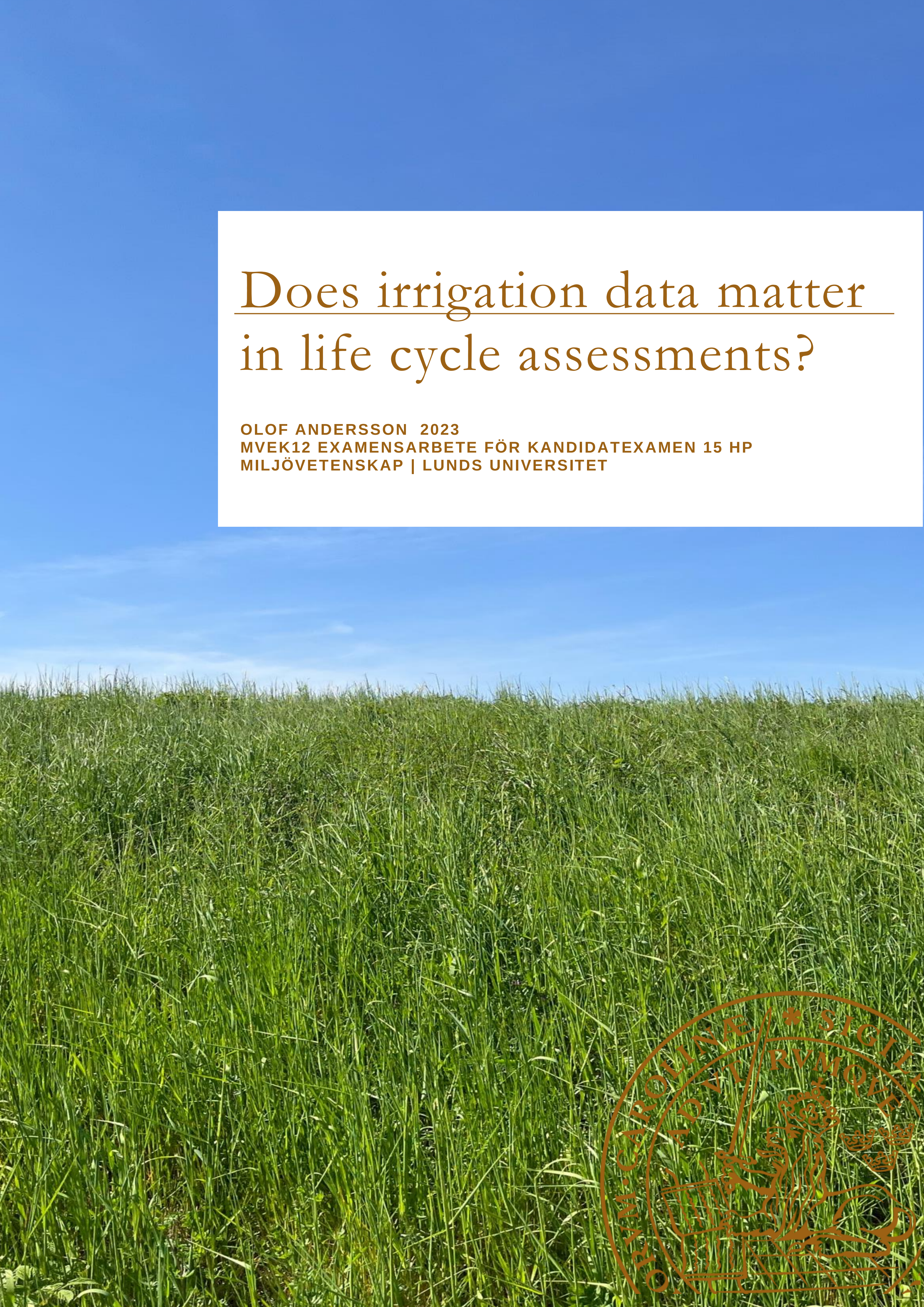

Does irrigation data matter in life cycle assessments?

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Sensitivity analysis of a comparative Agent Based Life Cycle Assessment evaluation of a subsidy for grass production in Götalands Södra Slättbygder

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2023

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Abstract

Biofuels are seen as a key substitute for fossil fuels and an essential tool for mitigating climate change. A sensitivity analysis was conducted on the AB-LCA (agent-based life cycle assessment) made by Raül López i Losada and his research team. Their AB-LCA assesses the environmental performance of a subsidy that generates an allocation of the arable land in Götalands Södra Slättbygder (GSS) that dedicate 25 percent of the arable land for grass leys later used for biofuel production. Irrigation data in the life cycle setup was identified as a sensitive input of interest due to its high variability. New, alternative irrigation data was collected from the Food and Agricultural Organization of the United Nations (FAO) and inserted in the life cycle system setup. A new impact result was generated with a life cycle assessment modeling software with the endpoint impact assessment methods ReCiPe 2016 and Impact World+. The collected irrigation data from FAO was on average 77 percent lower compared to the original data used in the AB-LCA which highlighted the importance of a sensitivity analysis like this. The substitution of irrigation data in the LCA software gave an average reduction in total impacts of 1,87 percent for human health and 2,33 percent for ecosystems, favoring the life cycle scenario where 25 percent of the arable land in GSS was covered by grass leys. The founding increased the environmental benefits of introducing grass ley rotations in GSS. This study showed that irrigation data matters for the AB-LCA impact results. The sensitivity analysis came to the same conclusion as the original AB-LCA which confirms that there are environmental benefits associated with dedicating 25 percent of the arable land in GSS to grass leys.

Keywords: Agent-Based Life cycle assessment, Arable grass rotation, Biofuel, Irrigation, Sensitivity analysis, Water footprint

List of Acronyms

BAU: Business as usual

FAO: Food and Agricultural Organization of the United Nations

GRASS: LCA scenario where subsidies generate a land use allocation where 25 percent of the arable land in Götalands Södra Slätbyggder is covered by grass leys.

GSS: Götalands Södra Slättbygder.

Populärvetenskaplig sammanfattning

Att byta från fossila bränslen till biobränslen är ett vanligt sätt för många verksamheter att bidra till en grön omställning. I takt med att klimatförändringarna förvärras och krav på åtgärder ökar, förväntas efterfrågan på biobränslen öka i Sverige samt andra delar av världen. För att säkra en hållbar omställning, är det viktigt att granska biobränslenas påverkan på miljö och människors hälsa. I en så kallad livscykelanalys, där all miljöpåverkan som associeras till en produkt eller tjänst sammanställs, undersöker Raül López i Losada och hans medarbetare, miljöpåverkan som uppstår av att odla gräs som används till produktion av biobränslen. Deras undersökning görs med hjälp av ett modelleringsverktyg där gräset antas odlas i Götalands Södra Slättbygder och förväntas täcka 25 procent av åkermarken i området. Modellen de använder för att få fram den totala miljöpåverkan är beroende av massor av data och en del antaganden. En sorts data i modellen som ofta skiljer sig beroende av dess ursprung är bevattningsdata. För att testa känsligheten i Raüls resultat, gjordes därmed i detta examensarbete en känslighetsanalys inriktat på bevattningsdata. En känslighetsanalys är en undersökning som testar rimligheten av en studies resultat genom att man ändrar antaganden för modellen i studien och ser hur det påverkar resultatet. Ny bevattningsdata hämtades från FN:s livsmedels- och jordbruksorganisation (FAO) och modelleringen av miljöpåverkan från att odla gräs i Götalands Södra Slättbygder upprepades. Bevattningsdatan från FAO var genomsnittligt 77 procent lägre än den bevattningsdata som använts i modellen tidigare. Med bevattningsdatan från FAO visade modellen att fördelarna med att odla gräs i Götalands Södra Slättbygder var marginellt större jämfört med vad Raül och hans medarbetare kommit fram till i sin forskning. Resultatet från den nya modelleringen med alternativa bevattningsdata visade att det fanns miljömässiga fördelar med att introducera odling av gräs i Götalands Södra Slättbygder. Det bekräftar slutsatsen som Raül och hans medarbetare kommit fram till och tyder på att deras resultat är robust.

