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CARBON VISION? A REVIEW OF BIOFUEL ENVIRONMENTAL SYSTEMS ANALYSES RESEARCH IN SWEDEN

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 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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SUMMARY

Biofuels have been promoted as a means to respond to future fossil fuel scarcity, geopolitical instability, energy self-sufficiency, and as a means to stimulate economic growth and mitigate climate change. To ensure that biofuels are produced sustainably, an increasing body of scientific literature has become available in recent years focusing on the environmental sustainability of biofuels, often using environmental systems analysis (ESA) approaches such as life cycle assessments. However, these studies only address some of potential environmental impact categories.

This study aims to review and compare the state-of-the-art in environmental systems analyses of biofuel production systems, internationally and in Sweden. This is done in order to determine how studies have portrayed the potential environmental impacts of biofuel production pathways. Furthermore, this study will identify the scope of environmental impact categories considered, if there is a focus on a narrow set of environmental impact categories, and if there is, why this may exist.

A systematic literature review has been conducted to identify environmental systems analyses of biofuels in Swedish research between 2000 and 2014, using f3 reports, Scopus, Web of Science and Springer research databases. The literature review resulted in the identification of 1,120 articles and reports. Upon applying exclusion categories and reviewing the articles, a total of 63 studies were analysed. Information on ESA approaches used, goals, impact categories, methods, biofuels analysed and other relevant information was compiled.

The results indicate that there is a pronounced focus on GHG emission related impacts. However, this focus has not inhibited other impact categories from being investigated in the environmental assessment of biofuels, which is consistent with international research on the environmental assessment of biofuels, characterised by a dominant focus on GHG emissions and energy use.

The narrow focus in environmental impact categories is discussed in terms of study dependent variables (i.e., goal of the study, methods, and data uncertainty and availability) and the influence of the dominant science-policy framework in Sweden. Whilst biofuel production is inextricably linked to climate policy, one should not forget that the broader context of the Swedish environmental objectives should also be taken into consideration when developing biofuel production systems in Sweden. This study provides information that can be used to support research for improved methods and the inclusion of more sustainability criteria for sustainability assessments of biofuels in Sweden.

SAMMANFATTNING

Biodrivmedel förs ofta fram som ett alternativ som begränsar det framtida fossilberoendet inom transportsektorn och samtidigt bidrar till att reducera geopolitisk instabilitet, öka självförsörjning av energi, stimulera till ekonomisk tillväxt och begränsa klimatpåverkan. Under de senaste åren har en ökande mängd forskning ägnats åt att utvärdera produktionen av biodrivmedel för att säkerställa att produktionen sker på ett hållbart sätt. Den forskning som hittills publicerats om miljömässig hållbarhet är ofta baserad på miljösystemanalysmetoder, såsom livscykelanalys, och omfattar i flera fall enbart vissa potentiella miljöpåverkanskategorier.

Den här studien granskar och jämför det rådande utförandet av miljösystemsanalyser av biodrivmedelsproduktion, internationellt och i Sverige, med syftet att bedöma hur studierna har belyst potentiella miljöpåverkanseffekter. Genom att identifiera vilka miljöpåverkanskategorier som inkluderas ges ett underlag till en diskussion kring huruvida den rådande synen på vilka miljöpåverkanskategorier som skall inkluderas är för snäv och vad det i så fall kan bero på.

Studien bygger på en systematisk litteratursökning och genomgång av de miljösystemanalyser av biodrivmedelsproduktion som gjorts i svensk forskning mellan åren 2000 och 2014. Sökningen täckte f3, Scopus, Web of Science och Springers databaser. Totalt identifierades 1,120 artiklar och rapporter varav 63 artiklar bedömdes relevanta för vidare analys. För dessa 63 artiklar ställdes information om miljösystemanalysmetoder, mål, miljöpåverkanskategorier, biodrivmedelstyper och annan relevant information samman och analyserades.

Resultaten visar på ett övervägande fokus på växthusgasrelaterade påverkanskategorier i de flesta av de svenska studierna. Dock har detta fokus inte begränsat inkluderandet och bedömmandet av även andra miljöpåverkanskategorier. Fokus från de svenska studierna är i linje med det fokus som återfinns i internationell forskning om biodrivmedels miljöpåverkan, med tyngdpunkt på växthusgasemissioner och energianvändning.

Utifrån resultaten diskuteras orsaker till den något snäva synen vad gäller miljöpåverkanskategorier. Diskussionen utgår både från analysberoende variabler (t.ex. syfte med studien, metoder, dataosäkerhet samt datatillgänglighet) och från den rådande forskningspolitiska strukturen i Sverige. Det kan konstateras att även om biodrivmedelsproduktion är starkt kopplad till klimatpolitiken och klimatpolitiska mål, bör man inte glömma att de svenska miljömålen har ett bredare perspektiv. Detta bredare perspektiv bör tas hänsyn till i utformningen av biodrivmedelsproduktionssystem i Sverige. Denna studie bidrar med information och resultat som kan användas som stöd för forskning och utveckling av förbättrade metoder för hållbarhetsbedömningar av biodrivmedel där fler hållbarhetskriterier inkluderas.

CONTENTS

ABBREVIATIONS

DME	Dimethyl Ether
dLU	Direct Land Use
dLUC	Direct Land Use Change
EC	European Commission
EF	Environmental Footprint
EU	European Union
EIA	Environmental Impact Assessment
ESA	Environmental Systems Analysis
EU	European Union
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester
FT	Fischer-Tropsch
FQD	Fuel Quality Directive
HVO	Hydrogenated Vegetable Oil
iLUC	Indirect Land Use Change
ISO	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
LBG	Liquid Biogas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land Use Change
MFA	Material Flow Analysis
RED	Renewable Energy Directive
RME	Rapeseed Methyl Ester
SFA	Substance Flow Analysis
SNG	Synthetic Natural Gas

1 INTRODUCTION

1.1 BACKGROUND

In the late 1990s, a number of OECD[1] countries set out to promote the use of biofuels (Keyzer et al., 2008). The development of biofuel production and consumption systems have been promoted as a means to respond to future fossil fuel scarcity; to diversify fuel production in light of geopolitical instability; to contribute to energy self-sufficiency; to stimulate economic growth in rural areas; and to mitigate climate change through the reduction of greenhouse gas (GHG) emissions (Cherubini and Strømman, 2011a; Gnansounou et al., 2009; Keyzer et al., 2008; Malça and Freire, 2011; van der Voet et al., 2010).

The increasing body of evidence that demonstrates the contribution of fossil fuel use to climate change has laid the ground for the use of biofuels to provide carbon-neutral transportation energy (von Blottnitz and Curran, 2007). Indeed, several authors have noted that climate change mitigation and the reduction of fossil fuel consumption are the primary reasons for the development of the biofuel sector (Cherubini and Strømman, 2011a; Cherubini et al., 2009; Malça and Freire, 2011). To this end, the European Union (EU) and many OECD countries have introduced policies to promote the use of biofuels, for example, through blending obligations and targets.

In 2009, the European Commission (EC) introduced the Renewable Energy Directive 2009/28/EC (RED) which sets mandatory national targets for a 20% share of energy from renewable sources by 2020, a 10% share of energy from renewable sources in the transport sector by 2020, and requirements for the use of biofuels and bio-liquids that are required to contribute to minimum GHG reductions (compared to a fossil fuel reference value) of 35% by 2013, 50% by 2017, and 60% by 2018 (Council Directive, 2009). The RED also requires that biofuels should not be made from biomass growing on land with high carbon stock or high biodiversity. Furthermore, the Fuel Quality Directive 2009/30/EC (FQD) set targets that require EU fuel suppliers to reduce the GHG emissions of each energy unit by 6% by 2020.

Despite the growing number of ambitious policies, targets and regulations promoting the production and consumption of biofuels, questions concerning the sustainability of bioenergy pathways have been raised (Cherubini and Strømman, 2011a) and biofuel production and consumption have often been the subject of controversy (Keyzer et al., 2008; Sheehan, 2009). van der Voet et al. (2010, p. 435) note that if biofuels are to be stimulated by policy then “we must be certain that this will actually be an overall improvement for our society”. For instance, whilst biofuels are promoted as a response to climate change, the agricultural production of bioenergy crops involves relatively intensive land use and agricultural practices that require fertilisers and pesticides, causing pollutants to enter water bodies (von Blottnitz and Curran, 2007). These practices can be a cause of concern for soils, water bodies and the atmosphere, especially when nitrogen fertilisers are used, leading to environmental impacts such as acidification, eutrophication and photochemical smog formation (Cherubini and Strømman, 2011a). This is compounded by

[1] Organisation for Economic Cooperation and Development

what Tilman et al. (2009) highlight as the importance of addressing the "trilemma" associated with biofuel production; meeting our energy, environmental and food production needs.

van der Voet et al.(2010, p. 435) suggest that the greater demand for sustainability assessments of biofuels, fuelled by biofuel policies and targets, has led to an "explosion" of Life Cycle Assessment (LCA) studies to support biofuel policy making. Indeed, LCA is a suitable tool for assessing the environmental sustainability of biofuel production and use, as its holistic nature allows for the assessment of different environmental impacts throughout the cradle-to-grave life cycle of the product in question. In this way, LCA is a useful tool to avoid 'problem-shifting' from one life cycle phase to another, from one region to another, or from one environmental impact category to another (Finnveden et al., 2009). However, LCAs of biofuels have often been limited to assessments of GHGs or energy balances (Gnansounou et al., 2009; van der Voet et al., 2010; von Blottnitz and Curran, 2007); and whilst global warming potential (GWP) is a very important impact category, it is by no means the only relevant category (van der Voet et al., 2010). Recent LCA studies which include multiple impact categories show that when compared to fossil alternatives, global warming benefits of biofuels are often negated by impacts in other impact categories such as eutrophication and acidification (van der Voet et al., 2010).

