Investigating the environmental implications of biogas pathways through integration of ecosystem service modeling and life cycle impact assessment to support regional energy transitions

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Acronyms

List of Abbreviations

Abby-Net: Albertan- Bavarian Research Network

CORDEX: Coordinated Regional Climate Downscaling Experiment

DEM: Digital Elevation Model

DALYs: Disability Adjusted Life-years

ESGF: Earth System Grid Federation
ER: Erosion

ES: Ecosystem services

EVT: Energy/Process Engineers

FAOSTAT: Food and Agriculture Organization Corporate Statistical Database

GCMs: General Circulation Models

GEO: Geographer/Environmental Professionals

GIS: Geographical information technology

H.E.R: Health, Ecosystem and Resources

InVEST: Integrated Valuation of Ecosystem Services and Trade-offs

JRC: Joint Research Center

KoWi: Communication/Social Scientists

MWel: Mega Watt Equivalent of Electricity

M: Meter

NDR: Nutrient delivery ratio

NVZ: Nitrate Vulnerable Zone

PEM: Proton Exchange Membrane

PtG-CH4: Power-to-Methane

PtG-H2: Power-to-Hydrogen

RCMs: Regional Climate Models

RCP 8.5: Representative Concentration Pathway

RGP: Renewable gas plants

SDR: Sediment delivery ratio

SNG: substitute natural gas

SOEC: Solid Oxide Electrolyze Cell

SRF: Short Rotation Forestry

SynGas: Synthesis Gas

SMHI: Swedish Meteorological and Hydrological Institute

TRL: Technology Readiness Level

WYM: Water yield model

LCA: Life Cycle Assessment

LCIA: Life Cycle Impact Assessment

PDF: Potentially Disappeared Function

SDG’s: Sustainable Development Goals

FU: Functional Unit

LCI: Life Cycle Inventory

NREL: National Renewable Energy Laboratory

GWP: Global warming potential

CED: Cumulative energy demand method

QAQC: Quality Assessment Quality Assurance

TRACI: Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

SRTM: Shuttle Radar Topography Mission

WFLDB: World Food Life Cycle Assessment Database

Dedication

This PhD work is dedicated to God, His mother Mary and all those who strive for a safer environment.

Research Motivation

Many Canadians in Alberta are still skeptical about transiting to a greener energy using biomass with the following reasons but not limited to;

Due to the abundance of fossil fuel, long cold periods for farm activities and other environmental impacts bothering within biogas production.

It is my opinion that when a good number of Canadians including the policy-makers have more knowledge and understanding of the exact environmental implications and tradeoffs of bioenergy, they can support energy transition more while paying attention to the environmental prosperity. This study will expose them to the climate change impact, eutrophication, land use change, respiratory issues, landuse, ecological and other environmental implication of using biomass for energy generation. Precisely, on what goes into the land, water and air in terms of emissions when 1 kg of maize silage is produced, digested and converted into CHP. The German energy transition plans at the other hand has moved ahead while trying to be independent from imported gas with more emphasis on biomass energy system. These inspire me to explore the benefits and most importantly the environmental impacts arising from these transitions to greener energy. Knowing that analysing both location aids the evolution of the renewable energy and ecosystems protection and that these processes can be applied one day in Nigeria also motivates me to push this research idea forward.

Personal Motivation

The burning desire to create and maintain a safe environment for all while venturing into bioenergy system has always been my driving force from time immemorial, also, an upsurge in the public suspicion over new bioenergy technologies and their anticipated hidden environmental impacts that drive the public acceptance of current and future energy systems motivates me. This is also why I have studied environmental management from my bachelors and my first master's degree in England. Both studies exposed me into the world of energy systems, climate change issues, environmental emissions, mitigation challenges and solutions. My MBA has also exposed me to the use of energy in the business world and how best to integrate these knowledge's into an outstanding research papers and doctoral thesis. My involvement with the MDGs now SDGs also motivates me to carry on this project. Another big motivation was joining the research group of Prof. Ralf Ludwig who introduced me to the ABBY-NET (The Albertan-Bavarian Research Network for Sustainable Energy Transitions) group Abby-Net and gave me the opportunity to join numerous real life energy projects such as the SustainableGas project. Additionally, as every motivation needs support to blossom well like a tree planted by the river side, the NYSC presidential honours award bestowed on me by the president and the commander in chief of the federal republic of Nigeria (Dr. G. E. Jonathan) to pursue my academics (till PhD level) in any university and country of my choice via the Petroleum Technological Development Fund (PTDF) encouraged me. Other awards and scholarships during the course of my studies such as Mitacs Globalink Research Award Canada (the opportunity to run the project in two outstanding universities - U of C and LMU motivated me more). LMU travel grants and the completion scholarship had inspired me more and made it possible to achieve this life time goal. Most importantly, the vibrant working group of Prof. Ralf Ludwig motivates me to do more.

The structure of this Thesis

This Dissertation is structured and divided between two study areas to accommodate the works carried out in the two regions of Germany and Canada. The first case study is on how to aid German energy transition plans through the analysis of ecosystem and its services that could be affected when different types of agricultural feedstock are used for biogas production in Germany.

While the second case study deals with the comparative life cycle impact assessment of biogas pathways with the use of different openlca methods to support Canadian energy transition policies especially in Alberta. Data collection, mastering of the model and initial simulation was carried out in the University of Calgary.

Summary

The regional and global energy transition requires a growing share of alternative technologies powered by biomass sources, of which not all the environmental impacts arising from the transition are fully understood yet. The United Nations and the sustainable development goal (SDG's) seven encourage a cleaner, safer and modern energy production for all in other to uphold or instill environmental and climate protection. This study aims at applying an ecosystem service tool called Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model and a Life-Cycle-Impact Assessment (LCIA) modeling tools such as the openLCA in assessing the environmental, supply chain, and engineering perspectives of energy transitions holistically. The scope is on analyzing the impacts of maize silage (feedstock) production for the purpose of biogas/biofuel production using the Eco-indicator 99, E, E method, which analyzes the worst-case scenario of products or services). The impacts are reported and compared across the board (within each life cycle stage and with different assessment methods). On a regional scale, it provides robust quantitative estimates of GHG emissions, eutrophication, climate impacts, and land-use impacts of maize silage biogas/biofuel production. The broad aim of the project's first and second case studies is to explore the environmental impacts of bioenergy generation and its use. This is accomplished by assessing climate change, health impacts, and other ecosystem problems while finding tradeoffs across various impacts in both jurisdictions of Alberta, Canada, and German. The following hypothetical objectives were poised; (a) To assess the environmental effect of alternative energy technologies on land use, sedimentation, water & nutrient delivery with InVEST ecosystem services model. (b) To evaluate the potentiality of energy feedstock/substrates such as biomass (e.g., maize, forest residue & short-rotation plant) and suitable land space. (c) To explore the Life Cycle Impact Assessment of maize silage cultivation for the production of heat and electricity. (d) Analyze the most impactful flow/impact category within the LCA stages and compare them with the current natural gas production technology in Canada using different assessment methods of the openlca. And finally to attempt the integration of both models for a better overview of the foreseen impacts.

This study explores the opportunities and challenges of alternative/renewable energy technologies in the regions of (Canada) and (Germany) and their environmental impacts for proper policy decision-making within the interface of the energy transition, climate change, and environmental protection. Additionally, the result of the study reported in disability-adjusted life-years (DALYs) and potentially disappeared fraction (PDF) serves as a basis for determining

the appropriate political, legal, environmental, and ecological framework conditions for a "Master Plan Energy Transition," in which the role and function of sector actors are analyzed in detail. The study's scientific findings generate relevant information on the interconnectedness of renewable energy and the environment, which is also useful for both regions and globally, respectively.

The project is significant because it contributes to the existing body of knowledge on the need for the reduction of excessive emission of greenhouse gases, land conversion, and nutrient delivery through bioenergy generation and other energy transition activities that have the potential to increase global warming, damage water, and land resources. It helps to strike a balance between alternative energy development and environmental prosperity while expanding bioenergy. In the end, the study made valuable recommendations on how to integrate and simulate ecosystem services results from InVEST model into the Life Cycle Assessment tool and vice versa.

Zusammenfassung

Die regionale und die globale Energiewende erforder einen wachsenden Anteil an alternativen Technologien, die mit Biomasse betrieben werden, wobei noch nicht alle Umweltauswirkungen dieser Umstellung vollständig bekannt sind. Die Vereinten Nationen und das siebte Ziel für nachhaltige Entwicklung (SDGs) fördern eine sauberere, sicherere und moderne Energieerzeugung für alle, um den Umwelt- und Klimaschutz aufrechtzuerhalten oder zu fördern. Diese Studie zielt auf die Anwendung eines Ökosystemdienstleistungsmodells namens Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) und eines Modellierungswerkzeugs für die Lebenszyklusbewertung (LCIA) wie openLCA, um die Umwelt, die Lieferkette und die technischen Perspektiven der Energiewende ganzheitlich zu bewerten. Der Schwerpunkt liegt auf der Analyse der Auswirkungen der Produktion von Maissilage (Ausgangsmaterial) für die Biogas-/Biokraftstoffproduktion unter Verwendung der Eco-indicator 99, E, E-Methode, die das Worst-Case-Szenario von Produkten oder Dienstleistungen analysiert) und auf dem Vergleich der Auswirkungen insgesamt (innerhalb jeder Lebenszyklusphase und mit verschiedenen Bewertungsmethoden). Es liefert auf regionaler Ebene robuste quantitative Schätzungen der Treibhausgasemissionen, der Eutrophierung, der Klimaauswirkungen und der Auswirkungen der Maissilage-Biogas-/Biokraftstoffproduktion auf die Landnutzung. Das allgemeine Ziel des Projekts für die erste und zweite Fallstudie besteht darin, die Umweltauswirkungen der Bioenergieerzeugung und -nutzung zu erforschen, indem der Klimawandel, die Auswirkungen auf die Gesundheit und andere Ökosystemprobleme bewertet werden, während gleichzeitig Kompromisse zwischen verschiedenen Auswirkungen in den beiden in den beiden Rechsträumen von Alberta (Kanada) und Deutschland gefunden werden, und zwar mit den folgenden hypothetischen Zielen: (a) Bewertung der Umweltauswirkungen alternativer Energietechnologien auf Landnutzung, Sedimentation, Wasser- und Nährstoffzufuhr mit dem InVEST-Ökosystemleistungsmodell. (b) Bewertung des Potenzials von Energierohstoffen/Substraten wie Gülle und Biomasse (z. B. Mais, Waldrestholz und Kurzumtriebsplantagen) und geeigneter Flächen. (c) Untersuchung der Ökobilanz des Anbaus von Maissilage für die Erzeugung von Wärme und Strom. (d) Analyse der wirkungsvollsten Fluss-/Auswirkungskategorien innerhalb der LCA-Phasen und Vergleich mit der aktuellen Erdgasproduktionstechnologie in Kanada unter Verwendung verschiedener Bewertungsmethoden der openlca. Und schließlich soll versucht werden, die beiden Modelle zu integrieren, um einen besseren Überblick über die voraussichtlichen Auswirkungen zu erhalten.

Ziel dieser Studie ist es, die Chancen und Herausforderungen alternativer/erneuerbarer Energietechnologien in den Regionen (Kanada) und (Deutschland) sowie deren Umweltauswirkungen für eine angemessene politische Entscheidungsfindung an der Schnittstelle von Energiewende, Klimawandel und Umweltschutz zu untersuchen. Darüber hinaus dienen die Ergebnisse der Studie, die in behinderungsbereinigten Lebensjahren (DALYs) und potenziell verschwundenen Anteilen (PDF) ausgewiesen werden, als Grundlage für die Bestimmung der geeigneten politischen, rechtlichen, wirtschaftlichen, sozialen und ökologischen Rahmenbedingungen für einen "Masterplan Energiewende", in dem die Rolle und Funktion der Branchenakteure detailliert analysiert werden. Aus den wissenschaftlichen Erkenntnissen der Studie werden relevante Informationen über die Verflechtung von erneuerbaren Energien und Umwelt generiert, die auch regional bzw. global von Nutzen sind.

