accountable for upstream emissions, and (iii) primary biomass crops, only including direct emissions, is counterproductive and will in many cases not lead to a real increase in environmental sustainability. When LCA methodologies are used in policy tools, these methodologies must comprise a dynamic perspective allowing temporal and spatial changes and differences. To avoid unwanted environmental effects related to specific biomass feedstocks and resources, irrespectively if they consist of residual biomass or primary energy crops, this must be resolved by other, direct and dedicated policy tools. Furthermore, policy tools developed to stimulate a circular economy must be harmonized with corresponding policy tools developed in a biomass-based economy. Thus, policy tools promoting biofuels should be as general as possible and based on technology- as well as feedstock-neutrality, and focus on the specific biofuel systems real GHG performance and on diminishing unwanted fossil vehicle fuels.

As shown in Chapter 3, analyses of forest bioenergy systems provide varying results depending on method approach, such as the definition of reference scenarios, the spatial scale that is considered and how temporal system boundaries are set. While stand-level assessments are too narrow for informing policy development, landscape-scale assessment can provide a more complete representation of the dynamics of forest systems, as it can integrate the effects of all changes in forest management and harvesting that take place in response to – experienced or anticipated – bioenergy demand. It can therefore help to clarify how total forest carbon stocks are affected by specific changes in forest management. In general, information and knowledge from many scientific disciplines, applying a range of different methodologies, are needed to inform policy making for forest based bioenergy.

It was concluded that net climate change effects of bioenergy should be assessed in the specific context where bioenergy policies are developed and bioenergy is produced. For forest bioenergy, this often means that studies should analyse bioenergy systems as components in value chains or production processes that also produce material products, such as sawn wood, pulp, paper and chemicals. Concerning different bioenergy options, it was concluded that bioenergy based on by-products from forest industry processes (sawdust, bark, black liquor, etc.) is typically found to contribute positively to climate change mitigation also in the short-term. Tops and branches and biomass from some silviculture operations such as fire prevention and salvage logging are also often found to support short-term mitigation. Studies that do not consider dynamic factors (e.g., forest management responses to bioenergy demand) may find that the use of small diameter trees and slowly decaying residues (e.g., stumps) does not contribute to net GHG savings in the short- or even medium-term (several decades). The use of larger diameter roundwood for bioenergy is sometimes found to not even deliver net GHG savings on multi-decade to century timescales. Studies that include parallel sectors and employ biophysical-economic modelling for larger landscapes report mixed results. Results are more favorable if the increased forest biomass demand also triggers investments that increase forest area and productivity, which in turn result in carbon gains on the landscape level. An omission in most studies is that non-GHG climate forcers are not considered, despite that these can have a similarly large impact on the climate.

The study of methods (and associated terminology) for assessing and mapping ecosystem services in landscape revealed a significant diversity in methodological approaches and an inconsistent terminology. But we also found harmonization initiatives, such as the International Classification of Ecosystem Services (CICES) classification system, developed by the European Environment Agency (www.cices.eu). In summary, it was found that Proxy-based methods have the advantage that they are much less complex than, for example, direct mapping with survey and census approaches, or empirical production function models. But there are disadvantages, such as the risk of generalization error, which makes them unsuitable for landscape scale studies. Given the importance of high resolution and need for more complex methods and validation, most ecosystem services assessments with a landscape scope will need to limit the number of ecosystem services included in the study. To ensure that the most relevant ecosystem services are included, it is essential to involve stakeholders in the selection process. Practitioners with advanced GIS skills may benefit from creating their own models, but some existing models have been applied many times and with validated and acceptably accurate results. When using third-party models, it is imperative that these are properly evaluated on their suitability for the specific project beforehand, and also calibrated and validated using empirical data.