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Introduction

Biofuels are seen as a key substitute for fossil fuels and an essential tool for mitigating climate change (Chiaramonti et al., 2021; Dornburg et al., 2010). To replace fossil fuels, the European Green Deal creates incentives for European producers to supply biofuels and bio-based products (The European Commission, 2021). Grass can be grown as a source of bioenergy and can be transformed into biofuels such as bioethanol and biogas (Sánchez & Cardona, 2008; Zhong et al., 2016). One strategy for growing grass for bioenergy is to include grass ley rotation on intensive agricultural land. Thus, growing grass gives not only an energy source in the form of biofuel but also co-benefits in the form of carbon storage, water security and improved soil health which further leads to increased yields over time (Englund et al., 2023).

However, the increased use of bioenergy does not come without controversy or goal conflicts (Dornburg et al., 2010; Vera et al., 2022). The grass leys occupy areas critical for other societal values, such as food production (Vera et al., 2022). Outsourcing of food production could then lead to potential negative environmental impacts (Fuchs et al., 2020). Knowledge about the environmental impacts and benefits associated with biomass for biofuel production is necessary for enabling policymakers to make the best possible decisions to meet the societal energy demand in a sustainable way.

A Life Cycle Assessment (LCA) is a model used to quantify the environmental impacts of a product or service. The impact results from the LCA can be used to compare the environmental impacts of various products and is an important tool in policy-making and product design (Jolliet et al., 2016). Life cycle assessments have been done to quantify the environmental impacts of various types of biofuels in the past (Schmidt et al., 2015; Zoppi et al., 2023).

Today Raül López i Losada and his research team at the Centre for Environmental and Climate Science in Lund are conducting an Agent-Based Life Cycle Assessment (AB-LCA) for the growing of grass leys for biofuel production in the intensive farming region of Götalands Södra Slättbygder (GSS). GSS is an agricultural area in southern Sweden holding intensive crop farming generating high yields. The crops barley, wheat, rapeseed, and sugar beet are grown on the arable land with the highest production and cover 95% of that area. The highly productive land is rarely covered by any grass and long-term field experiments on areas with similar farming practices as in GSS suggest that the soil organic carbon (SOC) could be depleted (Brady et al., 2015; Zhou et al., 2019). Grass ley cropping systems contribute positively to increased accumulated SOC (Zhou et al., 2019). This could be a co-benefit of implementing grass leys in GSS, increasing the long-term productivity in the agricultural area.

The AB-LCA by López et al. aims to evaluate the environmental impacts of an agricultural policy intervention that would ensure that 25% of the agricultural land is allocated for growing grass leys. A sensitivity analysis is always recommended in LCAs to test the robustness of its results (Jolliet et al., 2016). Water footprints for different crops and irrigation data are complex to model since there are many varying aspects that affect water consumption in a certain area. Aspects such as climate, irrigation techniques, soil type, and water availability are examples of these varying aspects (Pfister & Bayer, 2014). About 70 percent of the global water resources is used for agriculture (Gleick, 2012). Efficient water management in agricultural systems is therefore critical for reaching the global goals regarding water use and water security (The Global Goals, 2015). Testing irrigation data in LCAs which is used in policy decisions, is important to ensure sound policies which contribute to increased water efficiency. The AB-LCA by López i Losada et al. lacks a sensitivity analysis testing the irrigation data in the AB-LCA. This can be of great importance due to the uncertainties regarding water footprint data in the LCA databases.

Purpose

This study aims to perform a sensitivity analysis for the Agent-Based Life Cycle Assessment conducted by Raül López i Losada and his research team on the introduction of grass for biomass production in the agricultural region of Götalands Södra Slättbygder (GSS). For the sensitivity analysis, irrigation data is the sensory input of focus. The sensitivity analysis will investigate how alternative irrigation data affect the impact results of the AB-LCA that summarize the environmental effects associated with growing grass for biofuel production in GSS.

This study will answer the following questions:

I. How much does the new collected irrigation data differ compared to the irrigation data from the Ecoinvent database used in the AB-LCA?

II. How much does the irrigation data affect the total impact assessment result of the AB-LCA on biomass production?

III. Does the new irrigation data affect the conclusions drawn from the AB-LCA made by López et al.?

Ethical reflection

No sensitive data or controversial methods are used in this analysis. The results from this thesis can, however, support policy decisions that can affect society. The result could affect the policy decisions which impact the land use distribution in GSS and other areas with similar environmental conditions. The potential change in land use distribution will likely affect the supply of local goods, the local livelihoods, and the trade dynamics in the area, which will have social and ecological effects. Another ethical discussion concerning this thesis is the question of food versus fuel. What should we prioritize, climate mitigation and renewable energy, or locally sourced food?

Method

Most of this thesis's data and background information is sourced from the unpublished AB-LCA[1] conducted by Raül López i Losada, Ralph K. Rosenbaum, Mark V. Brady, Fredrik Wilhelmsson and Katarina Hedlund. This sensitivity analysis is conducted on their comparative AB-LCA and their work will be referenced to as "the AB-LCA" or "López et al." throughout this thesis.

The Agent-Based LCA

The *functional unit* in the LCA is the unit on which the environmental impacts and emissions are based on (Jolliet et al., 2016). In this thesis, the agricultural landscape of Götalands Södra Slätbygder (GSS) serves as the basis for the functional unit. The LCA by López et al,. on which the sensibility analysis is conducted, is a comparative Agent Based LCA whose purpose is to support policymaking regarding land use in the area of Götalands Södra Slätbygder (GSS). In their AB-LCA, López i Losada et al. have simulated with the tool AgriPoliS, a subsidy to farmers for incorporating grass leys to their arable rotations. Agripolis stands for Agricultural Policy Simulator and is an Agent-Based Modeling (ABM) tool for modeling farmers' behaviors relative to certain policies (Happe et al., 2006). The subsidy was adjusted to achieve that 25% of the arable land of GSS is covered by grass leys which are later transformed into biofuels. The scope of the LCA includes all environmental impacts associated with land use in the agricultural land of GSS. One consequence of the introduction of grass leys on agricultural land is that other crops, normally grown in the highly productive area are replaced by the grasses. Since food crops with inelastic demand are displaced, the supply of these crops must be secured through imports. The environmental impacts generated from these imports is included in the impact assessment. The impacts in the LCA model are in this case divided into two parts, one impact generated by the land use of GSS, and one part generated by imports due to displaced crops.

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[1] *A comparative Agent-Based LCA evaluating a policy instrument to enhance production of agricultural biomass for biofuels*. Raül López i Losada. Centre for Environmental and Climate science. Lund University 22362, Lund, Sweden. Raul.lopez_i_losada@cec.lu.se

The comparative AB-LCA has two impact scenarios. The GRASS scenario, where 25% of the area in GSS is covered by grass leys, and the Business as Usual (BAU) scenario, where the present land use continues. The results from the impact assessment of the AB-LCA showed that the GRASS scenario had overall environmental benefits compared to the BAU scenario. In the GRASS scenario, most impact categories were lower than BAU's, except for a handful of impact categories. See Table 1.