Das Projekt ist von Bedeutung, weil es einen Beitrag zu den bestehenden Erkenntnissen über die Notwendigkeit der Verringerung der übermäßigen Emission von Treibhausgasen, der Landumwandlung und der Nährstoffzufuhr durch die Erzeugung von Bioenergie und andere Aktivitäten der Energiewende leistet, die das Potenzial haben, die globale Erwärmung zu verstärken und die Wasser- und Bodenressourcen zu schädigen. Sie trägt dazu bei, beim Ausbau der Bioenergie ein Gleichgewicht zwischen der Entwicklung alternativer Energien und dem Wohlstand der Umwelt herzustellen. Am Ende der Studie werden nützliche Empfehlungen ausgesprochen, wie die Ergebnisse der Ökosystemdienstleistungen aus dem InVEST-Modell in das Ökobilanz-Tool integriert und simuliert werden können und umgekehrt.

The first case study of this thesis is titled:

Considering the Environmental Impacts of Bioenergy Technologies to Support German Energy Transition. As published in March 2021.

Abstract I

Clean energy for all, as listed in the United Nation's SDG7, is a key component for sustainable environmental development. Therefore, it is imperative to uncover the environmental implications of alternative energy technologies. SustainableGAS project simulates different process chains for the substitution of natural gas with renewable energies in the German gas market. The project follows an interdisciplinary approach, taking techno-social and environmental variabilities into account. However, this research highlights the project results from the environmental perspective. So far, a detailed assessment of the environmental costs of alternative gas technologies with a focus on the process of the energy transition has remained rare. Although such data constitute key input for decision-making, this study helps bridge a substantial knowledge gap. Competing land-use systems are examined to secure central ecosystem services. An Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) serves as the modelling tool to fulfill this obligation. InVEST assesses ecosystem services (ES) that are or may be affected by alternative bioenergy technologies. Spatially explicit model results include the water provisioning from the Water Yield Model (WYM), soil erosion and sedimentation described by the Sediment Delivery Ratio (SDR), and nutrient fluxes (N) in response to changing land use are obtained through the Nutrient Delivery Ratio (NDR). The detailed model results are finally extrapolated, which provides a comprehensive image of the environmental impacts associated with bioenergy expansion in Germany from our combination of unique Renewable Gas Plants (RGP's). The final result shows that nutrient load will reduce in southern Germany by the year 2050 compared to the reference state, and biomass use will be reduced by 46%.

Additionally, the regional energy transition requires a growing share of alternative technologies powered by biomass sources, for which not all their environmental impacts are fully understood yet. The UN and the sustainable development goal (SDG's) seven encourage a cleaner, safer and modern energy production for all to uphold environmental and climatic protection. The second case study aims to apply Life-Cycle-Impact Assessment (LCIA) modeling tool such as the openLCA in holistically assessing the environmental, socio-economic and engineering perspectives of energy transitions. The scope is on analyzing the impacts of maize silage production for biogas/biofuel production using Eco-indicator 99, E, E method that analyzes the worst case scenario of products or services, while comparing the effects across board. It provides robust quantitative estimates of GHG emissions, eutrophication, climate impacts, and health and land-use impacts of maize silage biogas/biofuel production on a regional scale. The objectives of this section are to (a) explore different energy emission and climate change related

problems while finding the tradeoffs across various impacts when maize silage is used as feedstock in Canada (b) discover current natural gas production technology pathways in Alberta, the oil exploration province of Canada and compare them with the current study and previous results. The purpose of this study is to explore the opportunities and challenges of alternative/renewable energy technologies in the region of Alberta (Canada) and their environmental implications for proper policy decision-making within the interface of energy transition, climate change, and environmental protection. Additionally, to evaluate the environmental impacts of cultivating corn (maize silage) and it's processing (digestion and conversion) for the production of biogas for electricity and heat generation. From the study's scientific findings, relevant information on the interconnectedness of the bioenergy and the environment are generated, which are also useful for both regions and globally, respectively. The project is significant because it will contribute to the existing body of knowledge on the need for reduction of excessive emission of greenhouse gases, land conversion, and nutrient delivery through bioenergy generation and other energy transition activities that have the potential to increase global warming, damage water and land resources. It will help to strike a balance between the present and future alternative energy development and environmental prosperity.

KEYWORDS: Energy transition, Ecosystem services assessment, Life cycle impact assessment, Openlca Eco indicator 99, biogas/biofuel production, SustainableGas. Ecosystem services assessment, InVEST model

Hypothesis and research questions

Aim and Objectives

The purpose of this study is to explore the environmental impacts of biogas production to aid the Canadian and German heat & gas market future ambitions sustainably using InVEST and LCA tools with the following objectives;

1. To assess the environmental impacts of alternative or renewable energy on land-use, sedimentation, water & nutrient delivery keeping in mind that about 180kg N/ha/annum is in the EU nitrate vulnerable zone (NVZ).
2. To evaluate the potentiality of energy feedstock/substrates such as biomass (e.g. maize, forest residue & short-rotation plant) and suitable land space.
3. To investigate biogas environmental impacts and potential connections between ecosystem service and LCA models to provide spatially explicit insights about the environmental consequences of the entire life cycle biogas options

The research answers the following questions;

Will the modeling of the ecosystem services with the InVEST software provide more data that will help to reduce the environmental impacts of energy transition both in Canada and Germany?

Which of the flow or impact category contributes more to the environmental burden when maize is used for biogas production considering the LCA pathways (cultivation, digestion or conversion)?

How can this study`s LCIA result be incorporated into an ecosystem model to provide spatially resolved (i.e a measure of the smallest ecological impact) insights and details for the two jurisdictions?

Introduction

Environmental issues underpinning renewable energy technologies in the phase of energy transition cannot be overemphasized both in Germany and in Canada, as there is always an environmental consequence that goes with the way energy is generated and used. There has been a rise in the global electricity net generation from about 18.8 trillion kWh recorded in 2007 to about 35.2 trillion kWh that is expected in the year 2035 (A.I.M. Aly and R.A Hussein, 2014). This growth is fueled by several factors including population growth, lifestyle, and economic policies with an expectation to grow more. German heat demand was dominated more by imported natural gas to about 50 percent in 2016 with approximately 13 percent of renewable and 614 Tera watt-hour consumed capacity (Federal Ministry for Economic Affairs and Energy, Energy Data, 2019). Also, Germany ranks highest among the Green Economy Perception Index (Tamanini, J. et al., 2014).

Although renewable energy is perceived as being totally harmless by many schools of thought which is not completely true, the forecasted potential impact is not only on biodiversity and ecosystems, general global energy systems are also at risk. There is clear evidence that a rise in the surface temperature from warming has potential impacts on the entire ecosystem globally (Pndolfi, J. M. et al., 2011). Also, climate change simulations of Altmühl watershed in Bavaria show a significant increase in NO_3-N loads with an indication that there would be high & prolonged in-stream nutrient concentration by 2050 (Mehdi, B. et al ., 2015).

Currently, detailed assessments of alternative gas production technologies with a focus on suitable land locations, emissions reduction from nutrient & sediment, water usage, and other potential environmental impacts (e.g. land-use) have remained scarce. Although, such data are very important as they constitute a key input for new investments in energy infrastructure and policy decision-making processes. In Europe, Germany is leading in the production of biogas with a share of over 61% made possible by the support fostered by the German Renewable Energy Sources Act. The number of German biogas plants has increased to about 8000 with over 3,900MW_{el} installed capacity as at the year 2017 (FNR-Agency of the renewable resources, 2017). There are currently more than 9000 biogas facilities existing in the country [Thran, D. et al., 2020]. However, their environmental impacts are yet to be assessed exactly the same way we did in this project. SustainableGas project simulates the integration of Renewable Gas Plants (RGP's) in the German electricity & gas market in an interdisciplinary and environmentally friendly approach as funded by the Federal Ministry for Economic Affairs and Energy (BMWi). This project illustrates, however, the results from the environmental perspective where scenarios were developed for valuing & quantification of ecosystem services, water, sedimentation (erosion), and nutrient fluxes using Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) as the modeling tool. InVEST relies on geographical and ecological data for the provision of maps, quantification, and valuing of ecosystem services (ES). This allows decision-makers to assess quantified tradeoffs associated with alternative management choices for environmentally friendly energy projects. Moreover, the model incorporates the process of sedimentation of watersheds to give information on the destination of eroded materials (Bouguerra, S. and Jebari, S., 2020 and 2017).

Many scientists have written about the impacts of bioenergy in relation to German's energy transition. However, no retrieved literature has documented the environmental implications of our selected combinations of renewable gas plants until the year 2050 systematically and consistently as this study. Table.1 shows different RGP's capacity, impacts, and their required feedstock. Each of these unique RGP's mimics a real-life gas system and are supposed to function when it is economically, socially, and environmentally viable, otherwise any of them can automatically switch off if not in use to avoid economic waste or environmental negative effects. More insights on the SustainableGas scenario creation is found in appendix I, as the first case study of this thesis is based on the German SustainableGas projects.

Table 1. Renewable Gas Plant´s (RGP's) combination with their feedstock's, impacts and plant size.

Possible Impacts	**RGP (conversion) type**	**RGP name & size (MW1)**	**Substrate**
Land use change, ND, water	Bio-methane	Biomethane maize 10	maize silage
Odour/H_20 pollution, pest		Biomethane manure 2.5	manure/maize
Good biomass		Biomethane residues 10	Food residues
Regional impact	SNG (substitute natural gas) Heat Pipe Reformer	HPR imported pellets 1	imported wood pellets
Negligible	(HPR) technology	HPR straw 1	straw
Land Use Change/ Sedimentation	SNG	forest residues 30	forest residues
ND & Erosion		SRP 30	short rotation plantations
Low without tree cutting	Synthesis gas (SynGas)	SynGas forests Residues 30	forest residues
Regional impact	Gasifier with Absorbent Enhenced Reformer	Imported pellets 100	imported wood pellets
Medium water use	Power-to-Methane catalytic	Power-to-Methane Catalytic 6	Electricity + water
Medium water usage	Power-to-Methane biologic	Power-to-Methane Biologic 1	Electricity + water
High	Power-to-Hydrogen SOEC	Power-to-Hydrogen SOEC 0.1	Electricity + water
CH_4 emission	Power-to-Hydrogen partial stream methane reform (SMR)	Power-to-Hydrogen Steam Reformer 0.5	Electricity + water + methane
High	Power-to-Hydrogen Proton Exchange Membrane (PEM) electrolysis	Power-to-Hydrogen PEM 1	Electricity + water

Justification for analysing both regions using two different models

The primary purpose of the research is to provide a comprehensive analysis of the energy systems by explicitly modeling various ecosystem services (air, water and, land use), and their impact on climate change, health, and resources. Surprisingly, the mechanisms and the interactions of point-source (coming from one place) and non-point-source emissions that cause changes in the environment are poorly understood and require an integrated assessment from different boundaries using different modeling tools and frameworks as explained in the last section of this thesis (Conclusion, Outlook and Recommendation for the Models Integration).

Understanding the mechanisms between bioenergy generation and their impacts on the environment from these two regions of Canada and Germany figure 1, using these two models help draw a more comprehensive conclusion that could be applicable globally. Because, most countries are either producing more bioenergy or fossil fuel as well as a combination of the two, as seen in the two case studies. Though, the future energy systems are shifting more to bioenergy. Moreover, using two different methodologies and models to perform integrative analyses of energy systems and ecosystems for a sustainable co-evolution under dynamic boundary conditions helps predict energy systems' impact on water systems, land use, and the atmosphere in a more holistic and life cycle perspective. The two case studies research focus provides key data for predicting the impact of energy transition developments such as biogas on the environment in such diverse energy systems as those in Germany and Canada.