Translation of ecosystem services into the CICES classification system is in most cases relatively straight-forward. But the comprehensiveness and use of more technical terms in CICES may create a barrier for communication and interaction with those that lack in-depth understanding of ecosystem services. Given the importance of stakeholder involvement in assessments of ecosystem services, this is a clear disadvantage. It may therefore be beneficial to review the wording or to complement the typology with alternative, less technical, descriptions. This can preferably be coordinated with other initiatives that aim to inform policies and everyday practices, such as the Nature's contributions to people (NCP) concept within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

6 LIST OF PUBLICATIONS AND CONTRIBUTIONS TO EVENTS

6.1 PUBLICATIONS (ALPHABETICAL)

Berndes, G., Fritsche, U. (2016). May we have some land use change, please? Biofuels, Bioproducts and Biorefining, DOI: 10.1002/bbb.1656

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., Yeh, S. (2016). Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3. European Forest Institute.

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., Yeh, S. (2016). Forest biomass, carbon neutrality and climate change mitigation. Think Forest Brief. European Forest Institute.

Berndes, G., Bergh, J., Cowie, A., Egnell, G., Hetemäki, L., Kauppi, P., Khanna, M., Kurz, W., Lindner, M., Lundmark, T., Nabuurs, G.-J., Sims, R., Solberg, B. (2018). Forests, bioenergy and climate change mitigation: are the worries justified? Open Letter available at European Forest Institute.
http://www.efi.int/files/attachments/press_releases/letter_on_forests_bioenergy_and_climate_jan_16_final.pdf

Börjesson, P., Hansson, J., Berndes, G. (2017). Future demand for forest-based biomass for energy purposes in Sweden. Forest Ecology and Management,
http://dx.doi.org/10.1016/j.foreco.2016.09.018

Cintas, O., Berndes, G., Börjesson, P., Egnell, G., Hansson, J., Poudel, B., Ågren, G. (2016). The Role of Swedish Forest to Achieve the Climate Neutrality Target in the Energy Sector by 2050. Proceedings 24th European Biomass Conference and Exhibition. ISBN 978-88-89407-165 ISSN 2282-5819

Cintas, O., Berndes, G., Hansson, J., Poudel, B.C., Bergh, J., Börjesson, P., Egnell, G., Lundmark, T., Nordin, A. (2017). The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. Forest Ecology and Management,
http://dx.doi.org/10.1016/j.foreco.2016.07.015

Cintas, O., Berndes, G., Cowie, A.L., Egnell, G., Holmström, H., Marland, G., Ågren, G.I. (2017) Carbon balances of bioenergy systems using biomass from forests managed with long rotations: Bridging the gap between stand and landscape assessments. Global Change Biology Bioenergy, DOI: 10.1111/gcbb.12425

Cowie, A., Ximenes, F., Berndes, G., Brandao, M., Lamers, P., Marland, G. (2016). Policy institutions and forest carbon. Reply to “Rethinking forest carbon assessments to account for policy institutions”. Nature Climate Change 6 (Sept 2016) 805

Cowie, A. Berndes, G., Junginger, M., Ximenes, F. (2017) Response to Chatham House report “Woody Biomass for Power and Heat: Impacts on the Global Climate”. IEA Bioenergy, 13 March 2017.

Cowie, A. Berndes, G., Junginger, M., Ximenes, F. (2017) Response to Chatham House report "Woody Biomass for Power and Heat: Impacts on the Global Climate". Supporting document. IEA Bioenergy, 13 March 2017.

Dale VH, KL Kline, ES Parish, AL Cowie, R Emory, RW Malmsheimer, R Slade, CT Smith, TB Wigley, NS Bentsen, G Berndes, P Bernier, M Brandão, H Chum, R Diaz-Chavez, G Egnell, L Gustavsson, J Schweinle, I Stupak, P Trianosky, A Walter, C Whittaker, M Brown, G Chescheir, I Dimitriou, C Donnison, A Goss Eng, KP Hoyt, JC Jenkins, K Johnson, CA Levesque, V Lockhart, MC Negri, JE Nettles, M Wellisch (2017) Status and prospects for renewable energy using wood pellets from the southeastern United States. GCB Bioenergy DOI: 10.1111/gcbb.12445.