Table 1: Impacts of the GRASS and BAU scenarios on human health and ecosystems from the AB-LCA. The impacts are generated with the impact assessment methods ReCiPe 2016 and Impact World+. The total impact is divided into each impact category, darker orange color means a bigger contribution to the total impact. The red color highlights which scenario that has the highest impact compared to the other for each impact category.

ReCiPe 2016			
AREA	Impact Category	GRASS	BAU
Human Health	Fine particulate matter formation	3,8E+02	4,7E+02
	Global warming, Human health	1,8E+02	2,1E+02
	Human non-carcinogenic toxicity	4,6E+01	6,0E+01
	Human carcinogenic toxicity	2,7E+01	3,4E+01
	Water consumption, Human health	1,5E+01	8,7E+00
	Stratospheric ozone depletion	1,5E+00	1,8E+00
	Ozone formation, Human health	5,5E-01	7,2E-01
	Ionizing radiation	3,9E-02	4,7E-02
Ecosystems	Land use	5,5E+00	6,6E+00
	Terrestrial acidification	7,8E-01	9,3E-01
	Global warming, Terrestrial ecosystems	5,4E-01	6,4E-01
	Ozone formation, Terrestrial ecosystems	7,9E-02	1,0E-01
	Water consumption, Terrestrial ecosystem	1,1E-01	6,8E-02
	Freshwater eutrophication	4,5E-02	6,0E-02
	Terrestrial ecotoxicity	7,1E-03	8,7E-03
	Freshwater ecotoxicity	4,5E-03	5,4E-03
	Marine eutrophication	8,8E-04	1,1E-03
	Marine ecotoxicity	8,9E-04	1,1E-03
	Global warming, Freshwater ecosystems	1,5E-05	1,8E-05
	Water consumption, Aquatic ecosystems	3,0E-05	1,6E-05

IMPACT World+			
AREA	Impact Category	GRASS	BAU
Human Health	Water availability, human health	1,7E+03	9,4E+02
	Climate change, human health, long term	3,7E+02	4,4E+02
	Particulate matter formation	2,8E+02	3,3E+02
	Climate change, human health, short term	1,6E+02	1,9E+02
	Human toxicity non-cancer, short term	1,5E+02	1,6E+02
	Human toxicity non-cancer, long term	3,0E+01	4,6E+01
	Human toxicity cancer, short term	2,9E+01	3,7E+01
	Human toxicity cancer, long term	8,4E-01	1,5E+00
	Ionizing radiation, human health	1,6E-01	2,0E-01
	Ozone layer depletion	3,5E-02	4,0E-02
	Photochemical oxidant formation	2,8E-02	3,6E-02
Ecosystems	Freshwater ecotoxicity, long term	9,8E+08	1,2E+09
	Land occupation, biodiversity	3,7E+08	5,1E+08
	Climate change, ecosystem quality, long	8,2E+07	9,8E+07
	Terrestrial acidification	4,6E+07	5,6E+07
	Land transformation, biodiversity	4,2E+07	5,6E+07
	Climate change, ecosystem quality, short	3,4E+07	4,1E+07
	Marine acidification, long term	1,6E+07	2,0E+07
	Freshwater acidification	4,2E+06	5,0E+06
	Freshwater ecotoxicity, short term	1,9E+06	2,4E+06
	Marine acidification, short term	1,8E+06	2,1E+06
	Marine eutrophication	2,0E+06	2,0E+06
	Freshwater eutrophication	1,2E+05	1,9E+05
	Water availability, terrestrial ecosys.	2,1E+05	1,2E+05
	Water availability, freshwater ecosys.	5,3E+03	3,2E+03

LCA model and Impact Assessment

A life cycle modeling tool was used to model the environmental impacts of the functional unit GSS. SimaPro is a life cycle assessment modeling software where one can model and analyze complex lifecycles and measure the environmental impacts across all the stages of the lifecycle (*SimaPro*, n.d.). SimaPro was the LCA modeling software used in the AB-LCA and in this sensitivity analysis.

There are several ways to construct an LCA, and various impact assessment methods can be used to quantify the environmental impacts of the functional unit of interest. An impact assessment method quantifies the environmental impact of the chosen functional unit (Jolliet et al., 2016). Different impact assessment methods are based on different data. They have specific niches and different ways of weighing the emissions in the LCA. The choice of impact assessment method does therefore affect the obtained results of the LCA (Chen et al., 2021; Jolliet et al., 2016). The impact assessment methods ReCiPe 2016 and IMPACT World+ were chosen for this LCA. Both methods have indicators defined at an endpoint level quantifying the damage done to an area of protection caused by all emissions and resource extraction within the life cycle of the functional unit. The endpoint indicators, in this case, also called impact categories, group the impacts for all the processes within the life cycle with similar effects (Jolliet et al., 2016). All these groups or impact categories combined, make up the total impacts on the area of protection. This LCA considers all endpoint indicators within ecosystems and human health areas of protection, for both methodologies.

The unit DALY is used to measure the impact on human health and stands short for Disability Adjusted Life Year (Jolliet et al., 2016). DALYs are used in both impact assessment methods ReCiPe 2016 and Impact World+ (PRé Sustainability, 2022). The impact assessment methods ReCiPe 2016 and Impact World+ use two different units to quantify damage to ecosystems. ReCiPe 2016 use the unit “species yr” and Impact World+ use ”PDF.m2.yr” (Jolliet et al., 2016; PRé Sustainability, 2022). The unit “species.yr” stands for “species year” and describes the number of disappeared species per year. PDF.m2.yr stands for Potentially Disappeared Fraction of species over one square meter (PRé Sustainability, 2020).

Irrigation Data

The method of the sensitivity analysis consisted of several steps. Primarily, the results and data from the already conducted AB-LCA were analyzed. The irrigation data for the imported crops in the system was identified as a sensitive input of interest through dialogue with Raül López i Lósada. Irrigation data is an input of high variance (Aldaya et al., 2012), which highlight its relevance as a sensitive input.

To test the sensitivity and motivate further tests on the irrigation data as an input, a test run was made assuming that the irrigation input was 40 percent lower than the original inputs in SimaPro. A decrease of 40 percent was chosen since López i Losada and his colleagues working in the field believed that the irrigation data might be overestimated in the Ecoinvent database. The test run was done with both impact assessment methods, ReCIPe 2016.

Ecoinvent is a database that has collected reliable environmental data for the impacts of more than 18 000 human activities. The Ecoinvent datasets include the environmental impacts from a large number of industrial sectors such as agriculture, animal husbandry, building and construction, chemicals and plastics, energy, forestry, metals, textiles, transport, touristic accommodation, waste treatments and recycling, water supply and many more (*Ecoinvent*, 2020). The data used in SimaPro for modeling the AB-LCA is sourced from the Ecoinvent database, including the irrigation data (PRé Sustainability, 2022). Alternative irrigation data for crop imports in the LCA system was collected. Irrigation data associated with the production of the crops barley, wheat, rapeseed, sugar beet, and Maize originating from the countries Germany, France, Spain, Argentina, USA and was collected from FAO's databases AQUASTAT and FAOSTAT (FAO, 2020, 2021) and from the article by Debaeke & Hilaire (Debaeke & Hilaire, 1997). See Tables 2 & 3 in the results for the collected data. Irrigation data for rapeseed production in France was not available in the AQUASTAT database. Rapeseed fields in France are rainfed, according to Debaeke & Hilaire 1997. The French rapeseed is therefore assumed to have no water use for irrigation. The alternative data was converted to match the unit used in SimaPro in a spreadsheet, allowing the substitution of irrigation data. See Figure 1 for an overview of the data collection.