Additionally, Nigeria as an oil-producing country like Canada, is interested in learning how both distinctive regions are able to manage their energy transition ambitions to arrive at a common goal, which is a sustainable environment. Moreover, the research tasks performed has also indicated how German experiences maybe applied to the Canadian system or globally and showed which of the environmental impacts shall particularly be expected on the ecosystems when biogas is produced with maize silage. Most interestingly, the technological environment and the political objectives with respect to the evolution of the energy system and its environmental impacts in Canada and Germany do exhibit several significant parallels. However, in some dimensions, they are quite different. In the former, we observe a heavy dependence on fossil resources, while the latter has a politically established transition to an energy system that is heavily based on renewable sources. A careful analysis of both boundaries aids the evolution of renewable energy and ecosystems protection.

Figure 1a. Showing the geographical locations of the two study areas (Canada and Germany).

1.1 Aim and Objectives for case study 1

The purpose of this first case study is to explore the environmental impacts of the above-mentioned bioenergy technologies as a good option in reaching German heat & gas market future ambitions sustainably with the following objectives;

a. To assess the environmental effect of alternative energy technologies on land-use, sedimentation, water & nutrient delivery.

b. To evaluate the potentiality of energy feedstock/substrates such as manure and biomass (e.g. maize, forest residue & short-rotation plant) and suitable land space.

1.2 Overview of the SustainableGAS Project

The project investigates new strategies for alternative gas technologies in the German heat and electricity sector in an interdisciplinary manner. It is conveyed by Geographers/Environmental professionals otherwise known as (GEO) in this context, Communication/social scientists (KoWi), and Energy process engineers (EVT). Figure 1. Depicts the team work packages at a glance. The steadily growing share of bio-energies in the supply of electricity and heat leads to changes and partial impairment of eco-systemic material cycles. We investigate the interaction of renewable sources with the material and energy flows of the natural environment considering dynamically changing climatic conditions. To secure the main services of the ecosystem, targeted and competing land-use systems should also be investigated as we have. Therefore, land-use change and altered material flow between hydrosphere, soil, and plant is modeled using the InVEST model.

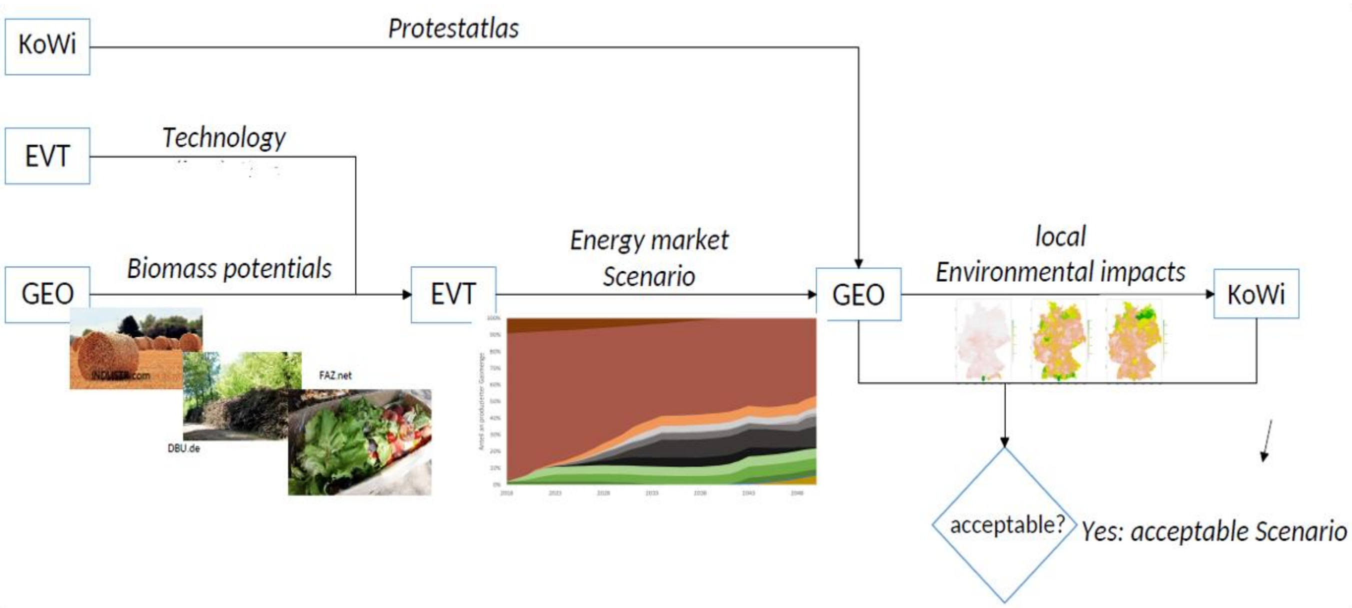


Figure 1b. SustainableGas Project workflow showing each partners responsibility at a glance.

Why SustainableGas project?

The overall broad objective of the SustainableGas project is to aid the heat supply of the Federal Republic of Germany, which is currently approximately 50% based on the use of imported fossil natural gas. In 2013, 50% of the heat demand was covered by natural gas. By contrast, only about 11% of renewable energy sources contributed to the heat supply. In order to significantly increase the share of renewable energies generally, it is also essential to establish renewable energies (biogas) in the gas market. Crucial issues for integrating renewable gases into the gas market that sustainableGas project is trying to solve include; The uncertainty in technical and economic potentials, the currently high cost of renewable gases due to insufficient market penetration, and the possible limited social acceptance of renewable gases. The large variety of renewable gas production process chains can only be met by a high degree of systematization to reliably quantify potentials, costs, and impacts on the environment, ecosystems, and climate. The project impressively demonstrates that the high development requirement are offset by high-cost reduction potential with an increase in the market penetration. In the past, numerous examples have shown that the implementation of new energy technologies was threatened or even failed due to but not only technical and economic hurdles also, in particular, to a lack of acceptance among the population and the energy industry. Currently, the further expansion of renewable energies is stagnating due to social resistance, despite broad agreement on the energy transition in general. Due to the outstanding importance of national and European natural gas supply, it is therefore vital to not only evaluate the potential of renewable natural gas substitutes at an early stage but also to identify acceptance risks and identify strategies to counteract the premature failure of potentially meaningful and important technologies. The project's target is the development of possible strategies for an environmentally and environmentally friendly use of renewable energies for natural gas substitution for the heat and electricity market. In particular, the interaction of these process chains with the heat supply from conventional and non-conventional sources. Criteria for evaluating the process chains are potentials, availability, costs, possible ecological consequences, and feedback on regional and global ecosystems due to social acceptance. The basis for the evaluation of the process chains is an agent-based simulation of different expansion scenarios up to the year 2050 exacuted by the project partners (engineering team). The agent-based and system-dynamic modeling enable the consideration of individual agent's feedback among each other on different system levels. Based on the projected potentials impacts proposed in this research and the simulation of the ecosystem services that could be affected using the InVEST model, a desired result is obtained. The project is divided into the following five work packages: AP1: Process chain analysis (efficiencies, CO_2 balance, costs) AP2: Feedback on land use, ecosystems, and climate WP3: Social acceptance of the process chains AP4: Agent-based modeling of possible expansion scenarios AP5: Evaluation and recommendations including pro-rata "indirect" heat generation with electricity and district heating from natural gas or renewable energies. For more information on the SustainableGas project see BMWi-Projekt SustainableGas website.

Although we have different types of RGP's combinations, this paper in this first case study focuses on the most perceived impactful technologies on our ecosystem. For example, (maize, short rotation plants & excessive forest residues) in addition to manure impacts & water requirements. Like a few other countries, Germany is now withdrawing from nuclear energy while relying more on renewables to change the nation's energy supply for transiting to a low carbon environment (Weber, G. and Cabras, I., 2017). An increased understanding of the environmental risks associated with energy production and transition is important to ensure future energy efficiency (Kühn, M. et al., 2016). Most of the physical damage from energy systems are found within the land-soil interface which subsequently leads to biodiversity loss (Martens, S. et al., 2017). While many scientists think renewable energy is profitable (N. Euliss, L. et al., 2011), it is vital to investigate their environmental impacts well before adoption.

1.3 InVEST Model

InVEST is a simplified modeling tool that relies on geographical and ecological information for the provision of maps, valuing and quantifying (Hamel, P. et al., 2017), of the distribution of ecosystem services across a landscape. (Walston, L. J. et al., 2021). This Environmental modeling tool is a suite of software used in valuing the benefits we get from nature that sustains our lives. Sediment delivery ratio (SDR) (Piyathilake, I.D.U.H. et al., 2020), Water yield model (WYM), and Nutrient Delivery ratio (NDR) were applied with the following InVEST inputs data shown in appendix a. InVEST is developed to enable decision-makers to assess trade-offs and compare different future scenarios in water, land use/climate change issues (Bagstad, K.J. et al., 2013 and Grafius, D.R. et al., 2016). In considering tradeoffs and modelling of multiple ecosystem services (Sharp, R. et al., 2016). InVEST model simulates ES that may be affected by the alternative gas facilities proposed in this project. Researchers have applied the InVEST water yield models with a focus on mapping and quantification of ES & water yield change (Redhead, J.W., 2018). In analyzing climate change impact and the assessing of water demand ratio under different global change scenarios (Leh, M.D. et al., 2013 and Terrado, M. et al., 2014). InVEST relies on locations and ecological information for the provision of maps (using Geographical Information System tool), valuing and quantifying (Bagstad, K.J et al., 2013, Boithias, L., 2014) of the distribution of ecosystem services across a landscape. The evaluation of the model's (SDR, WYM & NDR) output provides information about possible impacts on climate and biodiversity. This tool is useful for all the stakeholders for example renewable energy proponents, could also use InVEST to answer questions such as where do environmental services originate from? And where are they consumed? We used InVEST to compare alternative management options in terms of biophysical measures of services. Furthermore, secondary data were applied to enable the calibration, appendix b and analysis of spatial changes over a specific timeline for making useful projections.

1.4 Introduction to case study 2

Assessing the environmental impacts of renewable energy technologies has become more critical as climate change, population growth, eutrophication, land-use change, among other environmental challenges. Moreover, issues surrounding sustainable global energy transition cannot be over-emphasized. The climate conference held in Paris 2015 and more recently in Scotland (COP) 2021 preached the reduction of global temperature to an average of below 2 degrees Celsius. This reduction is necessary even as demand for energy use increases globally. In order to cut down on global emissions of CO_2, renewable energy-based agricultural feedstock is seen as a better substitute with lesser environmental impact (Filippa et al., 2020). Fuels from biomass sources will help improve the security of energy systems both now and in the future because of their renewable features, Karp and Shield, 2008, while reducing climate change, Ecotoxicity, and eutrophication impacts. Over 85% of their total primary and secondary energy use in Alberta alone is supplied by fossil fuels (Statistics Canada, 2013; 2019). The same is applicable in several countries of the world especially the oil-producing nations.