1.2 AIMS AND OBJECTIVES

There have been a number of review studies on the environmental impacts of biofuels. These are dominated by LCA reviews, which are often conducted in order to synthesize and discuss the key issues that are raised in studies performed by different authors on a specific topic, product or technology, as well as the influence of methodological choices on the studies' results (Fantin et al., 2014). Yet, LCA is one of a number of environmental systems analysis (ESA) tools that are applied to study the potential environmental impacts of biofuel systems and studies which review the environmental impacts of biofuel systems undertaken by other ESA tools are limited.

This study goes beyond reviewing and comparing the results of LCAs of biofuel production. Instead, it looks at all ESA studies of biofuels and poses the overarching question: Is there a *carbon vision* in ESA studies on biofuel production in Sweden? By *carbon vision* we mean the loss of peripheral vision concerning environmental impact categories other than carbon-related impacts (i.e., CO_2-eq) and indirect system consequences; or in other words, a dominant focus on carbon related impacts at the expense of other impact categories. Hence, the aim of this study is to identify if there is a focus on carbon emissions[2] in ESA studies conducted in Sweden and, if so, why this may exist. The objectives of the study are to:

- Identify the most common environmental impact categories used by the international research community in environmental assessments of biofuel production.

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[2] Carbon emissions can refer to the impact category Global Warming Potential (GWP), which provides the amount of equivalent carbon dioxide emissions, or carbon dioxide emission calculations from carbon footprints. Throughout the text, this will be referred to as GHG emissions, although when associated with impact categories, the GWP impact category will be used.

- Identify the environmental impact categories used by the Swedish research community in environmental assessments of biofuel production.
- Determine if there is a *carbon vision* in Swedish ESA research on biofuel production.
- If there is a *carbon vision*, provide recommendations to broaden the focus of environmental sustainability assessments of biofuel production.

1.3 SCOPE

The scope of this study is limited to Sweden for several reasons. Sweden is one of the leaders in advanced[3] biofuel production in the EU and, in 2013, it was the second highest consumer per capita, behind Luxembourg, of biofuels for transport (EurObserv'ER, 2014; Eurostat, 2015). The proportion of biofuels (mainly biodiesel, ethanol and biogas) used in road transportation increased from 8.5% in 2012 to 11% in 2013, which is in stark contrast to the overall trend in the EU which saw a 6.8% drop in consumption over the same period (EurObserv'ER, 2014).

Sweden has implemented the RED targets into their own national targets (10% renewable fuels in transport and 50% renewables in national energy mix by 2020). In 2013 Sweden met the EU target for 10% use of renewable fuels in the transportation sector (Energimyndighet, 2014) and reached 12% renewable fuels in the transportation sector in 2014 (Energimyndighet, 2015). Furthermore, Sweden has also set ambitious targets for its vehicle fleet which is to be free of fossil fuels by 2030 and for Sweden to have no net GHG emissions by 2050 (Swedish Government, 2008). The Swedish Parliament has also set a target of a 20% increase in energy efficiency by 2020 and a climate specific target of reducing GHG emissions by 40% by 2020. Furthermore, several national policy instruments (administrative, financial, R&D support and informational) have been implemented to promote biofuels. These include supply side instruments, such as tax exemptions for biofuels, mandatory blending rates, the environmental car rebate, the Carbon dioxide (CO_2) vehicle tax, and demand side instruments such as the "Pump Law", obligations for fuel suppliers to reduce GHG emissions, investment and R&D grants and climate investment programmes (Holmgren, 2012).

1.4 STRUCTURE OF THIS REPORT

Section 2 provides a brief introduction to ESA (Section 2.1) and LCA (Section 2.2). Since LCA has been the predominant ESA tool applied to biofuels, a review of previous international meta-studies on LCAs applied to biofuels is provided, as well as a summary of the salient aspects of LCAs of biofuels. Section 3 details the systematic literature review methodology that this report has followed. Section 4 presents the ESA studies identified in the systematic literature review, and analyses these studies in terms of their goals, the environmental impact categories considered and how the selection of these impact categories were justified. Section 5 discusses potential explanations for the current situation in Swedish biofuel ESA research. Section 6 provides the conclusions and recommendations for future ESA studies of biofuels conducted in Sweden.

[3] Second and third generation biofuels

2 ENVIRONMENTAL SYSTEMS ANALYSIS OF BIOFUELS

2.1 ENVIRONMENTAL SYSTEMS ANALYSIS

ESA is a common approach used to study the potential environmental impacts of biofuel systems. ESA is the application of systems analysis to describe and understand “the causes, mechanisms, effects of, and potential solution for specific environmental problems” (Wageningen University, n.d.). Many ESA tools have been developed to analyse the environmental impacts of different systems and to meet the demands of different decision-making situations (Finnveden and Moberg, 2005; Wrisberg et al., 2002). ESA tools require the use of interdisciplinary approaches to develop new insights to the causes, mechanisms, effects and potential solutions to environmental problems. These tools include analytical tools, such as LCA, material flow analysis (MFA), substance flow analysis (SFA), Energy Analysis (En) and ecological footprints (EF) (including carbon footprint and water footprint), and also procedural tools such as environmental impact assessment and strategic environmental assessment (Finnveden and Moberg, 2005). The majority of these tools are used to support decision-making (Finnveden and Moberg, 2005), however, they can also be valuable for, *inter alia*, accounting, learning, communication, marketing claims, policy support and development, environmental reporting and the identification of key environmental performance indicators (JRC, 2010; Moberg, 2006). This study has identified several ESA tools used to assess the environmental impact of biofuel production, including LCA, EF, MFA, En and economic assessments.

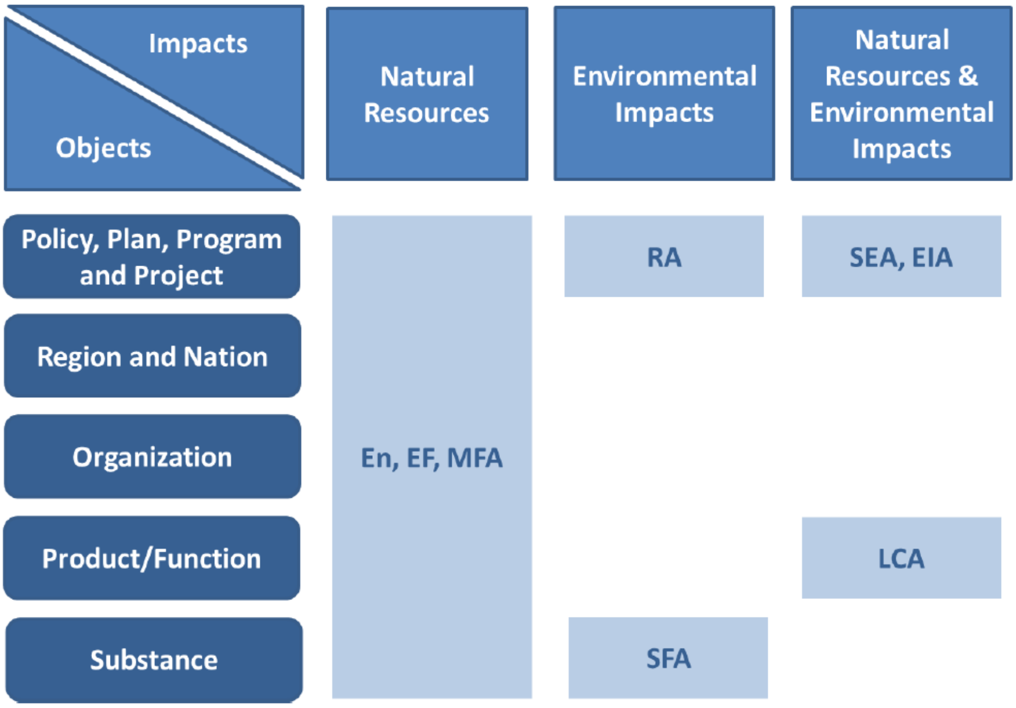

Figure 1: Environmental Systems Analysis Tools and their focus and objects studied.
(Martin, 2013) Adapted from Finnveden and Moberg (2005)
En-Energy Analysis, EF-Ecological Footprint, MFA-Material Flow Analysis, RA-Risk Assessment, SFA-Substance Flow Analysis, SEA-Strategic Environmental Assessment, EIA-Environmental Impact Assessment, LCA-Life Cycle Assessment

2.2 LIFE CYCLE ASSESSMENT

LCA is an ISO standardised analytical tool which has been widely applied to biofuel production systems. LCA is used to assess the potential environmental impacts and resource use of a product or service system throughout its entire life cycle; from raw material acquisition, production, use, end-of-life treatment (i.e., recycling), to final disposal (ISO, 2006). The total environmental impacts of a product system can be determined by summing the environmental impacts of each subsystem that make up the entire product system. LCA is comprised of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

LCA allows for the comparison of products and services from a systems perspective. Thus, it is a useful tool to avoid 'problem-shifting' from one life cycle phase to another, from one region to another, or from one environmental impact category to another (Finnveden et al., 2009). Wrisberg et al. (2002) highlight the main characteristics of LCA as 1) the comparison of different options to supply a given function, 2) following a cradle-to-grave approach, aiding companies to look beyond their gates, or governments to detect unforeseen consequences of their policies, 3) a comprehensive assessment of environmental interventions and environmental issues, and 4) the provision of quantitative or qualitative results.