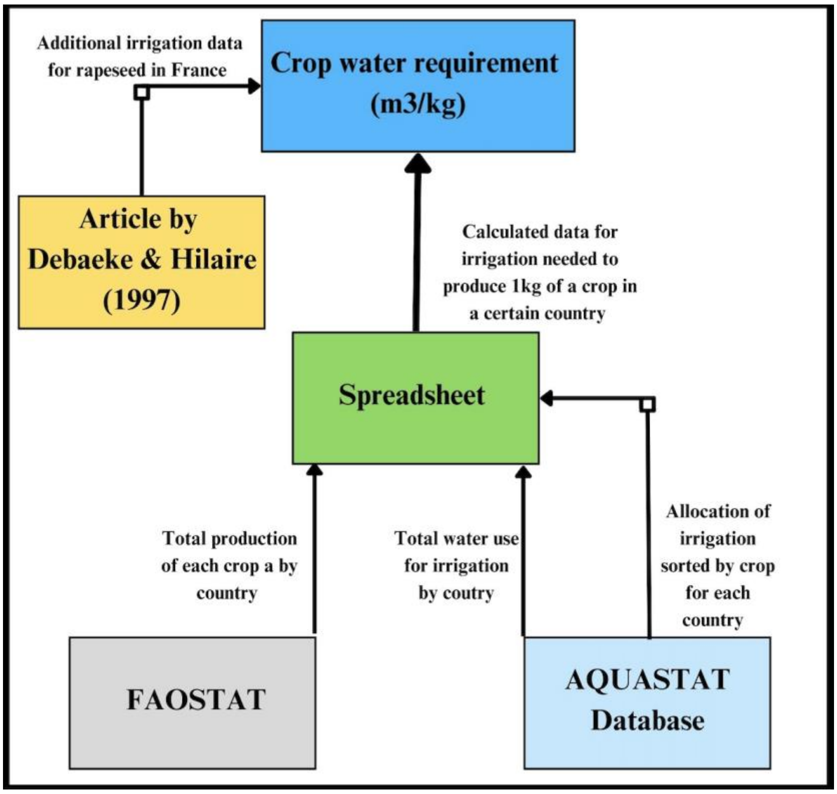


Figure 1: Flowchart showing the procedure of collecting new irrigation data for the impact assessment.

LCA operations for sensibility analysis

The environmental impacts associated with the production of one kilogram of barley, maize, wheat, sugar beet, and rapeseeds were collected from SimaPro. The impact assessments were done with two impact assessment methods in the software, ReCiPe 2016 and Impact World+. Just like in the AB-LCA, the impact category "Land transformation, biodiversity" was excluded from the analysis since the results were considered unrealistic. Barley, wheat, sugar beet, and rape seeds were assumed to be produced within the EU, and Maize was assumed to be globally produced since European production of maize was not available as an input in SimaPro. The alternative irrigation data was inserted in the processes in the system setup in SimaPro, substituting the original irrigation values. The impact calculations were run in SimaPro, producing a new per kilogram environmental impact for each crop. The new environmental impact quantities were processed in a spreadsheet to calculate the total environmental impacts associated with total crop imports. These impacts were added to those originating from GSS production. The total environmental impact for the functional unit GSS with the new irrigation data from FAO was quantified and visualized in the spreadsheet. With the results, new scenarios with the alternative irrigation data were created, named "BAU FAO" and "GRASS FAO". Environmental impacts were compared for the BAU FAO and GRASS FAO scenarios. The impacts for the new BAU FAO and GRASS FAO scenarios were also compared the BAU and GRASS scenarios from the original AB-LCA. These comparisons were made to see how the irrigation data from FAO influenced the impact results of the AB-LCA. Additionally, for the discussion of the results, the total impacts of one cubic meter of irrigation used in the countries covered by this study were modeled and collected from SimaPro.

Delimitations

This thesis has a narrow scope since it aims to conduct a sensitivity analysis on an existing LCA. The boundaries of the LCA are therefore the same in this sensitivity analysis as in the original AB-LCA. The AB-LCA is a cradle-to-farm gate LCA, meaning that it includes all the inputs going into the production of the crops and grass in the agricultural area of Götalands Södra Slätbyggder. The AB-LCA excludes impacts associated with the grass ley biofuel in the later stages of the lifecycle, such as the user and end-of-life phases. This is because the authors of the AB-LCA were interested in studying the sourcing of biomass for biofuels, rather than the whole life cycle which has been addressed in many LCAs in the past. The grass leys in this LCA are also specifically meant to be used as biomass for biofuels for transportation, not as bioenergy for other usages such as heating.

Results

Irrigation data

On average, for all the crops and countries, the irrigation data collected from FAO was 77% lower compared with the original irrigation data from the Ecoinvent database used in SimaPro (Tables 3 & 4).

Table 2: Irrigation data from the original Ecoinvent database used in SimaPro and the new data collected from the FAO databases and Debaeke & Hilaire, 1997.

Irrigation m3/kg						
	Germany (original)	Germany (FAO)	France (original)	France (FAO)	Spain (original)	Spain (FAO)
Barley	2,03E-01	7,50E-04	1,29E-01	6,92E-03	7,47E-01	1,76E-01
Rape	1,96E-01	2,48E-03	2,75E-01	0,00E+00	-	-
Beet	2,91E-03	8,23E-04	1,98E-03	1,18E-03	-	-
Wheat	1,43E-01	6,32E-04	1,23E-01	9,55E-03	7,14E-01	2,34E-01

Table 3: Difference between the original irrigation data in SimaPro and collected data from FAO and Debaeke & Hilaire, 1997 data, in percent.

	Germany	France	Spain	Average difference (%)
Barley	-99,60%	-94,60%	-76,50%	-90,30%
Rape	-98,70%	-100,00%	-	-99,40%
Beet	-71,70%	-40,20%	-	-55,90%
Wheat	-99,60%	-92,20%	-67,30%	-86,40%

Table 4: The original irrigation data from Ecoinvent and the FAO irrigation data for maize and the difference when comparing them in percent.

Irrigation per kg Maize (m3)			
	Original	FAO	Difference
Argentina	1,55E-01	6,89E-02	-55,60%
USA	2,45E-01	7,98E-04	-99,70%
India	3,60E-01	1,64E-01	-54,40%

Impacts

Compared with the original BAU and GRASS scenario, the BAU FAO and GRASS FAO scenarios had overall lower impacts on human health and ecosystems for both impact assessment methods (Figures 2 & 3). For the impact assessment method ReCiPe 2016 the impacts on human health for the GRASS FAO scenario was 4,38 percent lower compared to the original GRASS scenario, and the impact for BAU FAO was 0,96 percent lower (Figure 2). For Impact World+ the impact on human health was 1,21 percent lower for the GRASS FAO scenario and 0,94% lower for the BAU FAO scenario compared to the original GRASS and BAU scenarios (Figure 2). Using ReCiPe 2016, the impact on ecosystems was 1,22% lower for the GRASS FAO scenario and 0,52 percent lower for the BAU FAO scenario compared to the original GRASS and BAU scenarios (Figure 3). For Impact World+, the GRASS FAO scenario and the BAU FAO scenario had a 4,78 percent, respectively, 2,80 percent lower impact on ecosystems compared to the original GRASS and BAU scenarios (Figure 3). On average, the inserted irrigation data from FAO gave rise to impact results which were 1,87 percent lower on human health and 2,33 percent lower for ecosystems.