Though, Canada depends majorly on fossil fuel for their energy generation and use owing to the fact that they are one of the world oil producing country. Canadian government like many other nations of the world still supports bioenergy activities through an ecoENERGY initiative that granted about 1.5 billion dollars for a period of 9 years starting from 2008 for renewable energy productions. Also, another ecoAGRICULTURE Biofuel Capital program in 2011 allocated about 200 million dollars in support of agricultural production for bioenergy in response to energy transition call. A similar offer is pronounced in 2021 for Agricultural

Climate Solution to help farmers tackle climate change as mentioned in Government of Canada, 2021 and Whitman et al., 2011). In Canada, Alberta has the fourth largest biomass resources after Quebec, Ontario, and British Columbia provinces, according to Alberta Innovates Bio-solution, 2014. However, bioenergy development is still slow in the country at large. It is non-debatable whether bioenergy's feedstock, such as maize, are carbon neutral (they are not), or without environmental impacts, considering the fact that energy is being used during the cultivation, processing, and transportation periods. Conversely, Shapouri et al., 2002 referenced in Whitman et al., 2011 suggested that it is still debatable whether bioenergies are emission-free or not. Increased use of bioenergy technologies should not be at the expense of the environmental protection and prosperity, so all impacts have to be assessed from the onset and made known, as this study revealed.

1.5 Case Study 2 Scope and Functional Unit Definition

The primary study goal in this case study is to evaluate the environmental impacts of cultivating corn (maize silage), and it's processing (digestion and conversion) for the purpose of biogas for electricity and heat generation for the period of 30 years (2019-2050). The main focus is on the ecosystem and its services that could be affected by this process chain. The primary idea of this research is extracted from the SustainableGas project as inspired by the Albertan- Bavarian Research Network (Abby-Net). While the secondary input data used for the analysis comes from reviewed literature and Eco invent database simulated with the openLCA tool using the Eco-indicator 99 life cycle environmental impact assessment (LCIA) method, TRACI & ReCiPe methods too. The major mediums assessed are water (for eutrophication) due to nitrate problems, air for CO_2 (climate change, respiratory issues), land for acidification, land use change/land conversion and resources.

The Functional Unit (FU)

There are different units for this type of assessment, and 1 kg of maize silage (mass-based FU) has been chosen as recommended for this project and has also been used previously by (Boone et al., 2016; and Król-Badziak et al., 2021). Some other studies use energy-based functional units such as 1 meter cube of biogas for convenience's sake, as seen in Wang QL et al., 2016. Different renewable gas technologies (RGT) have been developed using the following feedstock's; Maize silage, manure, forest residue, municipal solid waste, and others within the SustainableGas project. However, this life cycle impact assessment (LCIA) focuses on maize silage for a 10 MW installed capacity biogas plant that supplies electricity and heat in Alberta, Canada.

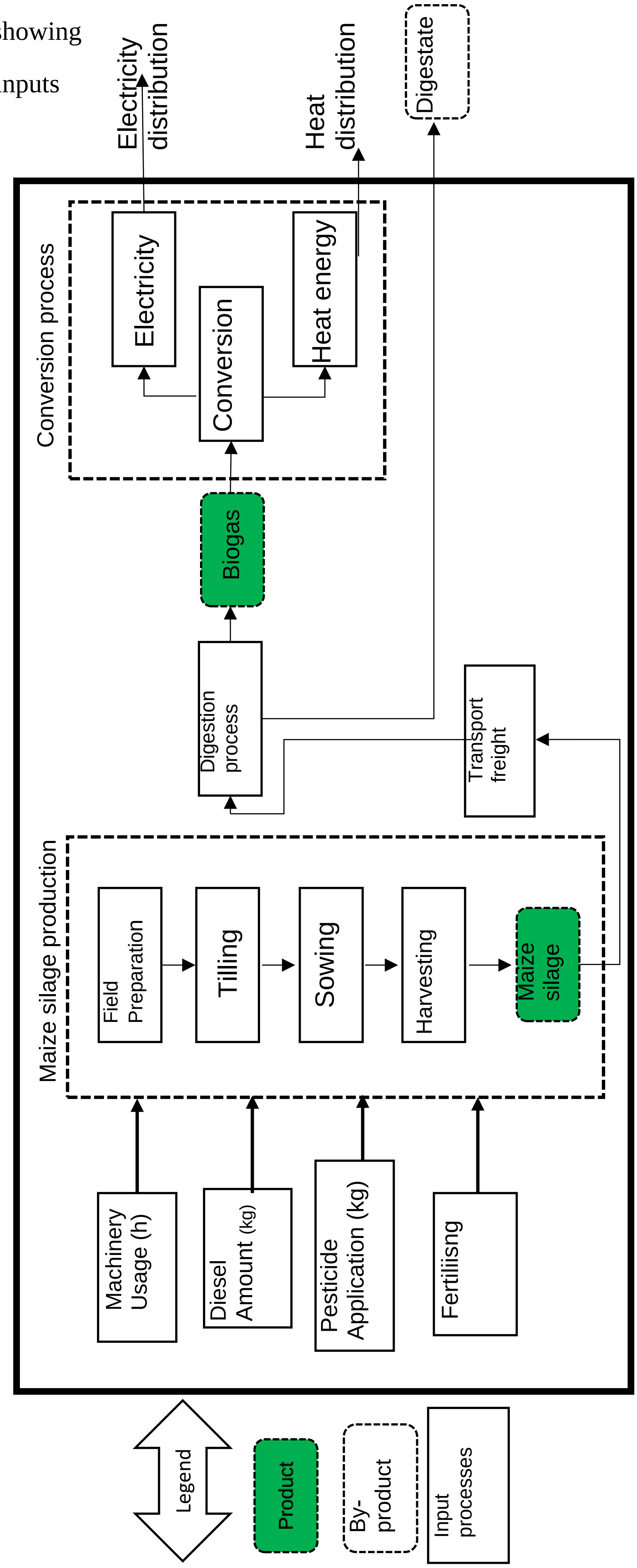
1.6 The system boundary

Every LCA study has developed scope and system boundary that guides it. This study's system boundary could be seen as cradle to gate since it covers maize cultivation, fertilizing, harvesting, drying, transportation, and processing (digestion and conversion into CHP). Furthermore, the final emission to land, air, and water arising from the process supply chain (Maize production and conversion processes) was assessed. It does not include the use of the final product (biogas) for manure, which is out of the scope, the decommissioning and final waste management was also not considered as it is not considered as a limitation.

And finally a clear comparison with its natural gas counterpart has been simulated. Figure 2. (System boundary diagram showing the inputs and outputs). This boundary is sufficient for this study as other literature, such as Bacenetti et al., 2016 has also used a similar boundary.

Data coverage: The dataset represents the production of 1 kg fresh matter of maize silage in the region. The average yield is 36330 kg/ha (wet mass) at a moisture content at storage of 65% was taken into consideration. This activity starts with soil cultivation after the harvest of the previous crop and ends after harvest and ensiling of the new maize plant at the farm gate. The dataset includes the inputs of seeds, mineral, synthetic and organic fertilizers applied, pesticides, herbicides, and all machine operations, including corresponding machine infrastructure and sheds constructed for the processing of biogas. Machine operations are needed for: soil cultivation, transport of seeds, fertilizers, and pesticides to the field as (20km) is considered for tro/fro, sowing, fertilization, weed control, pest and pathogen control, plant cutting, folding/loading, transport to farm, and processing site. Direct field emissions are also included. No irrigation is involved for maize production in the study area. Decommissioning and waste management were also not included as they are outside the study scope and system boundary, as mentioned earlier.

Figure 2. System boundary showing the products, processes and inputs



1.7 Reference flow

This is the amount of energy used, amount of chemicals, and quantity of fertilizer in kilogram needed to produce 1kg of maize silage.

The impact categories in this study include eutrophication potentials, land conversion, land occupation, acidification, climate change, total CO_2 emissions, and impact of the process chain on health, ecosystem & resources. The most important categories are the ones dealing with water and land since the goal of the project is to evaluate the environmental impacts with regard to direct ecosystem services, which has not been widely reported in the literature compared to the assessment of the CO_2 emissions that occupies most of the LCA studies carried out in Alberta.

1.8 Inventory data

For developing this environmental life cycle inventory for biogas production using maize silage as the feedstock, inputs such as nitrogen fertilizer, pesticides & herbicides, harvesting, transportation, etc. were considered. Output includes all the emissions discharged into the land, water, and air. For example, nitrates, ammonia & CO_2 were of concern. The inventory part deals more with the data collection in an iterative process, involving a large amount of collected data for different locations and from the Eco invent database, also known as the LCA inventory database. This databank has a publicly open and non-open access one; the US Life Cycle Inventory (LCI) databank is regulated by the National Renewable Energy Laboratory (NREL, 2012).

So far in this project, some of the input data and production procedures were adapted from the widely used databank, the Eco-invent paid database mentioned above, which is provided by the Center for Life Cycle Inventories Swiss. Also, few works of literature have been used to calibrate and validate this study such as (Jaroslav et al., 2021; Dressler et al., 2012; Fillipa et al., 2020; Aracli, C. et al., 2017; Jayasundara et al., 2014., and Kalu et al., 2021). Though, Whitman et al., 2011 found that fertilizer production consumed lesser energy, contrary to this study. The unit process contained within the production of maize silage for biogas or biofuel with their input and output data is shown in table 2, while the detailed inventory table is found in table 3.

Table 2. Unit process, input and output for maize silage production in short

UNIT PROCESS	INPUTS	OUTPUTS
Cultivation/tiling	Farm machines	GHG emission
Fertilization	N, P, Fertilizer	Nitrates,
Pesticide	Agrochemicals	Atrazine
Transportation, freight	t*Km distance travelled	CO_2/Fuel emission
Land transformation & occupation	Land use change	Heavy metal (lead), erosion
Drying	Agro machine	CO_2/GHG emissions

Table 3. Detailed inventory data including their providers, categories, and assumptions.

INPUT	VALUES	UNITS	CATEGORY	PROVIDER	COMMENT	LOCATION	SOURCE
Drying	1.0	m 3	016:Support activities to agriculture and post-harvest crop activities/0163:Post-harvest crop activities	market for drying of maize straw and whole-plant | drying of maize straw and whole-plant | Cutoff, U - GLO	Drying is one of the highest impact contributors	CA	Default value of 1.0 from Eco – invent database
Fertilising	1.0	ha	0161:Support activities for crop production 1.0 ha none fertilizing, by broadcaster | Cutoff, U - CA-QC	fertilizing, by broadcaster | fertilizing, by broadcaster | Cutoff, U - CA-QC	Dissel engine machine	CA	Eco-invent data
Fodder loading,	1.0	m 3	016:Support activities to agriculture and post-harvest crop activities/0161:Support activities for crop production	fodder loading, by self-loading trailer | Cutoff, U - CA-QC		CA	Eco-invent data
Maize grain	1.0	kg	011:Growing of non-perennial crops/0111:	maize grain production | maize grain | Cutoff, U - CA-QC	Functional Unit	CA	Eco-invent data
Nitrogen fertilizer	120	Kg	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics and synthetic rubber in	market for nitrogen fertiliser, as N_nitrogen fertiliser, as N	1 ton for 1 ha 1 hectare of cultivated	Czech	Jaroslav et al.,2021

P fertilizer	75.3 220	kgP 2O5	primary forms/2012:Manufacture of fertilizers and nitrogen compounds	| Cutoff, U - GLO	area &1 ton of grain 1 m3 of biogas is the FU	Poland Italy	Holka, Małgorzata, and Jerzy Bieńkowski Fillipa et al, 2020
Pesticide	1.0 0.57	kg	202:Manufacture of other chemical products/2021:Manufacture of pesticides and other agrochemical products	market for pesticide, unspecified | pesticide, unspecified | Cutoff, U - GLO		CA UK	Eco-invent data Adams, P:W:R et al 2015
sowing	1.0	ha	016:Support activities to agriculture and post-harvest crop activities/	sowing | sowing | Cutoff, U - CA-QC		CA	Eco-invent data
Tillage cultivator	1.0	m 2	/0161:Support activities for crop production	tillage, rotary cultivator tillage, rotary cultivator Cutoff, U - CA-QC		CA	Eco-invent data
Transport	20 30	kg* km	492:Other land transport/4923:Freight transport by road	market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 Cutoff, U - GLO	From farm to digestion gate assumption	DE	Adapted from Dressler et al, 2013 Kalu et al., 2021 Jayasundara et al., 2014

Herbicide	1.5	kg	Elementary flows/Emission to soil/agricultural		Assumed for production of 1kg per ha	IT	Dressler et al., 2012
Harvesting	2.5	m2	016:Support activities to agriculture and post-harvest crop activities/0161:Support activities for crop production	harvesting, by complete harvester, ground crops | Cutoff, U - CA-QC	By complete harvester machine	IT	González-García, S. et al, 2013

Case Study 1 Literature Review

2.1 Review of relevant studies

In Europe, Germany is a leader in the production of biogas, with a share of over 61% made possible by the support fostered by the German Renewable Energy Sources Act. In 2017, the number of biogas plants had increased to about 7,960 with 3,800MWel installed capacity (Strzalka. R et al., 2017 and FNR, 2017). However, none of these plants has the same combination as the RGP´s proposed in the SustainableGas project or has assessed their potential impacts on the ecosystem using the InVEST model. Moreover, the model incorporates the sedimentation process of watersheds to give information on the destination of eroded materials.