LCA is a comprehensive assessment of environmental interventions as it considers all attributes or aspects of the natural environment, human health and resources (ISO, 2006). Environmental impacts are conveyed in LCIA as either 'endpoint' categories (those that cover the whole impact pathway from emission to damage) on natural environment, human health, and resource depletion, or 'midpoint' categories (those which are defined at an intermediary point on impact pathway, before damage) which can include categories such as: global warming potential (GWP), stratospheric ozone depletion (OD), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (EP), human toxicity, eco-toxicity, biotic and abiotic resource depletion (AD), land use and water use[4]. Table 1 below provides some of the LCIA methods available and the impact categories covered by these methods.

[4] A brief summary of environmental impact categories can be found in von Blottnitz and Curran (2007, pp. 617–618)

Table 1: Environmental Impact Categories for different LCIA Methods (reproduced from www.openlca.org; Accessed 10 May 2015)

METHODS	Acidification	Blue/Green Water Use	Climate Change	Cumulative Energy Demand	Resource Depletion	Ecotoxicity	Eutrophication	Human Toxicity	Ionising Radiation	Land Use	Odour	Ozone layer depletion	Particulate Matter/ Respiratory Inorganics	Photochemical Oxidation
CML, 2001 (baseline)	✓	-	✓	-	✓	✓	✓	✓	-	-	-	✓	-	✓
CML, 2001 (non-baseline)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
eco-indicator 99 (E)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (H)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (I)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	-
Eco-Scarcity 2006	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
EDIP 2003	✓	-	✓	-	-	✓	✓	✓	-	-	-	✓	-	✓
EPA - default methods	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	✓	✓
ILCD 2011, endpoint	✓	-	✓	-	-	-	✓	✓	✓	✓	-	✓	✓	✓
ILCD 2011, midpoint	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (E)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (H)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (I)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (E)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (H)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (I)	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
TRACI 2.1	✓	-	✓	-	✓	✓	✓	✓	-	-	-	✓	✓	✓
USEtox	-	-	-	-	-	✓	-	✓	-	-	-	-	-	-

There are two different approaches taken in LCA, attributional LCA (ALCA) and consequential LCA (CLCA), which are both applied to biofuel production and use (Plevin et al., 2014). ALCA "aims at describing the environmentally relevant physical flows to and from a life cycle and its subsystems", whereas CLCA aims at "describing how the environmentally relevant physical flows to and from the technological system will change in response to possible changes in the life cycle" (Ekvall and Weidema, 2004). ALCA assesses the environmental impacts that can be attributed to the existing product system over its life cycle, whereas CLCA assesses the potential environmental impacts that occur as a consequence of producing a good or providing a service over its life cycle. Recently, there has been much debate on the utility of these different approaches in the context of supporting biofuel policy and developing insights into the indirect impacts associated with biofuels (see Anex and Lifset (2014)). In the biofuel research and policy spheres, this has mainly focused on the impacts related to direct and indirect land use changes[5].

2.3 LIFE CYCLE ASSESSMENTS OF BIOFUELS

LCA is the predominant tool used to portray the environmental performance of biofuels and they have been conducted to assess the implications that biofuel production may have on the "trilemma" in meeting our energy, environmental and food production needs (Martin, 2013; Tilman et al., 2009). There has been a large increase in the number of LCAs produced of different biofuel production processes (van der Voet et al., 2010).

Previous meta-studies of LCAs of biofuels have outlined various purposes, including 1) comparing biofuels to fossil alternatives, 2) obtaining information about the main environmental impacts related to biofuels and 3) using LCA to identify main hotspots in the chain (Van der Voet et al. 2010). This has provided a wealth of knowledge and data on processes, feedstocks and improvement potential for new biofuel production pathways. A search in SCOPUS (see Figure 2) confirms what van der Voet et al. (2010, p. 435) suggest to be the "explosion" of LCA studies conducted to support biofuel policy making in recent years.

[5] Direct and Indirect Land Use Change refer to the consequences that may arise from increased demand of bioenergy. Direct land use change (dLUC) refers to the conversion of land from one state to another due to increased biofuel production. Indirect land use change (iLUC) is related to market based agricultural commodities and the affects that increased biofuel may have on market behavior, which ultimately leads to increased land use (Höglund et al., 2013).

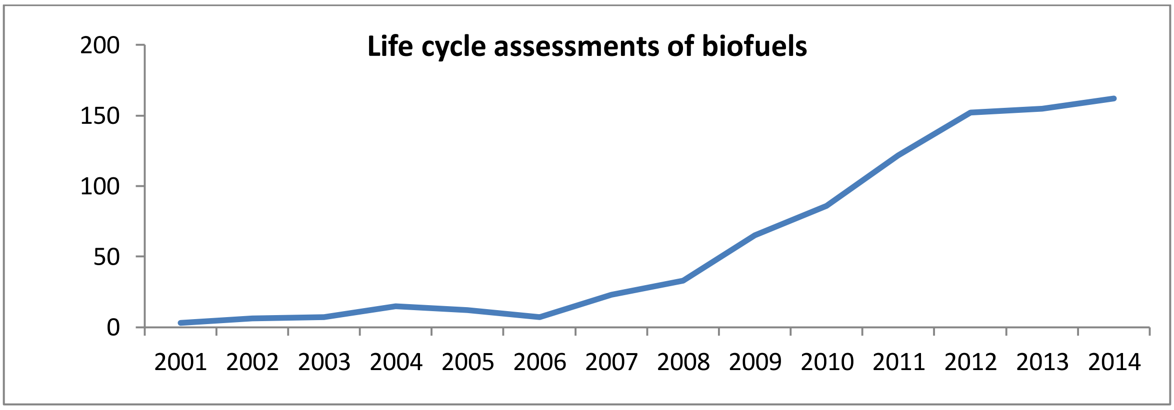

Figure 2: SCOPUS hits for 'LCA' and 'Biofuels' between 2000-2014 (10 May 2015)

The increasing number of LCAs has led to a growth in meta-studies of LCAs of biofuels, for instance: Kim and Dale (2005), Larson (2006), von Blottnitz and Curran (2007), Gnansounou et al. (2009), Majer et al. (2009), Yan and Crookes (2009), Davis et al. (2009), van der Voet et al. (2010), Hoefnagels et al. (2010), Cherubini and Strømman (2011a) and Malça and Freire (2011). Meta-studies often compare environmental impacts of the same or different feedstocks from various geographical regions, and/or investigate the influence of methodological choices and data issues on the divergence of results. Table 2 summarises international meta-studies of biofuel LCAs, and are thus considered to be representative of international research with respect to their aim and environmental impact categories used by the LCAs analysed in these reviews.

Cherubini (2010) and van der Voet (2010) investigated many of the details and results of previous quantifications, and concluded that outcomes for similar systems are diverging. This can be attributed to the methodological considerations used when conducting the LCAs, which include (Cherubini et al., 2011, 2009; Martin, 2013; van der Voet et al., 2010):

- the choice of reference system for comparison
- system boundaries
- functional unit
- data
- characterization factors and
- allocation methods used.

Developments of biorefinery systems in recent years have also added to the difficulty of applying LCA due to outputs of an array of valuable products (Ahlgren et al., 2013; Martin et al., 2015). Furthermore, the impact categories used to compare the fuels are varied throughout the studies. van der Voet et al. (2010) suggest that many studies are insufficient to provide sustainability analyses of biofuels, as crucial impact categories (besides GWP) are seldom outlined.

Table 2: Impact assessment method of LCA studies

Study	Description
von Blottnitz and Curran (2007)	*Aim* In this study, the authors analysed 47 studies, published between 1997–2004, that compared bio-ethanol systems to conventional fuel systems on a life cycle basis or using LCA. This was done in order to detect the trend in results in terms of feedstock type of location. *Environmental impacts considered* Of the 47 studies analysed, 7 went beyond the scope of energy and GHG emissions to include impact categories such as resource depletion, global warming, ozone depletion, acidification, eutrophication, human and ecological health and photochemical smog formation. von Blottnitz and Curran (2007) state that whilst the LCAs typically reported that bio-ethanol resulted in reduced resource use and GWP, impacts such as AP, human and ecotoxicity (occurring mainly during the growing and processing of biomass) were more often unfavourable than favourable when compared to conventional fossil fuels.
van der Voet et al. (2010)	*Aim* van der Voet et al. (2010) analysed 67 studies, published between 2005–2010, with the aim to provide a better understanding of why LCA studies may lead to diverging results and how to practically deal with the methodological limitations of LCA. *Environmental impacts considered* The authors note that of the 67 studies analysed, all studies included GWP (CO_2-eq), 20 included EP and AP, 12 included POCP and 11 included toxicity. The authors note that in the more recent LCAs comparing biofuels to fossil fuels, studies that included impact categories other than GWP showed that, in general, the benefits of GWP were offset by greater negative scores for other impact categories.
Cherubini and Strømman (2011)	*Aim* Cherubini and Strømman (Cherubini and Strømman, 2011b) analysed 94 studies, published in 1997–2010, aiming at analysing the different approaches that LCAs of biofuels have taken to face issues such as selection of functional unit, reference systems used, change in carbon pools and land-use changes (LUC), non-CO_2 emissions from soils, effects of agricultural residue removal, and solving coproduct allocation. *Environmental impacts considered* The authors noted that of the 94 studies analysed, 86 included GHG emissions, 68 included primary energy demand, and 47 of these LCAs were exclusively limited to these two impact categories. Furthermore, Cherubini and Strømman (Cherubini and Strømman, 2011b) state that for human toxicity and ecotoxicity, as well as other impact categories, most but not all bioenergy systems lead to an increase in impact when compared to fossil systems.