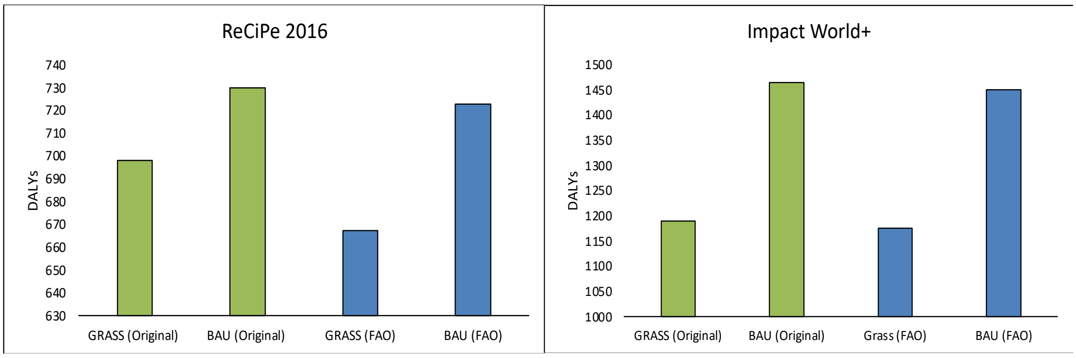


Figure 2: Impacts on human health counted in DALYs for the scenarios GRASS Original, BAU Original, GRASS FAO, and BAU FAO with the impact assessment methods ReCiPe 2016 and Impact World+.

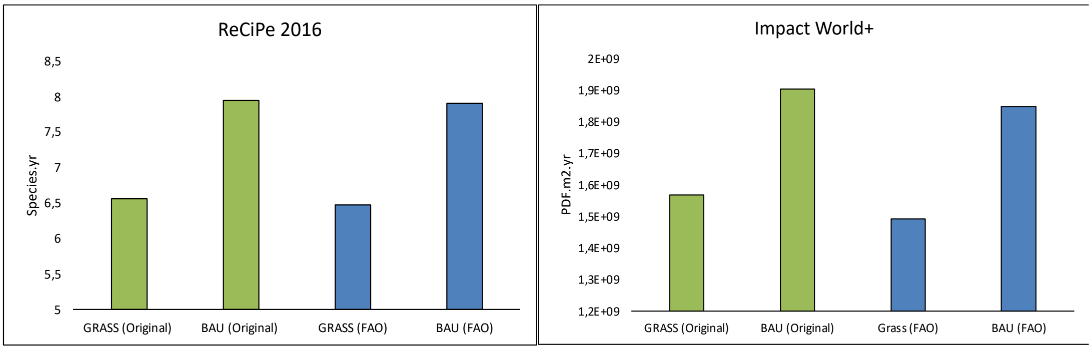


Figure 3: Impacts on ecosystems for the scenarios GRASS Original, BAU Original, GRASS FAO and BAU FAO. The impact assessment methods used is ReCiPe 2016 and Impact World+. The impact on ecosystems is counted in the unit species.yr for ReCiPe 2016 and in PDF.m2.yr for Impact World+.

As one can see in Figure 4, relative to BAU, both the original GRASS scenario and GRASS FAO had a lower overall impact on human health and ecosystems. For ReCiPe 2016 the difference in impact between GRASS FAO and BAU was 3,46 percent greater for human health and 0,70 percent greater for ecosystems compared to the original GRASS scenario relative to BAU (Figure 4). For Impact World+ the difference between GRASS FAO and BAU was 0,22 percent greater for human health and 1,68 percent greater for ecosystems compared to the original GRASS scenario relative to BAU (Figure 4). The GRASS FAO scenario had on average an impact relative to BAU which was 1,84 percent lower for human health and 1,19 percent lower for ecosystems compared to the original GRASS scenario.

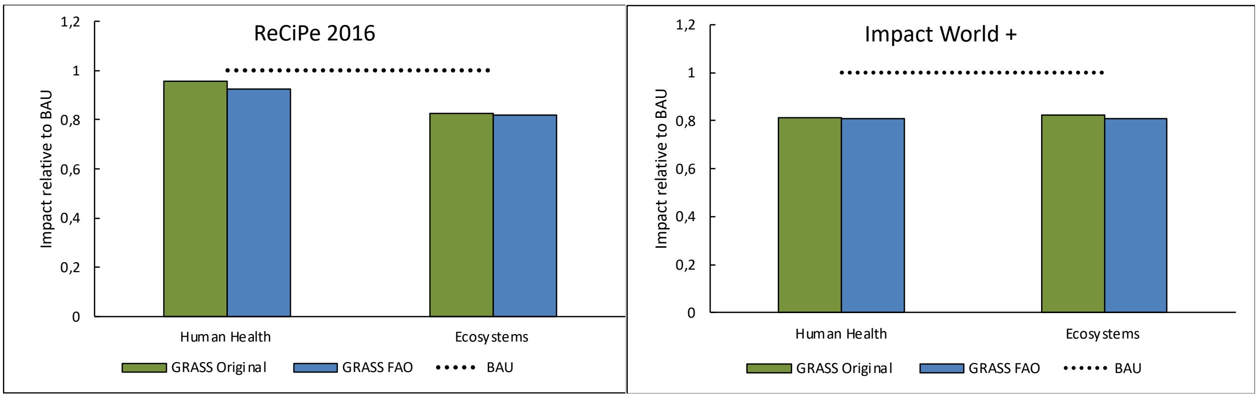
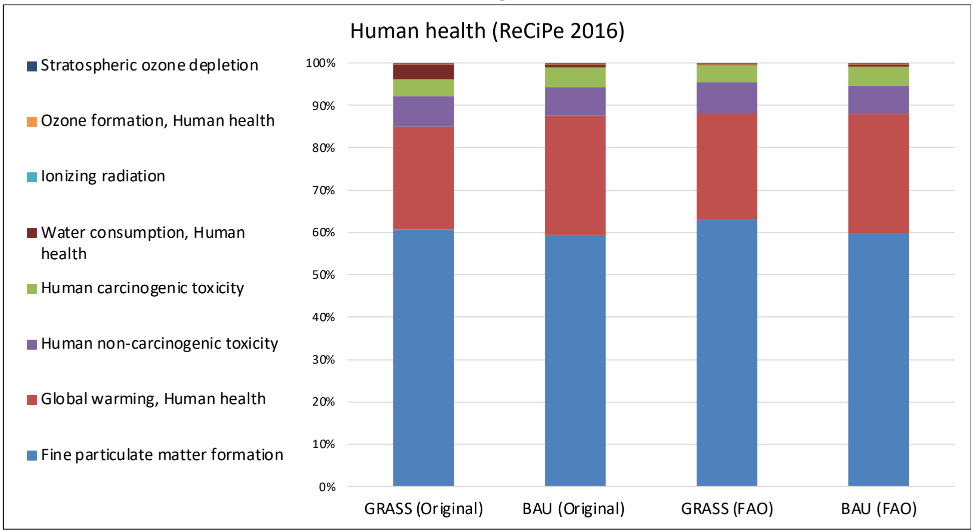


Figure 4: Impact results on Human Health and Ecosystems from the original AB-LCA by López et al and the new AB-LCA with the inserted FAO irrigation data relative to impacts associated with the scenario business as usual (BAU). The impact assessments were done with the assessment methods Impact World+ and ReCiPe 2016.

Change in impact categories

For impacts on human health counted with ReCiPe 2016, the impact categories with the greatest contribution to the total impact on average for all the scenarios were Fine particulate matter formation (60,73%); Global warming, Human health (26,43%), and Human non-carcinogenic toxicity (6,96%). For Impact World+, the greatest contributing impact categories to the total impact were Climate change, human health, long term (29,47%); Particulate matter formation (23,05%); Water availability, human health (19,98%); Climate change, human health, short term (12,46%) and Human toxicity noncancer, short term (11,33%) (Figure 5).