Nonetheless, many researchers have applied the InVEST water yield models with a focus on mapping and quantification of ES & water yield change in West Africa (Leh et al., 2013); analyzing climate change impact (Terrado et al., 2014), and assessing water demand ratio under different global change scenarios by Boithias et al., 2014. Another school of thought has it that greening of energy production, Cucchiella F. et al., 2017, and cleaner energy development that minimizes impacts on the environment through net-regenerative development should be an overarching aim for all bioenergy projects. The German government has now withdrawn from nuclear while relying more on renewables to change the nation's energy supply for transiting to a low carbon environment, Chen. C. et al., 2019 and Weber, G and Cabras, I., 2017.

Therefore, an increased understanding of environmental risks associated with renewable energy production is important to ensure energy efficiency, Michael Kühn et al., 2016, as most of the physical damage is found within the land-soil interface, which subsequently leads to biodiversity loss, as stated in Martens et al., 2017. Although more scientists think renewable energy is profitable, as cited in Weber, G and Cabras, I., 2017, yet their environmental impacts have to be well investigated. Renewable energy process chains tend to be area-intensive and affect the spatial configuration of terrestrial and aquatic ecosystems through fragmentation or isolation, or outflow regimes and rates. As a rule, anthropogenic changes in the landscape place a significant burden on ecosystem functions and services (Häggmark, L et al., 2000), (Ekka, A. et al., 2020).

Common methods of assessing land use and ecosystem changes include the methods of Landscape metric that uses geographic information systems (GIS) or remote sensing (Verkerk, P. J., et al., 2019) to derive and quantify geometric indicators of the landscape. For the design, prognosis, and analysis of the ecological consequences and feedback effects of landscape changes and changed material flows, models are increasingly being used that fundamentally determine their structure, complexity, and application direction. The spectrum ranges from artificial neural networks (Bagstad, K. J. et al., 2013) to process-based and area-differentiated environmental models (von Trentini, F. et al., 2019), to model concepts for immediate decision support as mentioned in (Bagstad, K.J. et al., 2013). Despite significant public attention and numerous reviewed studies (Peh, K:S: H et al., 2013), there are no one systematic model developments so far that can be used to project the full ecological consequences of the energy transition in totality.

Worthy of note is that different challenges are discouraging Germany from achieving a complete or higher percentage of the ongoing energy transitions. Such challenge includes lack of renewable energy storage facilities, excessive dependency on fossil gas importation, and low public adoption of renewables (not in my backyard), economic/cost factor, Technological Readiness to Market (TRM, many are still in the pilot stage) and the overall unknown environmental impacts from alternative energy technologies. For obvious reasons many citizens or community members kick against siting of bioenergy projects near their community still and this is also a challenge (socially).

As a rule, anthropogenic changes on the landscape place a significant burden on ecosystem functions and services (Lindenmayer, D. B., and Fischer, J. 2006; McIntyre, S. and Hobbs, R. 1999; M.J. Metzger, 2006) and bioenergy development is one of the cause. Common methods of assessing land use and ecosystem changes include the methods of Landscape metric that uses geographic information systems (GIS) or remote sensing (M. Antrop, V. van Eetvelde, 2000) to derive and quantify landscape geometric indicators. Many literature have assessed ecosystem and ecosystem bioenergy challenges, however not holistically and comprehensively as this study in both study areas.

Case Study 1 Methodology

3.1. Data sets & Analysis

The ecosystem services were evaluated with the chosen InVEST model packages (SDR, WYM & NDR) in line with their functional application. The SDR model assessed the rate of sediment movement down the slope (erosion) caused by the new RGP´s. It calculates soil loss or amount of average eroded sediment per annum and the proportion of the lost soil that reaches the stream (Peh, K.et al., 2013 and Woznicki, S.A. et al., 2020). The goal of the InVEST (SDR) model here is to model a spatially distributed production of sediment and its removal overland to the river. The SDR model is also used to evaluate the effects of various factors on erosion as changes in sediment load in the water are important in this study because of their impacts on German water systems. SDRmax is the maximum SDR value that can reach a pixel. It defines a fraction of topsoil particles that are smaller than coarse sand.

Our SDR model is calibrated with the soil erosion map that was produced by the European Soil Data Center (ES-DAC). The procedure is based on a comparison of both maps on ArcGIS. The output/results of the SDR model were brought close to the EU soil erosion map by changing the calibration parameters such as (SDRmax, C-factor and P-factor in the Biophysical Table). Parameters such as kb and IC0 as mentioned in (Borselli, L., Cassi, P. and Torri, D., 2008), was used to determine the relationship between hydrological connectivity (i.e. the degree of connection between land areas and rivers) and the sediment delivery ratio (Vigiak, O. et al., 2012). Figure 3-left shows InVEST SDR, figure 3-right is the JRC SDR map used for calibration as publishe in, (JRC, 2018).

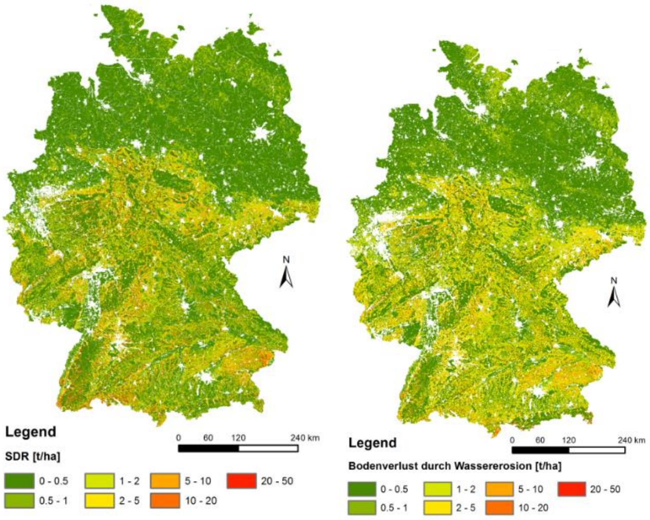


Figure 3. Output of the InVEST SDR model (left) and the (JRC) map of soil loss due to water erosion [t/ha] (right), similar pattern is observed in (Panagos, P. et al., 2015).

3.2. The water yield model (WYM)

The WYM of the InVEST tool predicts water consumption, values & quantifies natural water yield (Pessacg, N. et al., 2015 and Tallis, H. et al., 2014). The model uses local environmental condition, land use land cover data as an input to calculate water consumption and water yield at the watershed level. It determines annual water yield value per grid-cell by deducting water lost through evapotranspiration from the average annual precipitation during our simulation. It also calculates the value of energy that would be produced when water reaches a hydroelectric plant whereby providing economic & biophysical outputs (Grafius, D.R. et al., 2016).

To demonstrate how well and robust our WYM works, we calibrated and compared the InVEST raster file (figure 4 left and right). The WYM reference map adapted from JRC shows annual averages of net runoff (freshwater availability) from (1990-2010) as simulated by the LISFLOOD model. It is important to note that using only the InVEST-output map is not sufficient for the interpretation of hydrological processes or for making management decisions, hence, the need to calibrate.

One of our important calibration parameters in the WYM is the Z parameter. It is vital because of its empirical constant nature that describes the local precipitation pattern and hydrological characteristics, the Z parameter values are typically between 1 and 30, (Sharp, R. et al 2016). When the Z parameter has a higher value, then the WYM will simulate a higher water yield and vice versa. In this project, the Z parameter was estimated to be 30 to accommodate the whole of Germany. Our WYM performed well, similar to what Reedhead et al, found while running WYM for 42 catchments in UK.

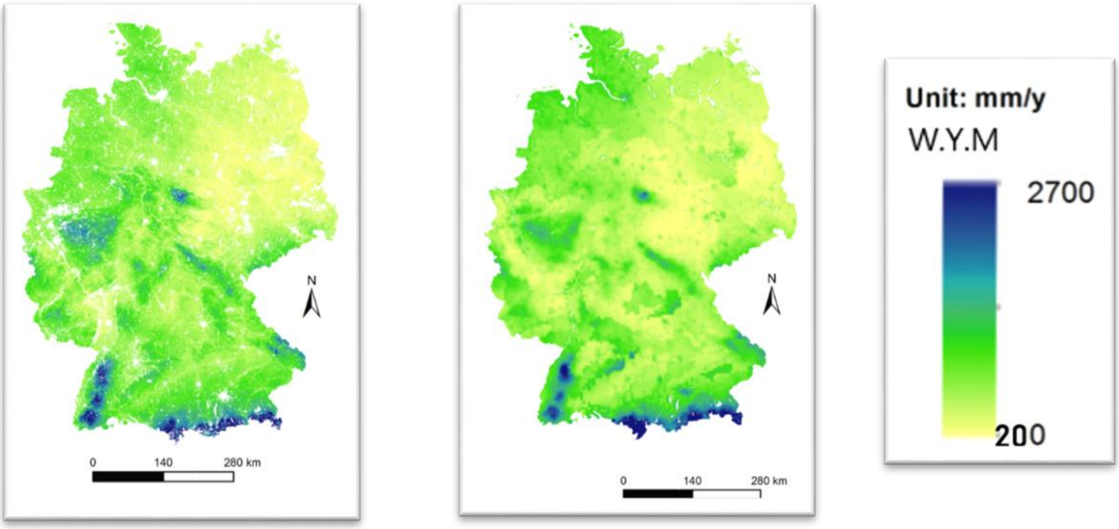


Figure 4. (Left) InVEST water Yield model-resolution 250m, (right) JRC water Yield reference map from LISFLOOD model-resolution 5km.

3.3 The Nitrate delivery ration model (NDR)

The NDR model was applied due to its ability to map nutrient sources from water catchment areas and their transport to water body. It uses topographic routing with movement of nutrient along the landscape to the water body. The model was rigorously calibrated with simple parameterization following [Tallis, H. et al., 2014], to cover the whole of Germany since there are different environmental conditions in different municipalities. For example, precipitation and evapotranspiration levels in the south are different from the one in the north. Calibration of our NDR model is necessary to gain confidence in the output, since the NDR factor approach is qualitative in nature and reflects change in different scenarios. A suitable literature is used as the reference map for the calibration. The calibration parameters for the NDR model are: Threshold flow accumulation, Borselli k parameter (relationship between hydrological connectivity determining factor), subsurface critical length, and subsurface maximum retention efficiency. Our InVEST map figure 5 (left), while figure 5 (right) is Bach calibration model.