3 METHODOLOGY

Reviews can be used to compare the environmental impacts of different products or energy production systems, to identify environmental criticisms of the product/service system, to define a framework for the application of tools in specific systems and to provide reliable information about the environmental impacts of products or systems for decision-making and policy-evaluation purposes (Fantin et al., 2014). In this study, a systematic literature review was conducted to identify the environmental impact categories considered in Swedish biofuel research. This approach was employed due to its applicability to find relevant articles and apply exclusion criteria to fulfil the aims of the study (Green et al., 2006; Zumsteg et al., 2012). Similar methods have been applied by Zumsteg et al. (2012), Muench and Guenther (2013) and Martin et al. (2012) to review LCAs and studies on biofuel production. Figure 3 depicts the process used for the systematic literature review of scientific articles from scientific databases.

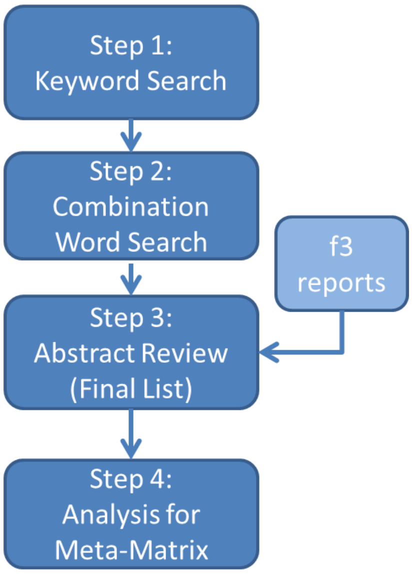

Figure 3: Methodology for Literature Review

Step 1 of the literature review was to identify scientific literature on Swedish biofuel research between 2000 and 2014[6]. Scientific databases from Springer, Web of Science and Scopus were used in order to capture literature available from many publishers in an array of journals. To find relevant articles and environmental impact categories assessed, keywords for biofuels were used. The keywords for different biofuels included for instance biofuel, ethanol, biogas, biodiesel, methanol, dimethyl ether (see Table 3). Step 1 also included limiting the results to studies from Sweden and from researchers at Swedish research institutes and universities. As there was a large number of Swedish biofuel research articles available, combination words were then added to the search in Step 2 in order to limit the articles and focus on finding the salient environmental impact categories. The combination words included various environmental impact categories and methods,

[6] In this study, "Swedish biofuel research" included scientific articles related to Swedish biofuels and reports on biofuels produced by Swedish research institutes.

see Table 3. **Step 2** provided a collection of articles which were used for further in depth analysis in Steps 3 and 4.

Table 3: Keyword and Combination Words used in Literature Search

Keywords	Combination Words
Biofuels	LCA
Biofuel	EIA
Ethanol	Systems Analysis
Biodiesel	Environmental impacts
HVO	Life Cycle Analysis
SNG	Life Cycle Impact Assessment
Fischer- Tropsch	Strategic Environmental Assessment
DME	Environmental Impact Assessment
Methanol	
Biogas	
Hydrogen	

Step 3 included a review of the abstracts and results in each of the articles in order to exclude those articles which were outside of the scope of this study. In addition to scientific databases, reports produced from the f3 centre-Swedish Knowledge Centre for Renewable Transportation Fuels were reviewed and included in the literature review. The f3 centre is a research platform based on the development of sustainable renewable transport fuels in collaboration with many technical universities and research institutes in Sweden. The f3 centre has a small database with published reports from previous projects, many of which review LCAs and system analyses of biofuels. Other literature from, for example, reports, theses, dissertations and other sources from Swedish research institutes were not included in the review.

Steps 1-3 resulted in 152 articles from Scopus, 855 from Springer and 84 from Web of Science. A total of 27 reports were also reviewed from f3 database. Upon reviewing the articles, the literature review produced a total of 63 studies which were are analysed further in Step 4.

Step 4 included an analysis of all relevant information from the research such as the bibliographic information, biofuels assessed, impact categories reviewed, boundaries of the study, goal of the study, motivation for impact categories assessed and standardized methods used. The scope and goal of the studies were provided in either the introduction or aim/goal sections of the research. Standardized ESA methods were analysed by reviewing information provided in the methodology sections of the research. Information on the characterization methods, impact categories and their justification, system boundaries and other methodological considerations were also provided from the methodology sections. Other information such as biofuels reviewed, feedstocks and discussion of the impacts were provided throughout the text.

4 RESULTS AND ANALYSIS

4.1 TYPES OF ENVIRONMENTAL SYSTEMS ANALYSIS

Five ESA methods were identified in a total of 63 studies, see Table 4. Several studies combined more than one ESA method. LCA studies were those that explicitly stated they followed the LCA method (as set out in the ISO standard) or a life cycle approach (not specifically following the ISO standard) as their methodology. EF studies included systems analysis that did not explicitly state whether the LCA methodology was followed. These studies included analyses of CO_2, GHG emissions or LUC. Energy assessments were studies which included energy balances of biofuel production and/or consumption systems processes. MFAs included analyses of different substance and material flows (e.g. toxic substances and nutrients). Additionally, although economic assessments are not considered as ESAs, studies which combined ESA approaches with economic assessments have been included in this analysis.

Table 4: ESA Tools/Methods Used in the Reviewed Research

Study Type	**Total**
LCA	38
EF	26
En	16
MFA	7
Economic	4

4.2 STUDY GOALS

The environmental impact categories addressed in individual studies are depended on the study's goal. This is especially true for LCA studies, where the ISO (2006) standard states that the goal should establish the intended application, reasons for carrying out the study, intended audience and whether the results are intended to be used for comparative purposes which are disclosed to the public. Hence, the depth and breadth of the study differ considerably depending on this goal. The studies were analysed to identify the goal and were categorised into the following categories:

1) Studies that intended to assess only either GWP and/or energy use; 25 of the 63 studies limited their goal to the assessment of either GWP and/or energy use, these studies included 9 LCAs, 14 EFs, 11 Ens, 5 MFAs and 3 Economic assessments.

2) Studies that intended to assess environmental impact in general; the 25 that intended to assess environmental impact, in general, all followed the LCA methodology. All studies that intended to assess 'environmental impacts' included impact categories additional to GWP and En and on average considered 4.5 environmental impact categories per study. Only two studies stated that the goal of their analysis was to investigate 'environmental impacts' but only included GWP or En impact categories. For instance, Luterbacher et al. (2009, p. 1580) state that the goal of the LCA was "to identify the environmental hot-spots of the process and to evaluate its environmental performance", however, the authors only consider GWP and En. Likewise, Ekman et al. (2013, p. 52) note "… LCA is used to compare the environmental impact of biorefinery systems that are either based on the extraction methods developed here or conventional extraction processes. The environmental impact categories included are global warming potential (GWP) and the demand for primary energy."

3) Studies that intended to assess specified environmental impacts; a total of eight studies stated that their goal was to assess specific environmental impacts, such as: land use (Hansen et al., 2013; Sparovek et al., 2009), LUC (Ahlgren and Di Lucia, 2014; Langeveld et al., 2012) soil organic carbon (Björnsson et al., 2013; Langeveld et al., 2012) water use (Hagman et al., 2013), resource use (Kimming et al., 2011) and freshwater ecotoxicity (Nordborg et al., 2014). All studies in this category except for Nordborg et al. (2014) Sparovek et al. (2009) Langeveld et al (2012) also included GHG emissions in their analysis.

4.3 ENVIRONMENTAL IMPACT CATEGORIES

4.3.1 Environmental Impact Categories Considered

The environmental impact categories addressed in the ESA studies are illustrated in Figure 4. From this figure, it is evident that a large number of the studies focus on GWP (59 studies) and En (48 studies). Other notable impact categories identified: EP (19 studies), AP (17 studies), direct land use (dLU) (8 studies), direct land use change (dLUC) (8studies), POCP (7 studies) and indirect land use change (iLUC) (6 studies). Table 5 provides further details of the environmental impact categories addressed by individual studies.

Of the 38 LCAs, all considered GWP, 11 only considered GWP, 11 considered GWP and impacts related to land use and 20 considered impacts other than those related to land use, such as EP, AP, POCP, etc. Of the 28 EFs undertaken, all but two considered GWP, 14 only considered GWP, 7 considered land used related impacts (2 of which did not consider GWP) and 3 considered impacts other than those related to land use, such as EP, ecotoxicity and water use.