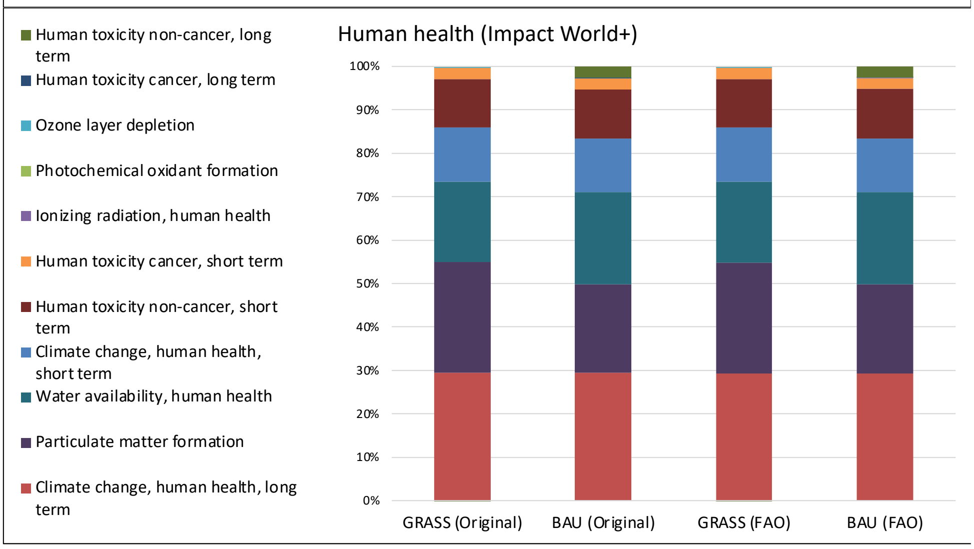


Figure 5: The total impact on human health for the original GRASS and BAU scenarios, as well as the new GRASS (FAO) and BAU (FAO) scenarios. The total impact is divided into the separate contributing impact categories presented as percentages for the impact assessment methods ReCiPe 2016 and Impact World+.

For the impact assessment method ReCiPe 2016, the impact categories with the biggest contribution to the total impact on ecosystems on average for all the scenarios were Land use (77,36%), Terrestrial acidification (12,15%) and Global warming, Terrestrial ecosystems (7,79%) (Figure 6). For Impact World+ the main impact categories, on average, were Freshwater ecotoxicity, long term (62,97%); Land occupation, biodiversity (25,21%) and Climate change, ecosystem quality, long term (5,02%) (Figure 6).

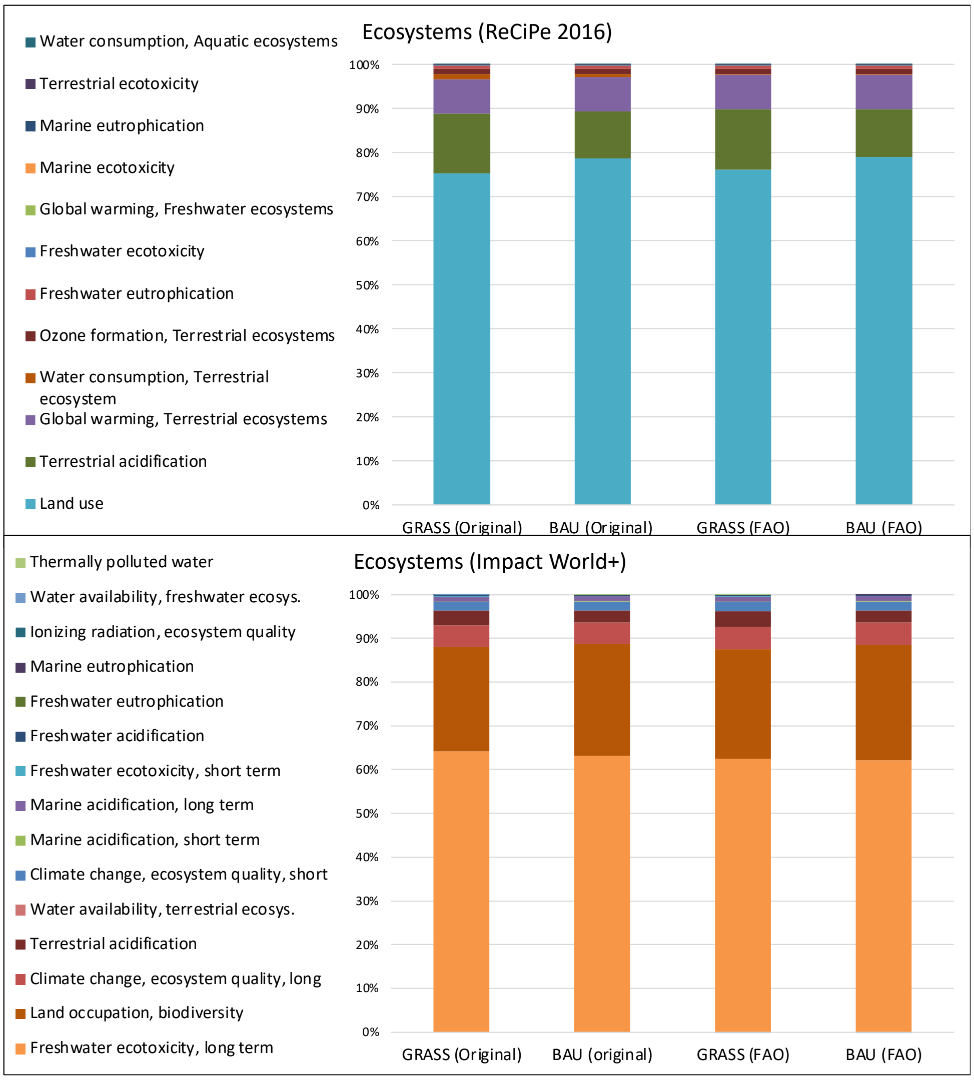


Figure 6: The total impact on ecosystems for the original GRASS and BAU scenarios, as well as the new GRASS (FAO) and BAU (FAO) scenarios. The total impact is divided into separate contributing impact categories presented as percentages for the impact assessment methods ReCiPe 2016 and Impact World+.

The impact categories for human health which differ most when comparing the original GRASS and BAU scenarios to the GRASS FAO and BAU FAO scenarios were "Water consumption, human health", and "Fine particulate matter formation" for ReCiPe 2016. Climate change, human health, long-term; and Water availability for Impact World+ (Table 5A).

For ecosystems, the impact category data differs most for ReCiPe 2016 was "Water consumption, Terrestrial ecosystems". For Impact World+, "Freshwater ecotoxicity, long-term" was the impact category that changed most when swapping the original irrigation data with the irrigation data from FAO (Table 5B).

Table 5: Table visualizing an overview of the impact assessment. Darker blue color for the impact category means a bigger contribution to the total impact on the areas of protection. ΔGRASS and ΔBAU show the difference in the contribution of impact between the original GRASS and BAU scenarios and the GRASS FAO and BAU FAO scenarios. The green color marks the impact category with the biggest difference when comparing the impacts from the original scenarios with the FAO scenarios. Impact on human health is counted in DALYS for both impact categories. For ecosystems, the unit species.yr is used for ReCiPe 2016 and $PDF.m^2.yr$ is used for Impact World+.

A.