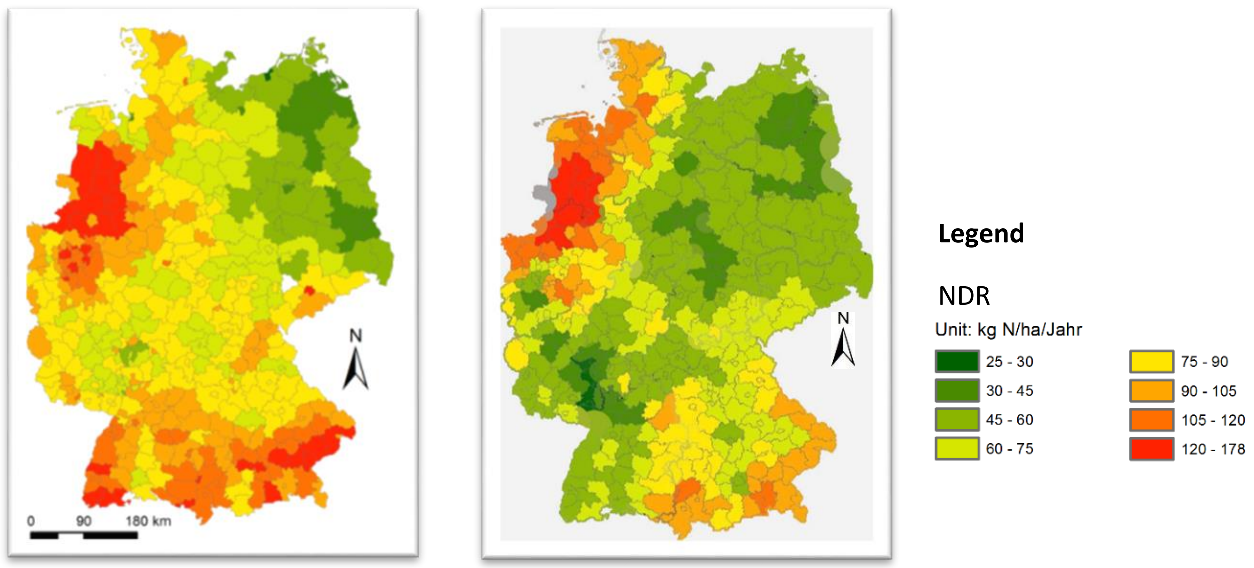


Figure 5. The left map shows an average nutrient load per hectare that reaches the river from InVEST, while figure 5- right is the nutrient balances for different regions according to Bach, Martin, (2012).

Our model shows more nutrient delivery in southern Germany compared to the northern part which could be explained by the new biogas plants built in between the research years. Also, the excessive use of fertilizer for maize cultivation to power the plants within a 7 years' period caused the difference in both maps.

3.4 InVEST model Input Data

All the input datasets were in the same cell size as required in the InVEST software, this study used 250m resolution for each pixel as recently updated in the global soil grids. Evapotranspiration (actual) is the function of root-restricting layer depth (The depth of the soil at which root penetration is inhibited as a result of physical constraints), land use, plant available water content (The fraction of water stored in soil profile for plant use) and reference evapotranspiration. Digital elevation model, an elevated value for each cell, a GIS raster file was refilled, and rearranged for closing up the loops, eliminate sinks and to ensure routing to known water network (Moore, R.V. et al., 1994) before running it in the InVEST suite for more accurate result. ArcGIS mapping tool was used for viewing, organizing and analysing the output maps from the InVEST model. Further input data & clarifications are found in the InVEST user guide/manual by Sharp, R. et al., 2014.

3.5. Land Use Map Reclassification

The existing CORINE 2012 land use/land cover map was reclassified into 13 classes using the ArcGIS tool, which now includes; 1-Urban, 2-Agriculture, 3-Pasture, 4-Forest, 5-Natural Green Areas, 6-Rocky Area without Vegetation, 7-Wetland, 8-Wine, Fruits & Berry Land, 9-Water, 11-Maize, 12-Rapeseed, 13-Wheat, 14-Soya Beans. CORINE 2012 has no information about different agricultural activities in Germany. Therefore, more modifications (reclassification) to include the required energy crops were necessary, figure 6. This adjustment helped in easy identification of the areas that could have a significant environmental impact on land due to the sitting of the new RGP´s. CORINE is widely used in the EU for the analysis of ES, and it has a coarse-scale dataset of 100 m resolution. In this study, we up-scaled to 250m resolution, which remains appropriate for a nationwide ES assessment where data with fine-scale may likely result to computational limitations (Grafius, D.R. et al., 2016). The land use map was manipulated with the R-code. This code includes six criteria for the reclassification of the land use map in the following other; firstly, the pixels with the ideal conditions for agricultural activities were extrapolated. These pixels have been defined with the following criteria: CORINE land use map, where the slope is less than 8 and the soil texture is not the sand. The second part of the code divides the extrapolated pixels into five classes: corn, wheat, soya beans, rapeseed, and agriculture. Also, note that during the reclassification, the number 10 was excluded, which is why we have land-use types 1,2,3,4,5,6,7,8,9,11,12,13, and 14, where 11 (maize) is the most important for obvious reasons.

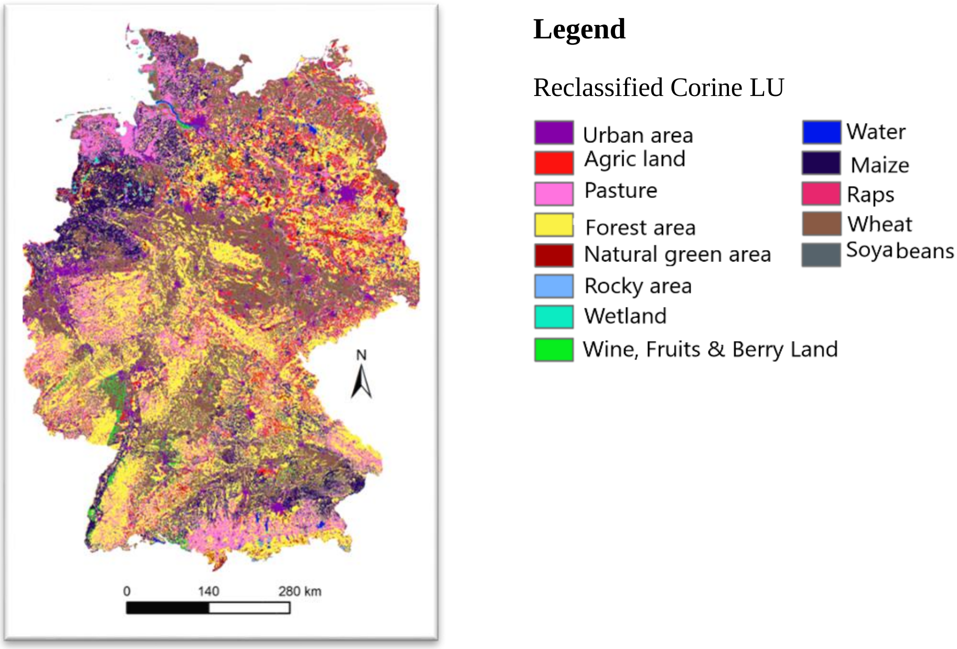


Figure 6. Reclassified land use map to include the agricultural land use vital for energy feedstock's needed in our RGP´s. Our reclassified map shows more maize in the west where our new maize RGP's can be suitably located.

1-Urban Area, 2-Agriculture, 3-Pasture, 4-Forest, 5-Natural Green Areas, 6-Rocky Area without Vegetation, 7-Wetland, 8-Wine, Fruits & Berry Land, 9-Water, 11-Maize, 12-Rapeseed, 13-Wheat, 14-Soya Beans.

Case Study 1 Result Analysis

The project's outcome saw a complete environmental evaluation of the process chains with regards to the availability and potentialities of the feedstock to develop strategies for the environmentally sound use of renewable energies in the gas network.

The result highlights assessed environmental consequences of alternative energy technologies on land use, sedimentation, water & nutrient delivery for our proposed RGP's. No retrieved literature has documented the environmental implications of our selected combinations of renewable gas plants until the year 2050 systematically and consistently as this study.

In the obtained SDR result after the comparison and calibration, similar patterns were observed from both maps figure 2. This is an indication that our methods (input data & calibration) are valid for the InVEST SDR. Even though, the original EU map from the JRC has a spatial resolution of 100 m, which was up-scaled to 250 m to cover the study area and for the purpose of clear comparison. The WY model reference map adapted from JRC shows an annual average of net runoff (freshwater availability 1990-2010). Although the JRC map has a 5 km resolution, we can still observe similar patterns on both maps. That is why our model calibration result is considered valid. Also, in the NDR result, similar patterns and range of loaded nutrients in median kg/hectare/year in counties were observed from the reference and our modeled maps. Nevertheless, ours showed more nutrient delivery in the south-western region compared to the reference map for the non-sustainable scenario. However, there is an apparent similarity in the northeast (figure 4) for both maps for the reference and current state. The EU's highest nutrient export limit is about 170-180 kg N/ha/year, according to [European Soil Data Centre (ESDAC), 2019 and Busico, G. et al., 2019]. Germany is already within the vulnerable limit zones, which is why we have modeled the nutrient to reduce its impacts to the barest minimum.

The model gave good results in terms of relative magnitude export of nutrients across different German river catchments, as suggested by our output map in the sustainable scenario. Our result shows that the percentage of changes analyzed with the NDR model considering the two scenarios are lower in the sustainable scenario. For example, soya beans cause a 10% change, while in the non-sustainable scenario, Soya beans cause a 50% change. In the sustainable scenario, the energy crops & agriculture residue are less utilized by reducing the demand or the amount of maize silage needed to power the RGP's and then increasing the plant efficiency from the technical side compared to the non-sustainable scenario.

4.1 Feedstock's with direct environmental impacts

Massive tonnes of biomass is required to run the RGPs that have a direct impact on land-use change, which explains why the environmental impacts of these feedstocks were not to be neglected from the onset. Water consumption, land occupation, and nutrient delivery, especially for (maize & short rotation forestry) are of importance here. Also, the forest residue has an impact on erosion depending on how many tons of it that is harvested per hectare table 4. [Verkerk, P. J et al., 2019. The final analysis saw a reduced amount of feedstock's from the crop and forest residue in the green scenario, which is more sustainable. Invariably, the lesser the feedstock harvested, the lesser the environmental impacts. It is more environmentally friendly to increase the gas or heat efficiency from the used technology than increase the feedstock quantity.

Table 4. Illustrates how many tons of biomass feedstock's that can be harvested per hectares in a year for our RGP´s.

RGP's type	**Biomass per RGP [t y^{-1}]**	**Type of biomass**	**Harvest [t/ha^{-1}] Source**
Bio-methane Maize RGP:	52414.8	Maize	93.3 Bioenergy In Germany Facts And Figures, 2019
Manure RGP:	5783.7		
SNG Forest Residue:	51923.1	forest residues	1.5
Syngas Forest Residue:	51923.1		
SNGSRPs:	52597.4	short rotation forestry	12

4.2 Nitrate Vulnerable Zones Assessment

The nitrate's most vulnerable zones were assessed by evaluating the impacts of nitrates on groundwater levels and found that the nutrient concentration is already very high in some German counties. Therefore, there is hardly any further land potential for these areas with high concentration, especially for sitting of maize & manure RGP's sustainably. This is because the maize and manure RGP's discharge fertilizer/manure components to the nearby water bodies that could cause eutrophication.

Using the InVEST model, we simulated the nutrient delivery to show nutrient inputs in water from farmland or other point sources to ascertain the criticality of the nitrate vulnerable zones in Germany. Results were aggregated to a municipality level to determine the local impact. Our model simulated high nutrient concentration in the reference state (2019), and low concentration in some municipalities, figure 7. For example, in the Bavarian region in the year 2050, there will be a reduction of nutrients which is one of the reasons we chose this as the green scenario with less environmental impact.