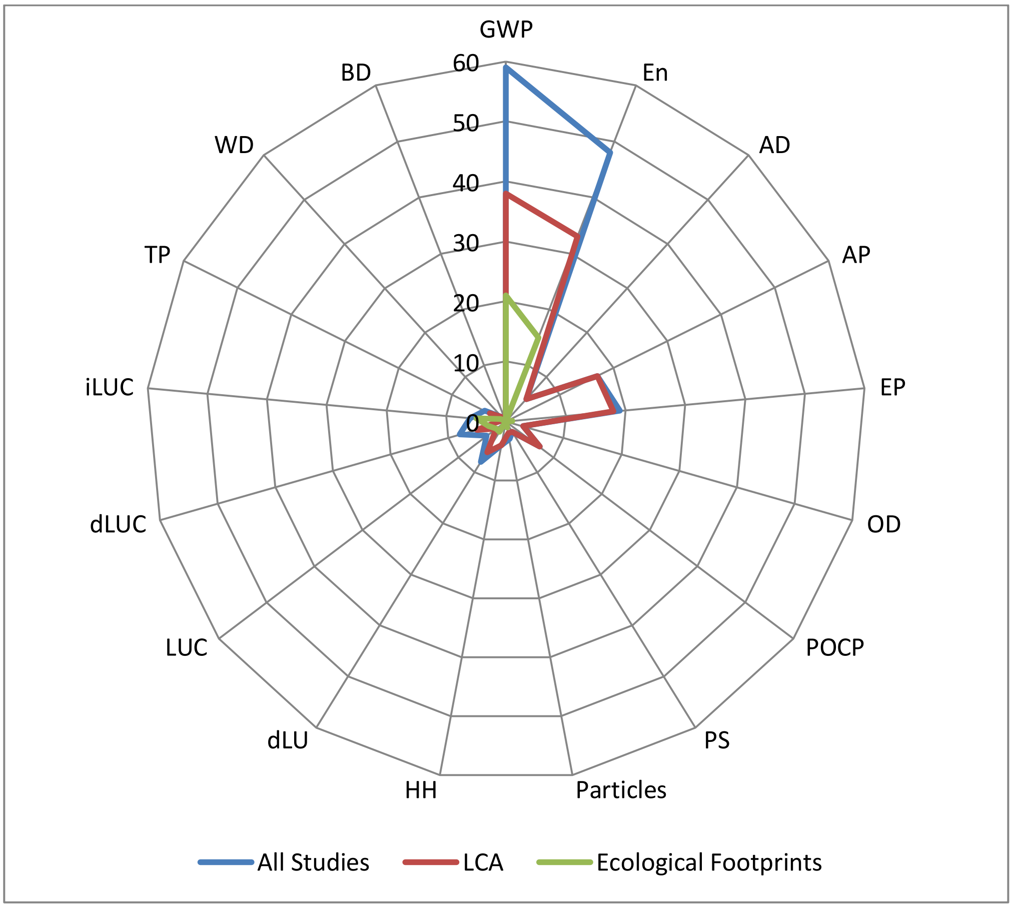

Figure 4: Number of Studies and the Environmental Impact Categories Portrayed in the Studies

GWP-Global Warming Potential, En-Energy Assessment, AP-Acidification Potential, EP-Eutrophication Potential, AD-Abiotic Resource Depletion, dLU- Direct land Use, LUC- Land use change, dLUC- Direct land use change, iLUC- Indirect land use change HH-Human Health, OD-Ozone layer depletion, PS-Photochemical Smog Creation, Pc-Particulate Emissions, TP-Toxicity Potential, POCP-Photochemical Oxidation Creation Potential, WD-Water Depletion, BD-Biodiversity

Table 5: Impact Categories and Motivation for then in Studies Reviewed

Author	Year	Impact Categories	Motivation
Ahlgren & Lucia	2014	GW, iLUC	No motivation
Ahlgren et al.	2008	GW, En, AP, EP, LUC	No motivation
Ahlgren et al.	2009	GW, En, AP, EP	No motivation
Ahlgren et al.	2013	GW, En, dLUC, iLUC	No motivation
Alvfors et al.	2010	GW, En, dLUC	No motivation
Andersson & Harvey	2006	GW, En	No motivation
Arvidsson et al.	2011	GW, En, AP, EP	GHG and energy most important aspects when reviewing biofuel sustainability. Eutrophication and Acidification of interest for biofuels.
Bauer & Hultenberg	2013	GW, En	RED Method Limitations
Bengtsson et al.	2012	GW, AD, AP, EP, Particles, HH	Eutrophication and Acidification for European context
Bernesson et al.	2006	GW, En, AP, EP, POCP	No motivation
Bernesson et al.	2004	GW, AP, EP, POCP	No motivation
Bernstad et al.	2011	GW, En, AP, EP, OD, POCP	"environmentally relevant and internationally accepted"
Bernstad et al.	2012	GW, En, AP, EP	Due to importance for Swedish EPA Objectives
Bezergianni et al.	2014	GW, En	No motivation
Björklund et al.	2001	GW, En	No motivation
Björnsson. et al	2013	GW, SOC	No motivation
Brau et al.	2013	GW, En	No motivation
Brynolf et al.	2014	GW, En, AP, EP, PS, Particles	No motivation
Börjesson and Mattiassoon	2008	GW, En, LUC	No motivation
Börjesson et al.	2013a	GW, En	No motivation
Börjesson et al.	2013b	GW, En, dLUC	No motivation
Börjesson et al.	2013c	GW, En	No motivation
Börjesson et al.	2011	GW, En, EP, dLUC	RED Method Limitations
Börjesson	2009	GW, En, LUC	CO2 targets
Caspeta et al.	2013	GW, En	No motivation
Ekman et al.	2011	GW, En, EP, dLUC	No motivation
Ekman et al.	2013	GW, En	No motivation
Englund et al.	2012	GW, iLUC, dLUC	No motivation
Garraín et al.	2014	GW, En	RED Method Limitations
González-García et al.	2012	GW, En, AD, AP, EP, OD, POCP, HH, TP	No motivation

González-García et al.	2011	GW, En, AD, AP, EP, OD, PS, HH, TP	CML Baseline Impact Categories
Gustavsson & Karlsson	2006	GW	CML Baseline Impact Categories
Hagman et al.	2013	GW, WD	No motivation
Hagman et al.	2013	GW, WD	WD due to gap in research
Hansen et al.	2013	GW, dLUC, iLUC	No motivation
Janssen et al.	2014	GW, En, AP, EP, POCP	Based on CML Method and motivated how applicable for process
Jensen et al.	2012	GW, SOC	No motivation
Joelsson and Gustavsson	2012	GW, En	New tech
Johansson et al.	2014	GW, En	No motivation
Karlsson & Börjesson	2013	GW, En	No motivation
Karlsson et al.	2014	GW, En	No motivation
Khatiwada et al.	2012	GW, LUC	No motivation
Khatiwada et al.	2011	GW, En	No motivation
Kimming et al.	2011	GW, En, AD	No motivation
Lageveld et al.	2012	Particles, SOC, iLUC	Motivation for land and water use impacts
Norberg et al	2013	GW, En	No motivation
Lubbe and Sahlin	2012	GW	GHG most interesting parameter in biofuels
Luterbacher et al.	2009	GW, En	New technology, Policy Mandates for GHG emissions
Margeot et al.	2009	GW, En	Significance for Swedish Context and Magnitude of Impacts
Martin et al.	2014	GW, En, AP, EP	No motivation
Naqvi et al.	2013	GW, En	No motivation
Nordborg et al.	2014	TP	New Method
Pettersson and Harvey	2012	GW, En	No motivation
Risen et al.	2013	GW, En	RED Method Limitations
Samiei and Fröling	2014	GW, AD, AP, POCP	Novel Comparison of Entropy with other Impacts
Sparovek et al.	2009	LUC	No motivation
Suer et al.	2011	GW, En, AP, EP, POCP, HH, LU, TP	Builds on proven/accepted models and significance for Swedish context
Tidåker et al.	2014	GW, En, AP, EP, LU	No motivation
Tufvesson et al.	2013a	GW, En, AP, EP	RED Method Limitations
Tufvesson et al.	2013b	GW, En	No motivation
Wang et al.	2013	GW, En,dLUC	No motivation
Wang et al.	2012	GW, En, EP, dLUC	No motivation
Wetterlund et al.	2012	GW, En	No motivation

GWP-Global Warming Potential, En-Energy, AP-Acidification Potential, EP-Eutrophication Potential, LU-Land Use, LUC-Land Use Change, dLUC-direct land use change, iLUC-indirect land use change, HH-Human Health, POCP-Photochemical ozone creation potential, Ec-Economy, TP-Toxicity potential, SOC-Soil organic carbon, OD-Ozone layer deplation, WD-water use/depletion

4.3.2 Justification of Impact Category Selection

Analysis of the justification for the selection (inclusion or exclusion) of impact categories reveals a significant lack of transparency. Only 22 of the 63 studies provided a justification for the selection of impact categories; this included 15 of the 38 studies who explicitly mentioned that the LCA methodology was followed.