ReCiPe 2016			
AREA	**Impact Category**	**ΔGRASS**	**ΔBAU**
Human Health	Fine particulate matter formation	2,31E+00	1,48E+00
	Global warming, Human health	2,41E+00	1,67E+00
	Human non-carcinogenic toxicity	1,45E+00	1,00E+00
	Human carcinogenic toxicity	1,25E+00	9,23E-01
	Water consumption, Human health	2,32E+01	1,94E+00
	Stratospheric ozone depletion	7,37E-04	5,44E-04
	Ozone formation, Human health	6,25E-03	4,14E-03
	Ionizing radiation	7,05E-03	7,16E-03
Ecosystems	Land use	6,31E-04	4,37E-04
	Terrestrial acidification	1,99E-03	1,23E-03
	Global warming, Terrestrial ecosystems	7,27E-03	5,02E-03
	Ozone formation, Terrestrial ecosystems	9,07E-04	6,01E-04
	Freshwater eutrophication	1,85E-03	1,09E-03
	Water consumption, Terrestrial ecosystem	6,66E-02	3,26E-02
	Terrestrial ecotoxicity	3,32E-04	2,33E-04
	Freshwater ecotoxicity	5,69E-04	4,21E-04
	Marine ecotoxicity	1,07E-04	7,92E-05
	Marine eutrophication	2,70E-07	1,89E-07
	Global warming, Freshwater ecosystems	1,98E-07	1,37E-07
	Water consumption, Aquatic ecosystems	7,77E-06	2,41E-06

<50%
20-50%
10-20%
1-10%
>1%

B.

IMPACT World+			
AREA	**Impact Category**	**ΔGRASS**	**ΔBAU**
Human Health	Climate change, human health, long term	6,93E+00	4,83E+00
	Water availability, human health	1,13E+00	4,53E+00
	Particulate matter formation	1,12E+00	7,55E-01
	Climate change, human health, short term	2,12E+00	1,47E+00
	Human toxicity non-cancer, short term	9,07E-01	6,12E-01
	Human toxicity non-cancer, long term	9,24E-01	6,47E-01
	Human toxicity cancer, short term	1,17E+00	8,70E-01
	Human toxicity cancer, long term	3,03E-02	2,15E-02
	Ionizing radiation, human health	1,83E-02	1,78E-02
	Ozone layer depletion	4,92E-04	3,64E-04
	Photochemical oxidant formation	3,44E-04	2,27E-04
Ecosystems	Freshwater ecotoxicity, long term	7,22E+07	5,15E+07
	Land occupation, biodiversity	3,24E+04	2,15E+04
	Climate change, ecosystem quality, long	1,52E+06	1,06E+06
	Terrestrial acidification	3,24E+04	2,15E+04
	Climate change, ecosystem quality, short	4,59E+05	3,18E+05
	Marine acidification, long term	3,65E+05	2,54E+05
	Freshwater acidification	3,96E+04	2,76E+04
	Freshwater ecotoxicity, short term	1,61E+05	9,58E+04
	Marine acidification, short term	4,59E+05	3,18E+05
	Marine eutrophication	2,17E+04	1,33E+04
	Freshwater eutrophication	2,83E+04	1,99E+04
	Water availability, terrestrial ecosys.	8,34E+00	6,79E+00
	Water availability, freshwater ecosys.	4,30E+02	3,18E+02
	Thermally polluted water	9,89E-04	8,21E-04
	Ionizing radiation, ecosystem quality	6,54E+03	4,31E+03

For ReCiPe 2016, the impact categories standing for most of the impacts generated by one cubic meter of irrigation on human health were "Water consumption, Human health", "Fine particulate matter formation" and "Global warming, Human health" (Table 6A). For Impact World+ the impact category "Water availability, human health" stood for most of the impact on human health (Table 6B). Focusing on ecosystems ReCiPe 2016, "Water consumption, Terrestrial ecosystems" was the impact category that stood for most of the impacts generated from irrigation. For Impact World+, the impact category "Freshwater ecotoxicity, long term" stood for most of the impacts on ecosystems.

Table 6: Summed impact results for one m^3 of irrigation in the countries Germany, France, Spain, India the US, and the input process "irrigation Rest of the World" with the impact assessment methods ReCiPe 2016 (A) and Impact World+ (B). The contribution to the total impact on Human Health and Ecosystems for each impact category is visualized as percentages.

A.

ReCiPe 2016		
Human health		
Impact category	**Impact (DALYS)**	**% of total impact**
Water consumption, Human health	5,92E-06	74,37%
Fine particulate matter formation	8,15E-07	10,23%
Global warming, Human health	6,25E-07	7,85%
Human non-carcinogenic toxicity	3,11E-07	3,91%
Human carcinogenic toxicity	2,86E-07	3,60%
Ozone formation, Human health	1,58E-09	0,02%
Ionizing radiation	1,51E-09	0,02%
Stratospheric ozone depletion	1,71E-10	0,00%
Ecosystems		
Impact category	**Impact (species.yr)**	**% of total impact**
Water consumption, Terrestrial ecosystem	3,34E-08	90,80%
Global warming, Terrestrial ecosystems	1,89E-09	5,13%
Terrestrial acidification	5,09E-10	1,38%
Freshwater eutrophication	3,92E-10	1,07%
Ozone formation, Terrestrial ecosystems	2,29E-10	0,62%
Land use	1,39E-10	0,38%
Freshwater ecotoxicity	1,27E-10	0,34%
Terrestrial ecotoxicity	6,97E-11	0,19%
Marine ecotoxicity	2,38E-11	0,06%
Water consumption, Aquatic ecosystems	6,23E-12	0,02%
Marine eutrophication	5,65E-14	0,00%
Global warming, Freshwater ecosystems	5,15E-14	0,00%

B.

IMPACT WORLD+		
Human health		
Impact category	**Impact (DALYS)**	**% of total impact**
Water availability, human health	2,02E-04	98,33%
Climate change, human health, long term	1,81E-06	0,88%
Climate change, human health, short term	5,51E-07	0,27%
Particulate matter formation	3,63E-07	0,18%
Human toxicity cancer, short term	2,70E-07	0,13%
Human toxicity non-cancer, short term	2,10E-07	0,10%
Human toxicity non-cancer, long term	2,07E-07	0,10%
Human toxicity cancer, long term	6,92E-09	0,00%
Ionizing radiation, human health	4,05E-09	0,00%
Ozone layer depletion	1,06E-10	0,00%
Photochemical oxidant formation	8,57E-11	0,00%
Ecosystems		
Impact category	**Impact (PDF.m2.yr)**	**% of total impact**
Freshwater ecotoxicity, long term	1,59E+01	95,47%
Climate change, ecosystem quality, long	3,98E-01	2,38%
Climate change, ecosystem quality, short	1,19E-01	0,71%
Marine acidification, long term	9,53E-02	0,57%
Water availability, terrestrial ecosys.	4,87E-02	0,29%
Terrestrial acidification	3,66E-02	0,22%
Land transformation, biodiversity	2,62E-02	0,16%
Marine acidification, short term	1,03E-02	0,06%
Land occupation, biodiversity	7,41E-03	0,04%
Freshwater ecotoxicity, short term	6,84E-03	0,04%
Freshwater acidification	5,55E-03	0,03%
Water availability, freshwater ecosys.	1,83E-03	0,01%
Marine eutrophication	5,58E-04	0,00%
Freshwater eutrophication	9,96E-05	0,00%
Thermally polluted water	2,01E-06	0,00%
Ionizing radiation, ecosystem quality	2,40E-10	0,00%

Discussion

Difference in irrigation data

Since there are many gaps in the reporting of water data within the Ecoinvent database (Pfister et al., 2016), the irrigation data used from Ecoinvent in the AB-LCA is modeled which always brings some uncertainty (Pfister & Bayer, 2014; Siebert & Döll, 2010). The alternative irrigation data collected from FAO was, on average 77% lower compared to the original irrigation data from the Ecoinvent database. This suggests that the standard irrigation data used in SimaPro might be overestimated which confirms the concerns of the research team. It's important to keep in mind that the new irrigation data collected in this thesis is only one alternative source of irrigation data for the crops. This finding does therefore not prove that the original irrigation data from Ecoinvent is false in any way. Both modeled and reported data have their uncertainties, it's hard to tell which one is correct. But it is important to know how the choice of data influences the LCA outcome.