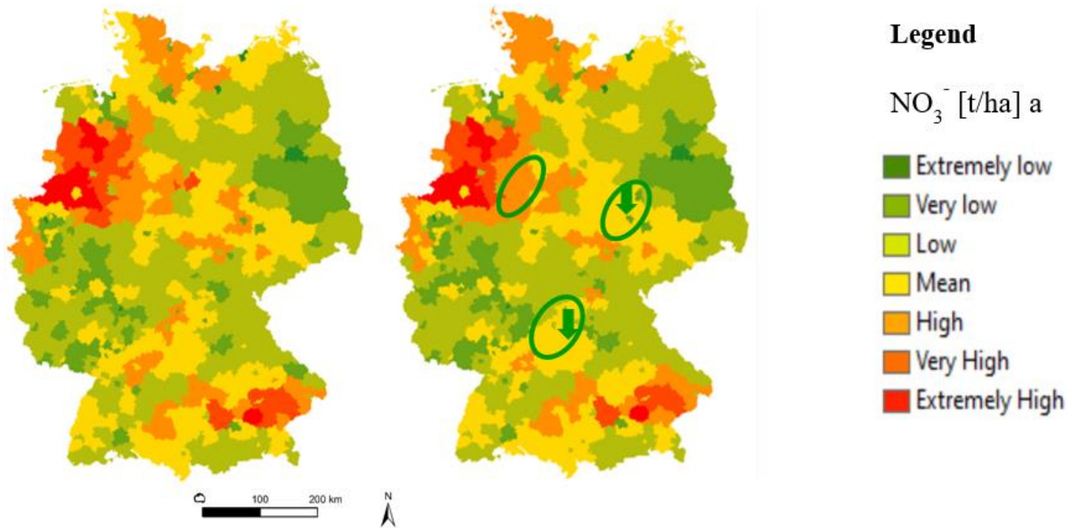


Figure 7. NDR (NO_3^- [t/ha] a) result for current state 2019-left (high) and future 2050-right (low) scenario on nitrates concentration in tons per hectare at municipality level as simulated by our model.

The green arrows in the map shows how nutrient delivery will decrease in the year 2050. North West will experience lower nitrate loads as well as the south in 2050 compared to current situation and same is applicable in the eastern part of the country. Our sustainable scenario forcasted more use of power to X (hydrogen) from 2045 upwards when they are technologically ready and no maize biogas plant. This is explainable as the RGP's powered with maize will automatically switch off (when it is no more cost effective and environmentally safe) while the ones powered with water and electricity will strive more starting from the year 2045 upwards when they are more technologically ready and affordable.

4.3 Impact of Land Use Change on Erosion

We analyzed the impact of erosion using the InVEST SDR model for different scenarios and found that erosion is higher in the south compared to the north with higher disparities in some municipalites. Additionally, we modeled and calibrated our result with the existing standards. The output map shows that most areas in the southwest for (2018-2030) will expect slightly higher erosion loads in the future (>5 %) figure 8. This erosion increase could be critical for these regions that have extremely high erosion rates already according to (German federal ministry for geosciences and raw materials)

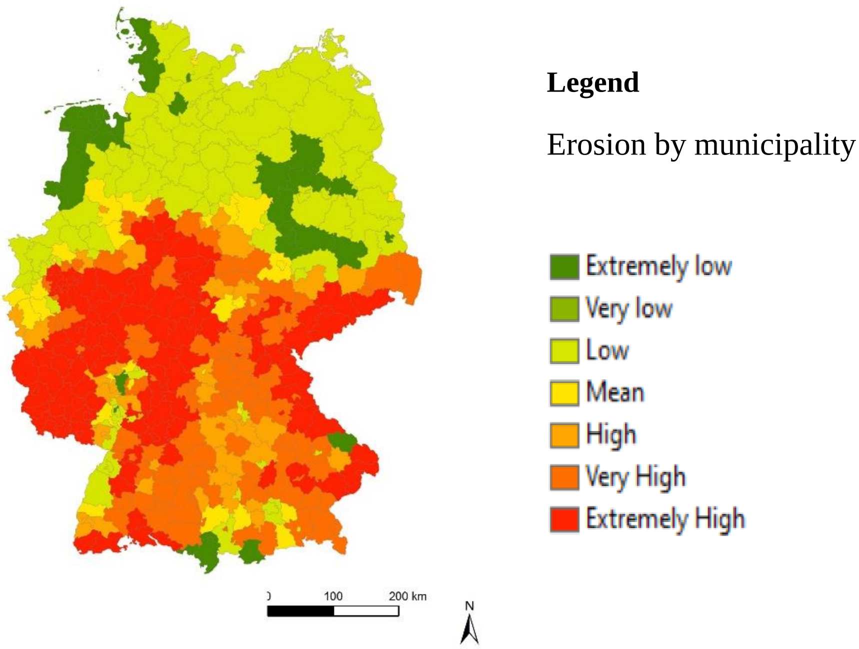


Figure 8. German erosion potentials by municipalities in tons per hectare per annum, according to the German federal ministry for geosciences and raw materials before our reference state.

Discussion for the case study 1

5.1 Sitting of the RGP´s

The locations of the RGPs are crucial for studying their environmental impacts due to diverse local environmental conditions, which may include soil types, availability of feedstock, and climate conditions. In this case study, locations of RGPs were carefully selected by looking for environmentally, technically, and socially balanced areas. These drivers play critical roles in the selection of the locations for the new RGP, considering the existing biogas facilities in the country. The R-script program, which we used for the localization of these RGPs, is described as follows; defining pixels in the land use map that can be used for maize production; in this process, a suitable land location for maize cultivation with less impact on the ecosystem was defined and selected. At the same time, the collection of forest residues (FR) and short rotation forestry (SRF) is described in table 5 for the two different scenarios (sustainable and non-sustainable).

Table 5. Selected pixels from the land use map which can be suitable for maize and for the short rotation forestry production in the sustainable scenario are 2, 11, 12, 13, and 14. While for the collection of forest residues, only land use type 5 which is the natural green area is suitable.

	Non-sustainable		**Sustainable**		
Type of RGP	Biomethane Maize/Manure	SNG Short rotation.F	Biomethane Maize/Manure	SNG F.Residue	SNG Short rotation.F
Biomass	Maize	SRF	Maize	FR	SRF
LUC, which can be used for growing biomass	2, 4, 6, 11, 12, 13, 14	2, 4, 6, 11, 12, 13, 14	2, 11, 12, 13, 14	5	2, 11, 12, 13, 14
Slope	<5°	<5°	<5°	/	<5°
Soil texture	2, 3, 4, 5, 6, 7, 8, 9, 11	/	2, 3, 4, 5, 6, 7, 8, 9, 11	/	/
Protest Atlas	1, 2, (3)	1, 2, (3)	1, 2, (3)	/	1, 2, (3)

Note: For the land use reclassification, each number in table 3 represent a land use type for easy understanding: 1-Urban Area, 2-Agriculture, 3-Pasture, 4-Forest, 5-Natural Green Areas, 6-Rocky Area without Vegetation, 7-Wetland, 8-Wine, Fruits & Berry Land, 9-Water, 11-Maize, 12-Rapeseed, 13-Wheat, 14-Soya Beans.

In sitting the RGP's, suitable locations were found using R-script coding, and the summary of the number of possible locations when different transportation distances were applied is represented in figure 9. It shows that only ~3% of possible RGP's locations were lost when the transportation distance of 40 pixels instead of 240 pixels was applied. These losses were regarded as insignificant. As 40 pixels represent an economically reasonable transportation distance for the maize. The transportation distance, which can also be more or longer, was shortened in order to speed up the optimization method. We have estimated that within a distance of 40 pixels, enough maize that can power one RGP's is produced. This is important and rigorous, especially when hundreds of locations were to be found for different types of RGP's.

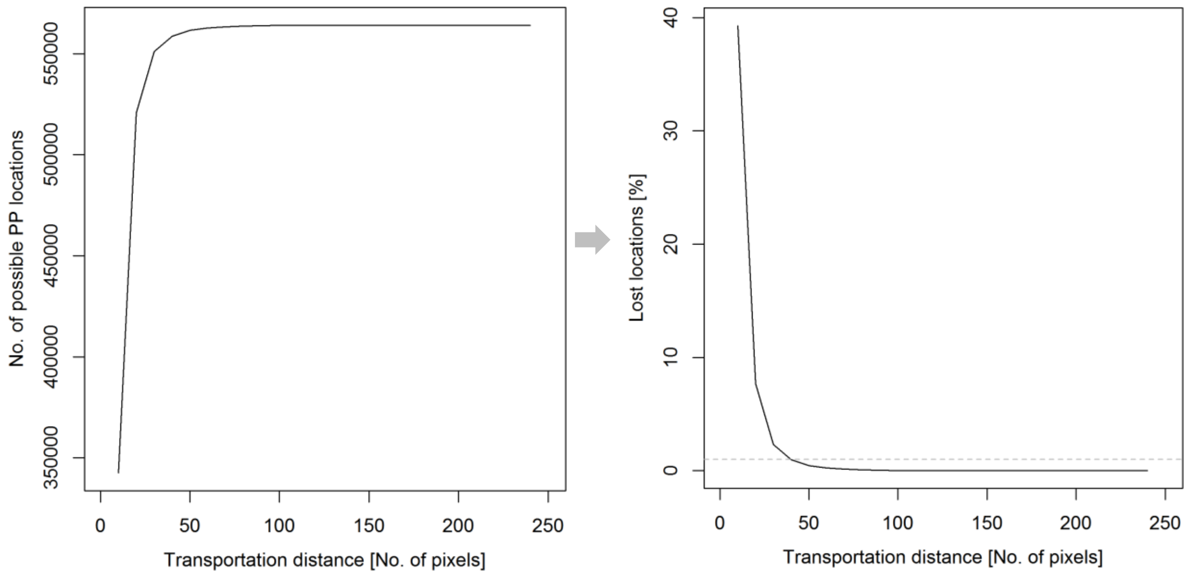


Figure 9. Transportation distance vs. number of possible locations for new RGPs (left) percentages of lost locations (right).

Note that the dotted lines in the graph above signify about 3% lost location. Also, when the transport distance is 50 km, 350,000 possible location for new RGP is found which is the shortest. While 250 km transport distance produces 550, 000 new RGP's potential location.

5.2 Environmental impacts of manure feedstock

Since some of the impacts associated with a few RGP´s feedstocks could not be simulated in InVEST model (e.g., manure powered RGP), literature reviews of relevant and related publications were employed. Impacts of manure RGP considered here are water & land pollution, pest breeding ground, and offensive smell that could pose a health hazard for humans around the farm. Also, the permissible distance limit for transport emission of 20 km round trip (10 to & 10 from RGP´s site) was assessed. The trip is calculated at an average of 60km/h = (60km covered in 60 minutes). This would mean transporting the manure from the farm to the biogas plant for 2km in 2 minutes, 10 km for 10 minutes one way alone (Daniel-Gromke, J., 2018). This 10 km distance for one way was reduced to 5 km in (Statistik Deutschland, 2019) for wet manure, with a 40 tons truck that consumes 30.53 liters of fuel per 100 km.

Additionally, manure undergoes some reactions such as; fermentation, ammonia volatilization, decomposition, and nitrification. These reactions are temperature dependent facilitated by environmental elements. And the end product results in the emission of nitrous oxide, carbon dioxide, ammonia, and methane which could be harmful to the environmental systems. Although, (Strzalka, R. and Eicker U., 2017) argued that biogas facility has the tendency of reducing emissions from manure. This could be particularly true, but not without emissions in the long run.