Justification for including GHG emissions

Several studies motivated their selection of GHG emissions through the following justifications:

- Exploring RED guidelines (Ahlgren and Di Lucia, 2014; Börjesson et al., 2013a; Englund et al., 2012; Karlsson and Börjesson, 2013; Khatiwada et al., 2012; Tufvesson et al., 2013).
- Important reason for using biofuels is the reduction of GHG emissions (Hagman et al., 2013a).
- Considered the most important aspect in assessing biofuels (Arvidsson et al., 2011), (referring to findings by Buchholz et al. (2009)).
- Parameter of interest in biofuel production studies (Luterbacher et al., 2009).
- Comparability with national and international targets on GHG emissions (Börjesson et al., 2013b; Englund et al., 2012).

Justification for including impact categories other than those related to GHG emissions

A number of different justifications were provided for the selection of environmental impact categories other than those related to GHG emissions. For instance, Bernstad and la Cour Jansen (2011) assessed GWP, AP, OD, POCP and nutrient enrichment from biogas production; justifying the choice of the impact categories by stating that the chosen impact categories are "*environmentally relevant and internationally accepted with ISO 14042*." In another study by Bernstad and la Cour Jansen (2012), environmental impact categories GWP, AP and EP were justified as they were said to be consistent with the Swedish environmental objectives (Swedish EPA, 2008), see Box 1. Martin et al. (2014) selected GWP, EP and AP to show both local and global impacts, but give no reason for choosing the specific categories, other than their large contribution, i.e. having impacts greater than 10,000 kg for the system. However, Martin et al (2014) also stress the importance of considering impacts other than GWP to identify important processes in the life cycle and include local and global impacts. Similarly, Arvidsson et al. (2011) provide GWP, AP and EP, although the embedded fossil energy category is also included in their assessment of different hydrotreated vegetable oil (HVO) fuels, arguing that the impact categories showed a significant impact on the total results.

Börjesson and Tufvesson (2011) apply recommendations from ISO 14044 and include GWP, EP and energy balances. However, no motivation for the choices is given. However, discussion of the planetary boundaries (Rockström et al., 2009) and the importance of including many impact categories is expressed.

Three papers (González-García et al., 2012, 2011; Janssen et al., 2014) considered several impact categories, the selection of which seems to be due to their availability in the LCIA method (i.e. CML baseline) that was used.

Emissions which may affect local systems were also explored by a number of authors. Hagman et al. (2013a), for instance, review water use due to water scarcity. Some of the studies use a life cycle approach but chose not to review GHG emissions. For instance, Nordborg et al. (2014a) include toxicity assessments due to the current lack of such studies in the literature. Risén et al. (2013a) also include nutrient recycling potential in their study. Höglund et al. (2013) express the need to review more impact categories in biofuel studies and review soil organic carbon (SOC), biodiversity and nutrient leakage. Their study was based on LUC, for which concern was expressed that GHG may not be the only important category to consider as there are many important environmental and social aspects to consider. None of the studies reviewed quantified biodiversity, although biodiversity was discussed in the limitations several studies; see 4.3.4.

Box 1: Swedish Environmental Objectives (Swedish EPA, 2015)

Swedish Environmental Objectives

The Swedish Environmental Production Agency has issued objectives to ensure environmental quality by 2020 (Swedish EPA, 2008), and have noted that in a recent review that more action is needed to ensure that further degradation does not occur (Swedish EPA, 2015). The Swedish environmental objectives include:

1. Reduced Climate Impact
2. Clean Air
3. Natural Acidification Only
4. A Non-Toxic Environment
5. A Protective Ozone Layer
6. A Safe Radiation Environment
7. Zero Eutrophication
8. Flourishing Lakes and Streams
9. Good-Quality Groundwater
10. A Balanced Marine Environment, Flourishing Coastal Areas and Archipelagos
11. Thriving Wetlands
12. Sustainable Forests
13. A Varied Agricultural Landscape
14. A Magnificent Mountain Landscape
15. A Good Built Environment
16. A Rich Diversity of Plant and Animal Life

4.3.3 ESA Methods and Choices

Table 6 shows the various impact assessment methods used in the 38 studies that explicitly followed the LCA methodology. Furthermore, almost half (47%) did not document the LCIA method used.

Table 6: Impact assessment method of LCA studies

Method	**Total**
IPCC	10
CML	3
EcoIndicator 99	3
EPD	2
EDIP	1
ReCiPe	1
No Data	18

4.3.4 Discussion of Impact Categories

Half of the studies (30) documented the limitation of their assessments with respect to impact categories considered, and discussed the need to consider additional impact categories. For instance, in the discussion section of the studies, authors discussed the implications of considering biodiversity (Karlsson et al., 2014; Langeveld et al., 2012; Risén et al., 2013), SOC (Bernstad and la Cour Jansen, 2011; Englund et al., 2012; Höglund et al., 2013; Karlsson et al., 2014; Kimming et al., 2011) and impacts due to site dependency (Nordborg and Cane, 2014; Suer and Andersson-Sköld, 2011).

4.4 BIOFUELS ASSESSED

The studies reviewed included a number of different biofuels, as seen in Figure 5. As Figure 5 shows, the most prevalent biofuel assessed was ethanol, followed by biogas and biodiesel.

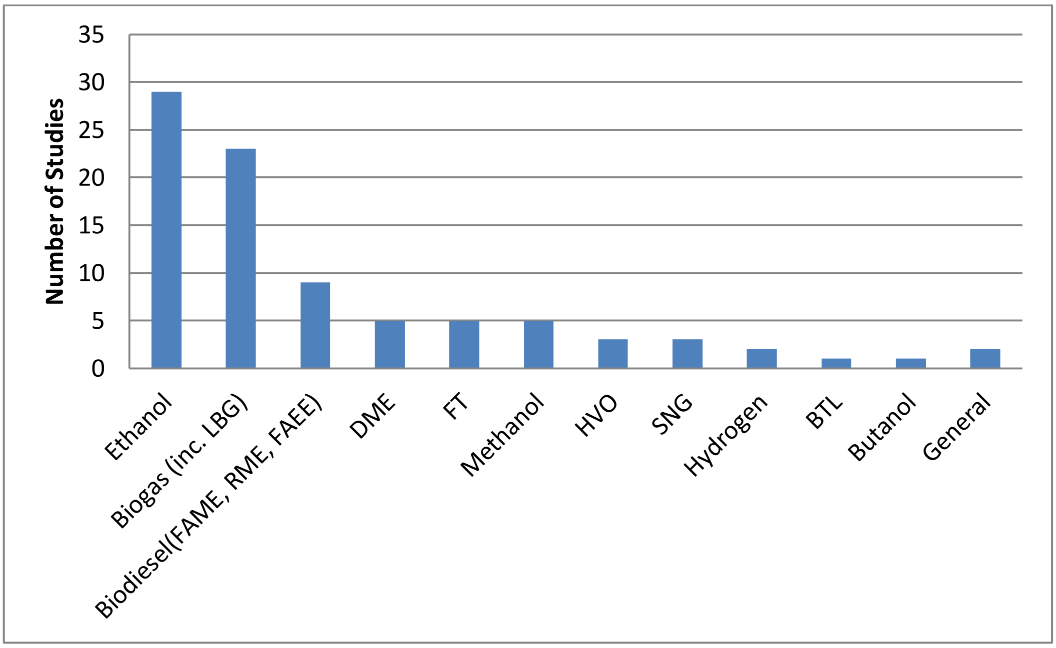

Figure 5: Biofuels reviewed in the studies

LBG-Liquid Biogas, FAME-Fatty Acid Methyl Ester, RME-Rapeseed Methyl Ester, FAEE-Fatty Acid Ethyl Ester, DME-dimethyl ether, FT-Fischer-Tropsch, HVO-Hydrotreated Vegetable Oil, SNG-Synthetic Natural Gas, BTL-Biomass to Liquid

5 DISCUSSION

5.1 IS THERE A CARBON VISION?

Figure 4 would suggest that there is an overly dominant focus on GHG emissions in biofuel ESA research in Sweden. When looking at the goals of the ESA studies, for 25 studies (40%) the goal involved a self-imposed limitation to focus on GHG emissions. However, another 25 (40%) intended to address the general environmental impacts of either biofuel production and/or consumption and addressed on average 4.5 impact categories, whilst 12% intended to specifically focus on impacts other than GHG emissions or energy use (8% of the studies did not specify their focus).

Breaking the ESA studies into their various types, we see that whilst all the LCA studies considered GHG emissions, only 11 of the 38 (29%) solely focused on GHG emissions. Furthermore, just over half of the studies (53%) considered impacts other than those related to GHG emissions and land use. For the 11 LCA studies that considered land use, 6 considered direct LU or LUC and 5 considered the GHG emissions from dLUC or iLUC. For EFs, all but two studies considered GHG emissions and14 studies (54%) only induced GHG emissions. For the 7 EF studies that considered land use, 2 considered dLU or LUC and 5 considered the GHG emissions from dLUC or iLUC.

This indicates that whilst there is clearly a dominant focus on GHG emissions, this focus has not inhibited other impact categories from being investigated in the environmental assessment of biofuels.