Englund, O. and Berndes, G. (2016). The Roles of Public and Private Governance in Promoting Sustainable Bioenergy. In: Le Bouthillier, Y., Cowie, A., Martin, P., and McLeod-Kilmurray, H. (eds). The Law and Policy of Biofuels. Edward Elgar Publishing, UK.

Englund, O., Berndes, G., Cederberg, C. (2017). How to Analyse Ecosystem Services in Landscapes — a systematic review. Ecological Indicators, 73:492-504.

Fritsche, U., Berndes, G., Cowie, A., Dale, V., Kline, K., Johnson, F.X., Langeveld, H., Sharma, N., Watson, H., Woods, J. (2017). Sustainable energy options and implications for land use. Working paper for the Global Land Outlook 2017, produced for the UNCCD secretariat and IRENA. International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany.

GBEP-IEA Bioenergy (2016) Examples of Positive Bioenergy and Water Relationships, a report from the GBEP-IEA Bioenergy collaboration within the GBEP Activity Group 6 "Bioenergy and Water". Editors: Berndes, G, Chalmers, J., Fingerman, K., Fritsche, U., Olsson, E., Rossi, A.

Junginger, M., Berndes, G., Cowie, A., Fritsche, U., Mai-Moulin, T., Smith, T., Stupak, I. (2017). Sustainability of bioenergy supply chains Summary report from an inter-Task workshop, 18-19 May 2017, Gothenburg, Sweden. IEA Bioenergy: Inter-Tasks Sustainability of Bioenergy Supply Chains ExCo: 2017:08

Nordborg, M., Sasu-Boakye, Y., Cederberg, C., Berndes, G. (2016). Challenges in developing regionalized characterization factors in land use impact assessment: impacts on ecosystem services in case studies of animal protein production in Sweden. International Journal of Life Cycle Assessment, doi: 10.1007/s11367-016-1140-7.

Scott-Bentsen, N., Larsen, S., Berndes, G., Birdsey, R. et al. (2016). Forests and forest management plays a key role in mitigating climate change. Response to Naudts, K. et al. Europe's forest management did not mitigate climate warming. Science 351(6273): 597-600. DOI: 10.1126/science.aad7270.

Thiffault, E., Berndes, G., Lamers, P. (2016). Challenges and Opportunities for the Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes. In: Thiffault, E., Berndes, G., Junginger, M., Saddler, J., Smith, T. (Eds.). Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes. pp 190-213, Elsevier Inc. ISBN: 978-0-12-804514-5.

6.2 CONTRIBUTIONS TO EVENTS (CHRONOLOGICAL)

* Indicates that project participants were involved in the organization or the event.

Workshop: Climate effects of bioenergy systems, Berlin, 29 October, 2015 (IEA Bioenergy)*

Roundtable discussion at The Swedish Royal Academy of Forest and Agriculture Sciences, KSLA: Kolinlagring i mark – betydelse och möjlig roll i klimatarbetet, Stockholm, 3 December, 2015 (KSLA Committee for Energy Issues)*

Lecture: Bioenergy: supply potentials and contribution to climate change mitigation. Swedish Society for Nature Conservation, Stockholm, 9 February, 2016.

Workshop: Landscape management and design for food, bioenergy and the bioeconomy: methodology and governance aspects, Göteborg, 15-16 March, 2016 (IEA Bioenergy + several other organizations).*

Lecture: Bioenergy: supply potentials and contribution to climate change mitigation. Svensk Energi, Stockholm, 21 March, 2016.