Production of biofuels has been proven to cause high pressure on the water systems in southern Europe due to its water footprint (Sevigne et al., 2011). Since the pressure on water resources is high today (Aldaya et al., 2012) and will certainly increase over time as global warming progresses (FAO, 2022), efficient water management is highly important (Aldaya et al., 2012; FAO, 2022). This, to reach the sixth global goal which aims to ensure availability and sustainable management of water and sanitation for all (The Global Goals, 2015). Specifically target 6.4 focusing on increasing wateruse efficiency to ensure freshwater supplies (The Global Goals, 2015). Sensitivity analyses testing irrigation data, like this thesis, plays a role in developing efficient water management in agricultural landscapes. It is important to have robust and tested irrigation data when conducting LCAs. This is to make sure that policymakers have the best possible information accessible to make policy decisions that ensures sustainable water resource management while taking other goals and values into account, such as mitigating climate change and securing food supply.

Impact comparison

The substitution of irrigation data gave a difference in the impact assessment results, both in absolute impact and for the life cycle scenarios relative to one another. Even if the difference was small in total impact, on average 1,87 percent for human health and 2,33 percent for ecosystems, it's still meaningful results that nuances the original results of the tested AB-LCA. The difference was a reduction in impact pointing in a direction that is in line with the results from the AB-LCA and favors the GRASS scenario (Figure 4). Also, the impact categories with the highest decrease when using the FAO data were in general the same categories that had a higher impact on human health and ecosystems in the GRASS scenario compared to BAU in the original AB-LCA (Tables 1 & 5). This concludes that the GRASS scenario has lower impacts on human health and ecosystems compared to business as usual (BAU) when using reported irrigation data from FAO (Figure 4). The sensitivity analysis for irrigation data does therefore confirm the previous conclusions drawn in the original AB-LCA. Confirming that the introduction of grass leys rotations in Götalands Södra Slätbygder (GRASS scenario) has environmental benefits compared to the business as usual (BAU scenario) in the area.

This conclusion could serve as background for the promotion of bioenergy production in Sweden. Bioenergy of this type competes with other values like food production (Vera et al., 2022). Outsourcing of food production has its own environmental and societal effects (Fuchs et al., 2020), which have been taken into account in this LCA. Future policy decisions promoting bioenergy can, however, have effects on trade dynamics generating unforeseen environmental impacts which can challenge the environmental good of biofuel production.

Focusing in-depth on the differences caused by changing the irrigation data in the impact assessment, the impact generated by some impact categories changed more than others. Starting with ReCiPe 2016, one of the impact categories that changed the most was "Water consumption, Human health", see Table 4A. Since irrigation was the modified input, it is not surprising that an impact category dependent on water resources is significantly affected (Huijbergts et al., 2017). It is also logical that the impacts coming from this specific category are lower in the FAO scenarios (Table 5A) since the irrigation data from FAO expected 77% less irrigation on average for the imported crops in the system.

For Impact World+ human health, there was no impact category that stood out significantly. This is not surprising since the difference in the total impact between the original scenarios and the FAO scenarios wasn't large (Figure 2 & Figure 4).

For ecosystems ReCiPe 2016, the impact category with the highest variability is "Water consumption, Terrestrial ecosystems" (Table 5A). It is an impact category reliant on water resources, which makes irrigation data have a significant effect on the impact (Huijbergts et al., 2017). This impact category stands for less than one percent of the total impacts on ecosystems, so even if the variance between the FAO and original scenarios is big for this impact category, it does not affect the total impact result greatly. This is seen in Figure 3 where the difference between the original GRASS and BAU scenarios and the FAO scenarios was on average less than one percent for ecosystems ReCiPe 2016. For ecosystems Impact World+, "Freshwater ecotoxicity, long term" is the impact category with both the highest significance and change when comparing the original scenarios with the FAO scenarios. Freshwater ecotoxicity is strongly connected to water management, which makes irrigation influence that impact category (Bulle et al., 2019).

For human health ReCiPe 2016, the impact categories "Fine particulate matter formation" and "Global warming, Human health" stands out with high variability (Table 5A). These impact categories do not have an obvious connection to irrigation or water use at first sight, still, the differences can be explained by looking at the total impacts generated solely by irrigation and the distribution of those impact categories. One can see in Table 6A that for human health ReCiPe 2016, the impact categories "Fine particulate matter formation" and "Global warming, human health" stands for 10,23%, respectively 7,85% of the total impacts of one cubic meter of irrigation. This explains the high difference in these impact categories when comparing the original impact scenarios with the FAO data scenarios. Looking at Table 6, one can see that the impact categories with the highest difference when comparing the original scenarios with the FAO scenarios generally also stand for the biggest part of the impact on human health and ecosystems which is generated by one cubic meter of irrigation.

In the end, the resulting impact from one's life cycle assessment is determined by what is included in the system setup, which processes are included in the inventory, and what impacts can be related to those processes (Jolliet et al., 2016). In this specific system setup and input inventory, the changed irrigation data had a marginal but still visible effect on the overall impact assessment.

Limitations of LCA

When making life cycle assessments, one must be aware of the uncertainties of the impact modeling and be cautious not to make rushed conclusions. Since this is a comparable LCA, the results only tell us which scenarios in this LCA that are preferable in terms of environmental performance. The results can't be used as quantitative data in other comparisons with different life cycle setups and tell which land use strategy is best in another geographical area. One must also be cautious to use the impact results from a modeled LCA as objective truth. There are many uncertainties associated with impact assessment methods (Chen et al., 2021), and it is hard to include all inputs in the inventory so it completely matches reality. We must not forget that the impact results are modeled in impact assessment software.

Assumptions are made, and data have their limitations. Therefore, the results from an LCA like this are good estimations of reality and can serve as good guidelines for policy decisions. The uncertainties do additionally highlight the importance of sensitivity analyses like this thesis, which tests assumptions and data.

In future studies, additional sensitivity analyses could be conducted on the AB-LCA to further analyze the robustness of its results and hopefully increase the validity of the study by López et al. Also, further research on the potential outsourcing of emissions to other countries would be interesting, since locally produced biomass can outcompete and displace local food production.

Conclusion

This sensitivity analysis concludes that there are differences between the modeled irrigation data in the Ecoinvent database and the reported irrigation data collected from FAO and Debaeke & Hilaire 1997. The irrigation data used in the sensitivity analysis was, on average 77 percent lower compared to the original irrigation data used in the AB-LCA. The great difference highlights the need for a sensitivity analysis like this. The substitution of irrigation data gave an average reduction in total impacts of 1,87 percent for human health and 2,33 percent for ecosystems. The reduction was bigger for the GRASS FAO scenario relative to BAU which increases the environmental benefits of introducing grass ley rotations in Götalands Södra Slättbygder. This gave a new impact result showing that the new GRASS scenario had less environmental impacts compared to BAU which confirms the conclusion made in the AB-LCA. Since this sensitivity analysis concludes the same fact as the AB-LCA, the results of the AB-LCA can be seen as robust in the aspect regarding irrigation data. This sensitivity analysis also highlights the uncertainties in LCA modeling and the importance of sensitivity analyses for securing valid information for land use and water management policy decisions. Policy decisions that affect our capability of reaching our global goals.

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