5.2 WHY IS THERE A DOMINANT FOCUS ON GHG EMISSIONS?

Due to the lack of motivations given for the selection of impact categories, it is difficult to determine from the studies themselves why the dominant focus on GHG emissions is present in Swedish ESA biofuel research. However, the following section discusses several issues as to why GHG emissions may have generally played such a central role in the environmental assessment of biofuels.

5.2.1 The Relevance of GHG Emissions for Biofuel Production and Consumption

The importance of GHG emissions for the development of biofuels was explicitly mentioned in several studies (See section 4.3); however, it was by far the most popular impact category, used in 59 of the 63 studies reviewed. van der Voet et al. (2010) also found that, internationally, studies have used primarily GHG emissions to portray the sustainability of biofuels, comparing them to fossil fuels and even comparing alternative production pathways for biofuels.

The dominant science-policy framework during the development of the biofuel sector in Sweden is likely to have a significant influence on ESA biofuel research in Sweden. Eklöf (2011) provides some extremely relevant insights into the link between biofuel and climate policy in Sweden.

At the heart of the connection between Sweden’s biofuel and climate policy was the assumption that the replacement of fossil fuels by biofuels would lead to a reduction in CO_2 emissions (Eklöf, 2011). Indeed, until relatively recently, transportation biofuels were considered to be inherently carbon neutral (Johnson, 2009). Eklöf (2011) suggests that counterpoint to the EU and United States biofuel policy, energy security was not the primary factor for promoting biofuels in Sweden; as stated in the Swedish Climate Bill of 2006 “Regardless of the future availability of fossil fuels, Sweden shall be highly ambitious in its attempts to reduce greenhouse gas emissions” (Climate Bill, 2006).

Between 2003 and 2007, the development of Sweden’s biofuel policy saw global warming a major political problem which could be solved by, among other things, the refinement of biomass conversion technologies. For Sweden, what brought the global warming problem and biofuel promotion together were three interlinked tenants, 1) ecological modernization: where the economic growth and environmental protection can be achieved by innovation in green technology; 2) the nation as the principle agent: where Swedish forests can support the Swedish car, forest and pulp and paper industries, and 3) Sweden’s reputation as a global environmental role model: where a capacity for leadership in the global arena is bolstered by Sweden’s role as a moral leader in the global struggle against climate change. (Eklöf, 2011)

The science-policy framework in Sweden was built upon the basis that saw biofuels as environmentally friendly based on their GHG saving potential (Eklöf, 2011). In this frame, science was assigned to the duty of a problem identifier that could compel urgent political actions and relied on the perception of the sustainability of biofuels. However, this idea, that was previously taken for granted, was questioned when controversy over the sustainability of biofuels spilled into the public domain in 2007 and 2008 (Eklöf and Mager, 2013).

The focus on GHG emissions in biofuel research is related to the basic tenant that the intention to replace fossil fuels is based on the desire to reduce the impact on the climate that stems from their use. Hence, to be a viable replacement to fossil fuels, biofuels must have lower GHG emissions (from cradle to grave) than their fossil counterparts. Much of the research that has been conducted concerning the environmental sustainability of biofuels has focused on this point. However, determining the GHG emissions of biofuel production and consumption systems is not a simple task, calling for further research on methodological aspects. As such, the focus of research has shifted from comparing GHG emissions of biofuels with their fossil counterparts to determining *how* to compare GHG emissions of biofuels with their fossil counterparts.

5.2.2 Determining GHG Emissions

Determining the GHG emissions of biofuels, however, has proved to be a difficult venture, a source of controversy (Anex and Lifset, 2014) that calls into question the very basis for the support of transport biofuels (Eklöf, 2011). A number of studies have pointed to the importance of including dLUC, iLUC, biogenic carbon, soil carbon emissions and non-CO_2 emissions from soil in the accounting of biofuel GHG emissions and in their comparison to fossil fuels (Cherubini et al., 2011; van der Voet et al., 2010).

Indeed, Johnson (2009, p. 167) notes that “Today, researchers and governments generally accept that land-use change must be accounted in liquid biofuel footprints. This change of perception – accepting that biofuels are not automatically carbon neutral–was painful”, as it hurt producers that had already invested in new capacity and damaging the credibility of biofuels.

Gnansounou et al. (2009) notes that studies have shown that when these aspects are considered, results differ from previous studies which show GHG benefits of biofuels compared to fossil equivalents (see Fargione et al. (2008) and Searchinger et al. (2008)), questioning the production of biofuels as a climate change mitigation strategy. Hence, current scientific debate is still very much focused on the quantification of GHG emissions; which takes into consideration direct and indirect LUC and soil carbon emissions, for which there is still no consensus on how to include this aspect consistently in LCA (van der Voet et al., 2010).

With such a controversy over the account of GHGs—as a result of the policy-science frame that helped to establish the biofuel sector—much research is concentrated on appropriate methodologies for GHG accounting. This is reflected by the 10 studies which have investigated the implications of dLUC and iLUC on GHG emissions.

5.2.3 Influence of Regulation

In order to ensure that biofuels used in the EU had lower life cycle GHG emissions than fossil fuels, Gnansounou et al. (2009, p. 4919) notes that "public authorities in several countries have imposed minimum targets for biofuels to be eligible for incentives, i.e. sustainable biofuels". The RED is unique in that it specifically applies the LCA methodology to determine whether quantitative mandatory GHG emission reduction targets are met (Bicalho et al., 2012). Other EU directives that draw on the life cycle approach, such as the Waste Framework Directive 2008/98/EC, stop short of mandating the use of LCA, opting for the term 'life cycle thinking' as to reduce the burden to industry (Lazarevic et al., 2012, 2010).

The RED applies LCA as an accounting method to provide evidence of the effective reduction of GHG emission of 60% by 2018 compared to a fossil fuel reference value (Council Directive, 2009). The RED also requires that impacts on biodiversity and land use be considered. In 2012, the EC released a proposal to amend the RED and FQD to reduce the risk of indirect land use change (European Commission, 2012) which included, among others, the following new sustainability criteria:

- "biofuels from new installations to emit at least 60% less GHGs than fossil fuels
- emissions that might be caused by indirect land use change must be included in the reporting of fuel providers and EU countries. This will be done by estimating emissions that would take place globally when land is used for growing crops for biofuels to be used in the EU instead of growing food and feed crops (estimated iLUC emission values)" (European Commission, 2015a).

The RED does not appear to be a driving factor for studies to focus on GHG emissions, as only 6 studies noted that the RED guidelines were part of the motivation for their analysis.

5.3 METHODOLOGICAL LIMITATIONS OF EXPANDING IMPACT CATEGORIES BEYOND GWP

Further to the socio-technical explanations for a dominant focus on GHG emissions in biofuel ESA research in Sweden, there are also a number of methodological reasons why GHG emissions dominate the representation of other environmental impacts.

5.3.1 Data Uncertainty

Data limitations may limit the impact categories being used to assess the sustainability of biofuels. For instance, for the case of bio ethanol, von Blottnitz and Curran (2007, p. 616) suggest that it is not necessary to repeat detailing GHG and energy assessments (as reliable estimates can be made from existing literature) but that it is vital to collect data needed for the "disputed environmental categories of acidification, eutrophication, photochemical smog, human and ecotoxicity, as well as land use and its effects on biodiversity."

GHG emissions are readily available in life cycle inventories which facilitate the impact assessment of GHG emissions. Furthermore, authors may also choose to model systems based on previous literature, which may have limited data, in order to portray regional inputs and processes. As an example, Martin et al. (2014) use a combination of data from Ecoinvent and data sources such as (Bernesson et al., 2006; Börjesson et al., 2010) to model impacts from biofuels such as biogas and ethanol. By doing so, impacts other than the chosen categories (i.e. GWP, EP and AP) may not be applicable. Whilst using data from previous assessments and databases may be common in the literature, information used for computing some impact categories may be missing in many of the data sources, thus making the results for some impact categories less credible and reliable (Björklund, 2002; Weidema, 2000). Data available for assessments of Swedish biofuels from LCI sources (such as Gode et al., 2011; Hallberg et al., 2013) may not provide the spectrum of resource inputs needed to provide further impact categories, although the authors also stress the lack of available data for many of the processes provided.

Furthermore, data used and assumed to mirror Swedish conditions may not be modelled correctly in many of the studies. There is currently a lack of data from databases such as Ecoinvent and other databases to account for Swedish processes. Using data for 'comparable' European systems may lead to large differences in 'actual' emissions and thus sensitivity to the data should be reviewed. Furthermore, commercially available databases may not provide enough data to cover the spectrum of impact categories as seen in Table 1. For example, Nordborg et al. (2014) criticize LCI datasets available to account for pesticide use for being too simplified and not containing enough data for use in LCAs. van der Voet et al. (2010) also elaborate on the deficiency of databases in providing information used for water footprints. Furthermore, coupling regional data to global LCIA methods also lead to uncertainties, as discussed previously.