Webinar: Examples of Positive Bioenergy and Water Relationships in Africa, Asia and the Pacific and Europe, 6 April, 2016 (IEA Bioenergy & Global Bioenergy Partnership, GBEP, Activity Group Bioenergy and Water).*

Southeast United States Bioenergy Study Tour. Tennessee & Georgia, 10-14 April, 2016 (IEA Bioenergy + US DOE Oak Ridge Natl. Lab).*

Webinar: Examples of Positive Bioenergy and Water Relationships in the Americas, 25 May, 2016 (IEA Bioenergy och Global Bioenergy Partnership, GBEP, Activity Group Bioenergy and Water).*

Workshop: The world needs more land use change. European Conference and Exhibition, Amsterdam, 7 June, 2016 (IEA Bioenergy + several organisations).*

Presentation, European Conference and Exhibition, Amsterdam, 7 June, 2016.

Presentation: Forests and climate change mitigation – energy system transformation and the 2-degree target. Seminar at The Swedish Royal Academy of Forest and Agriculture Sciences, KSLA: "Forests, Bioenergy and the Global Climate", Stockholm, 22 June, 2016.

Workshop: Landscape Management and Design for Bioenergy and the Bioeconomy. Vancouver, 21 September, 2016 (IEA Bioenergy & BioFuelNet).*

Workshop: Mobilisation of forest biomass to produce bioenergy, biofuels and bioproducts: Challenges and opportunities. Vancouver, 22 September, 2016 (IEA Bioenergy & BioFuelNet).*

Presentation at event, The Role of Bioenergy in the Energy Union – Nordic Perspectives, organized by Sweden and Finland under the Chairmanship of the Nordic Council of Ministers. Finnish Permanent Representation, Brussels, October, 7, 2016.

Presentation of the report Forest biomass, carbon neutrality and climate change mitigation at a roundtable discussion and lunch meeting hosted by MEP Elizabeth Köstinger. Brussels, 12 October 2016.

Presentation: Biomass production in landscapes. Bioresource seminar, Århus, 22 November, 2016.

Lecture: Bioenergy and its impact on greenhouse gas mitigation – science and policy implications. Meeting with KSLA Committee for climate and land use towards 2030. Stockholm, 14 March 2017.*

Lecture: Bioenergy, carbon balances and climate change mitigation. Svebio annual meeting, Stockholm, 5 April 2017.

Workshop: Sustainability Governance. French Ministry of Foreign Affairs Conference Centre, Paris 25 April 2017 (International Energy Agency).*

Workshop: Understanding the Climate Effects of Bioenergy Systems. Göteborg, 16 May, 2017 (Chalmers & IEA Bioenergy).*

Workshop: Sustainability of bioenergy supply chains. Göteborg, 18-19 May, 2017 (IEA Bio-energy).*

Three presentations, European Conference and Exhibition, Stockholm, 12-15 June, 2017.

Roundtable discussion at The Swedish Royal Academy of Forest and Agriculture Sciences, KSLA: Multi-functionality and sustainability in the European Union's forests. 26 June, 2017 (IVA).

Seminar: Bioenergy, water and SDG implementation: experiences and linkages, World Water Week 2017. Stockholm, 31 August 2017 (IEA Bioenergy & Global Bioenergy Partnership, GBEP, Activity Group Bioenergy and Water).*

Presentation: Energy from Forests: Opportunities and Challenges. EFI 2017 Annual Conference. Oslo, 4-6 October 2017.

Workshop: Attractive systems for bioenergy feedstock production in sustainably managed land-scapes. Bioenergy Australia Annual Conference, Sydney, 20 November, 2017 (IEA Bioenergy).*

Seminar at the European Parliament in Brussels: What does science tell us about biofuels? Euro-pean Parliament, 10 January, 2018 (Hosted by MEP Fredrick Federley and MEP Sirpa Pietikäinen).*

Conference: Forests and the climate: Manage for maximum wood production or leave the forest as a carbon sink? The Swedish Royal Academy of Forest and Agriculture Sciences, KSLA, 12-13 March, 2018. (The Royal Swedish Academy of Agriculture and Forestry, The Royal Swedish Academy of Sciences, and The Royal Swedish Academy of Engineering Sciences).*

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