5.3.2 Impact Assessment Methodologies

For LCA studies, impact assessment methods are primarily modelled on global average basis. This entails that the modelling is done to assume average conditions, regardless of where the production takes place and conditions of the source. For the impact categories such as GWP and stratospheric ozone depletion, this issue is not relevant, as the impacts are aggregated and are independent of the source of the emissions (Finnveden et al., 2009). The applicability of the GWP indicator to nearly every case may lead to its use as an impact category in the vast majority of LCAs of biofuels. Furthermore, it may be difficult to include other impact categories into biofuel production systems as impacts may derive from a large number of sources and may be sensitive to where they are emitted. Characterization factors are required to be developed to include impacts throughout the life cycle and for different origins of the products and processes involved. Caution should be warranted, however, when choosing the LCIA methods if local impacts are to be modelled, as the impacts may be dependent upon the conditions regionally or locally depending upon the sensitivity of the local environment (Finnveden et al., 2009). An important example was outlined in a study by Potting et al.(1998), where great variations in acidification were found between countries in Europe. There has been work to develop site dependent characterization factors for LCIA, primarily with application in Europe (see Huijbregts et al. (2000), Krewitt et al (2001) Potting et al. (1998) and Finnveden and Nilsson (2005)), though factors for other countries are also present in the literature. As such, characterization factors can be developed for country specific production. Finnveden and Nilsson (2005) and (Seppälä et al., 2006) extend this to produce characterization factors specific to regions within Sweden to account for the diversity found in the large country and increase resolution. This may be applicable in other large countries and regions as well.

Impacts on, for instance, biodiversity have been developed for integration in LCAs (Curran et al., 2011; Koellner et al., 2013) to extend the assessments not only to environmental impacts but also to the implications that land use for different production practices, in e.g. agricultural and horticulture sectors, may have regionally and globally. Souza et al. (2015b) suggest that biodiversity is primarily shown as an endpoint category which models the loss in species richness over time. Despite this, functional and population effects are absent due to limited geographical and taxonomical focus. Nonetheless, Koellner et al. (2013) discuss the fact that biodiversity impacts may be best suited as a general impact category to cover the nature of e.g. biofuels, which have many inputs from a world market to make the assessments more generally applicable. Koellner et al. (2013) and Souza et al. (2015) provide short reviews of many of these studies and elaborate on past attempts to assess impacts of land use on biodiversity, ecological functions and ecosystem services. The studies found that there is often a limited geographic scope with limited applicability outside the studied area. Consequently, Koellner et al. (2013) provide guidelines for including biodiversity in LCAs for various products and processes with a broader regional focus.

The inclusion of water use in LCAs of biofuels is currently immature due to data gaps and methods (van der Voet et al., 2010). Of the 63 studies found in this assessment, only Hagman et al. (2013) reviewed water use for Jatropha production abroad. Although the water use issue may not be an imperative impact category to assess in a Swedish perspective, water use from different biofuels imported to Sweden are of concern as energy from biomass may have large water footprints compared to other energy sources (van der Voet et al., 2010).

5.4 GOING BEYOND ‘CARBON’ AS A ‘SUSTAINABILITY’ INDICATOR

In previous overviews of biofuel LCAs, van der Voet et al. (2010) and Cherubini and Strømman (2011) found that many studies provide limited impact categories, typically GPW and energy assessments. This was the case for 40% (25 of the 63 studies) of the ESA studies and 29% (11 of the 38 studies) of the LCA studies analysed in this study.

Laurent et al. (2012) suggest that focusing only on carbon footprint may risk problem shifting, which may possibly increase other impact categories. As an example, they found that shifting from fossil fuels to renewable energy for electricity production does not necessarily reduce all impact categories. This is due to the fact that whilst impacts stemming from the burning of fossil fuels are reduced, there may be an increase of impacts in upstream processes of the life cycle related to infrastructural development, leading to depletion of resources and increased impacts related to toxicity for human health. van der Voet et al. (2010) also elaborate on the fact that several biofuel studies have shown an increase in toxicity and eutrophication potential for biofuels in comparison to fossil fuels. These conclusions are also independent of other methodological considerations including allocation choice, making these impacts important to address. Furthermoe, when discussing the sustainability of biobased systems, von Blottnitz and Curran (2007) and Parajuli et al. (2015) stress the importance of assessing different impact categories and identifying solutions that are broad enough in scope as to avoid the shifting of environmental impacts.

In this context, some current Swedish research funding mechanisms focus on the need to synthesise knowledge on the sustainability aspects of biomass production, use and refining, specifically highlighting land use[7].

At the European level, Horizon 2020 research and innovation calls[8] related to biofuels generally come under the Societal Challenge category 'Competitive Low-Carbon Energy' and include a focus on land and water use in addition to GHG emissions;

> "… in the long-term perspective, new technologies of sustainable biofuels and alternative fuels need to be developed that radically improve the state-of-art, notably in regards to the following sub-challenges … c) Improving the economic, environmental and social benefits relative to fossil fuels and currently available biofuels, notably regarding cost reduction, minimisation of demand on natural resources (land and water in particular), enhanced energy balance, reduced GHG emissions (including carbon stock changes) and development of rural areas" (European Commission, 2015b, pp. 65–66).

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[7] See Formas Call: 'Research syntheses about sustainability aspects within different systems for production and use of forest raw materials and biomass'

[8] For instance: LCE-11-2015: Developing next generation technologies for biofuels and sustainable alternative fuels; LCE-12-2015: Demonstrating advanced biofuel technologies; and LCE-14-2015: Market uptake of existing and emerging sustainable bioenergy

6 CONCLUSIONS

This study set out to investigate whether or not there is a dominant focus on GHG related impacts at the expense of other impact categories in Swedish biofuel ESA. To this end, this study has reviewed ESA of biofuel production and consumption systems undertaken by Swedish researchers between 2000 and 2015.

The results indicate that there is a clear focus on GHG emission related impacts, with 59 of the 63 studies analysing GHG emissions. Furthermore, 25 of the 63 studies limited their goal to the assessment of GHG emissions. However, this focus did not inhibited other impact categories from being investigated, as demonstrated by the fact that 25 studies intended to address the general environmental impacts of either biofuel production and/or consumption and addressed on average 4.5 impact categories, and 8 studies intended to specifically focus on impacts other than GHG emissions or energy use (such as land use change, toxicity and water use). This indicates that whilst there is clearly a dominant focus on GHG emissions, this focus has not inhibited other impact categories from being investigated in the environmental assessment of biofuels.

These results are consistent with international research on the environmental assessment of biofuels, which is characterised by a dominant focus on GHG emissions and energy use, followed by the inclusion of impact categories such as AP and EP, and very few studies investigating the toxicity and water use of biofuel production and consumption systems.

7 RECOMMENDATIONS

Whilst biofuel production is inextricably linked to climate policy, one should not forget that the broader context of the Swedish environmental objectives should also be taken into consideration when developing biofuel production systems in Sweden. Policies and guidelines on quantitative and qualitative measures should take into account an array of impact categories to ensure biofuels are produced sustainably. This will require the development of more transparent and robust impact assessment methods; which will require interdisciplinary collaboration in the ESA and LCA fields.

The following recommendations highlight a number of actions targeted at specific stakeholder categories including: f3, the biofuel industry, the LCA community and Swedish and European policy-makers. For each stakeholder category they are listed in relative priority based on the importance as seen by the authors.

7.1 F3

- Ensure that data and methodological outputs from research projects are open access and made available for future studies to ensure transparency.
- Promote life cycle sustainability assessments of biofuels to allow for comparisons of biofuels based on sustainability criteria, including economic and social assessment.
- Develop a LCA task force to address and harmonize the use of LCA for biofuels in Sweden in order to coordinate and strengthen efforts among members.
- Foster dialogue with the Swedish Energy Agency to develop and promote new methods and knowledge produced to be introduced into policy for reviewing/comparing biofuels with fossil fuels.

7.2 BIOFUEL INDUSTRY

- Increase collaboration with the research community and policy-makers to co-develop assessment methods in order to improve LCA methodologies which are scientific yet feasible in-house.
- Increase the dissemination of knowledge to the public on the environmental impacts and potential improvements of producing sustainable biofuels.

7.3 LCA COMMUNITY

- Improve the availability and access to LCI data to improve transparency and reduce uncertainty.
- Include datasets in the publication of biofuel LCAs (and other products).
- Inclusion of more than GHG emissions as an impact category for sustainability assessments; e.g. as von Blottnitz and Curran (2007) suggest, focus should lie on improving availability of assessments for “disputed environmental categories”, specifically acidification, eutrophication, photochemical smog, human and ecotoxicity, land use and biodiversity.

- Improved data and LCIA methodologies for quantifying impacts for biodiversity, ecosystem services and toxicity.
- Development of regional specific characterization factors in order to show how impacts at different locations in the life cycle (e.g. different regions within a country) can have different effects depending on the source of emissions, extraction, etc.

7.4 POLICY MAKERS (SWEDEN)

- Provide LCI data used for sustainability assessments of biofuels under the Renewable Energy Directive program in order to improve data availability and transparency.
- Reflect on the role of biofuels in the boarder context of the Swedish Environmental Objectives, beyond the context of climate and energy policy.
- Take a lead in addressing environmental impact assessment methods to be introduced in policy together with researchers.

7.5 POLICY MAKERS (EUROPE)

- Harmonize assessment methods in order to avoid lack of transparency.
- Provide LCI data used for sustainability assessments of biofuels under the Renewable Energy Directive to improve data availability and transparency.
- Foster the development of dialogue with researchers and biofuel producers to create and monitor methods for impact assessment of biofuels beyond GHG emissions.
- Identify the potential positive impacts of biofuels beyond climate and energy policy.

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