5.3 Modifications of climate data

Processing of climate data for the years 2030, 2040, and 2050 were carried out by applying the EURO-CORDEX as used in (https://cordex.org, 2019, ClimEx. https://www.climex-project.org, 2020 and von Trentini, F. et al., 2019) in the following order; Climate projections of precipitation (mm) and near-surface temperature (°C) for Germany with a spatial resolution of 0.11° (approx. 12km) were obtained from the bias-adjusted EURO-CORDEX database at the Earth System Grid Federation (ESGF). The projections are based on the Regional Climate Model SHMI-RCA4 driven by three different General Circulation Models (GCMs) under the Representative Concentration Pathway (RCP8.5): CNRM-CERFACS-CNRM-CM5 (hereafter CNRM), IPSL-IPSL-CM5A-MR (hereafter IPSL) and MPI-M-MPI-ESM-LR-MR (hereafter MPI). The three climate projections were bias-adjusted by the Swedish Meteorological and Hydrological Institute (SMHI) using the Distribution-Based Scaling (DBS) approach (Wei Yang et al., 2010) and the Regional Reanalysis MESAN (Euro4M) as the reference dataset (Dahlgren, P. et al., 2016). Required inputs for the InVEST model are presented in table 6.

Table 6. Input climate data used in our InVEST model simulation.

Climate data - Input

NDR	-	Precipitation [mm]
SDR	-	Rainfall Erosivity Index [MJ*mm/(ha*h*yr)]
WYM	-	Precipitation [mm]
	-	Reference evapotranspiration [mm]

5.4 Recalculation of Precipitation and Erosivity Index in Steps.

For precipitation which is an important input for our InVEST model, a 30-year mean annual sums were calculated for the four periods and each climate simulation (CNRM, IPSL, and MPI) figure 10. The Rainfall Erosivity Index was first calculated on a daily basis following Eq.1 before calculating the 30-year mean annual rainfall erosivity.

$$R_e = 9.6 \cdot 10^{-7} \cdot (P_d \cdot T_a)^{2.6} \qquad (1)$$

Where R_e is the rainfall erosivity index [MJ*mm/ (ha*h*yr)], T_a daily mean temperature [°C] and P_d daily precipitation [mm];

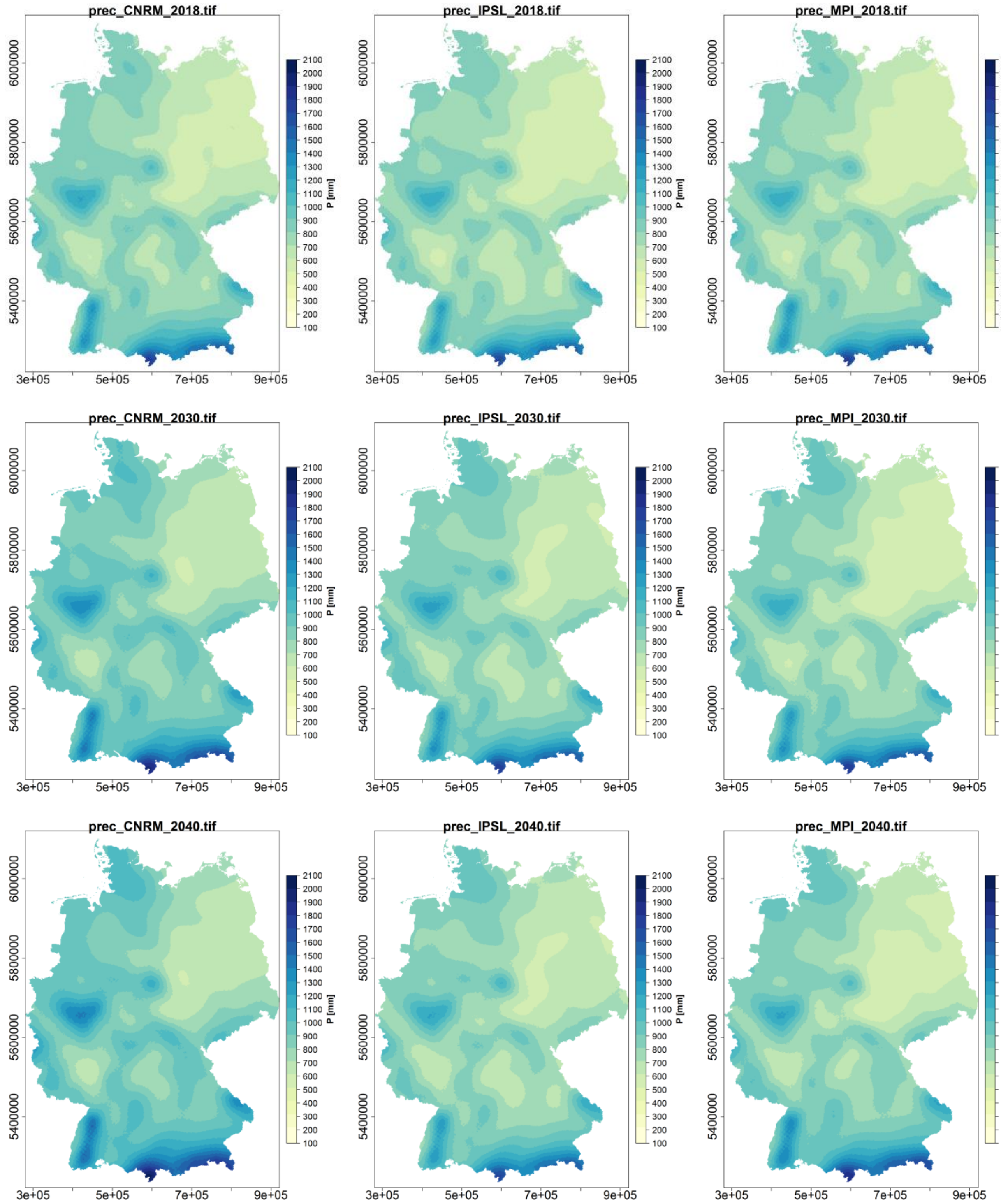
Step 1: Monthly mean temperature was calculated from daily temperature.

Step 2: Daily daylight was obtained from different cities such as Dresden, Berlin, Leipzig, Munich, Hamburg, Hannover, Stuttgart, Bremen, etc. for years 2009, 2010 and 2011. Differences of the length of daylight in the years 2009-11 are only minutes. Hence, it was assumed that mean monthly hours of these three years is equal in each year in the period 1980–2018.

Step 3: A bilinear interpolation of the length of daylight to the 0.11° (12km) climate model resolution was performed for each month.

Step 4: Mean annual Evapotranspiration $_{\text{(reference)}}$ was calculated for each grid point and interpolated with kriging method for entire Germany.

Step 5: 30-year mean Evapotranspiration $_{\text{(reference)}}$ for each period (1980–2010, 2016–2045, 2026–2055 and 2036–2065) was calculated.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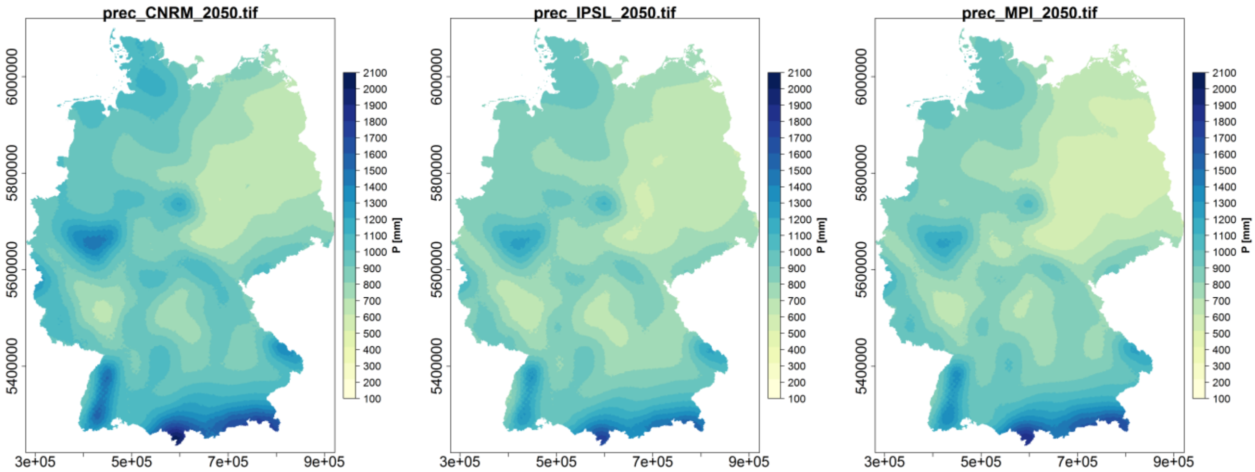

Figure 10. Precipitation [mm] for three different climate projections for four time periods (dark colour means high, light colour means low).

For the interpretation of the numbers on the X axis, 5400000 = 54, 000.00, 5600000 = 56, 000.00, 5800000 = 58, 000.00, 6000000 = 60, 000.00

The second case study of this Thesis is on life cycle impact assessment

Literature review for the case study two

6.1 Review of relevant LCIA studies

In this literature review of related studies previously carried out by other scholars, details of what authors have done in this field of study and about the model result are presented using LCA. Life Cycle Assessment (LCA) is a tool used to examine in a more comparative and comprehensive manner the environmental performance of products and services throughout their lifetime while presenting its results in a standardized form following the ISO 14040 and 14044 (ISO, 2018a and ISO, 2018b). It is an important tool for identifying trade-offs that will help in making environmentally friendly decisions on renewable energy projects. Some of the environmental aspects assessed in this study are the transportation distance and medium (freight road transport), fertilizers/chemicals, energy use, and emissions into the land, air, and water (L.A.W) within the supply chain. One of the features of energy systems LCA. explored in this study requires the complete analysis of the processes during the course of biogas products life cycle because, when life cycle impacts assessment is applied, an integrated efficiency of the complete process that considers initial input and the final output is determined (Abu-Rayash, Azzam, and Ibrahim Dincer; Ibrahim Dincer and Yusuf Bicer, 2018).

The Eco-indicator impact assessment method has been applied in this study to carry out the life cycle impact assessment (LCIA). Which show the environmental impact values in numbers or scores known as eco points, represented as the annual environmental impacts of an average European inhabitant. It simplifies the interpretation of the result while giving individual scores for each process, project, product, or unit. Eco-point (milipoint) is calculated based on relative environmental impacts represented in a point scale, where a point means an environmental load of an average European for production and consumption undertaken in an economy annually (The Netherlands: PRé Consultants; 2017 and Goedkoop M. Adamage who proposed an oriented method for life cycle impacts assessment in Eco-Indicator 99; 1999). The Eco indicator tool describes the damage made on the environment in three main categories such as on human health (H), ecosystem (E) and on resources (R) H.E.R. Some of the health impacts includes loss of life arising from an environmental degradation or chronic diseases caused by respiratory effects, climate change and carcinogenic effects to mention but a few. On the other hand, ecosystem quality impact involves eutrophication, land use change, impacts on species diversity and acidification among others. For the resources which is measured in terms of surplus energy needed for extracting low quality of minerals and energy products in the future, Eco-indicator assesses the depletion of those raw materials and their impact on energy systems.

The impact of eutrophication and acidification resulting from acidic substances from the air causes damage to the land and water ecosystem. The process involves the deposition of inorganic substances (for example, nitrates, ammonia, sulfuric acid, and phosphates) through the air to a nearby water and soil surface (when these substances mix with the atmospheric moisture, they can fall as acid rain). While the land use impact from conversion and occupation affects the area as the number of species increases with area size. Land damages are expressed in potentially disappeared fraction (PDF) multiplied by the life span and the area used. When the land ecosystem is damaged (loss of naturalness and loss of potential carbon sink), it changes the quality from acting as a resistance to erosion and flood. This can affect the groundwater protection ability, filtering and buffering capacity functions as mentioned in Lakhani, R. et al., 2014.

However, there is an increasing need to develop a more bio-based economy with modern and cleaner energy systems to reduce greenhouse gas emissions from fossil fuel use, Goglio et al., 2018.

Although the use of biomass sources as a renewable energy feedstock has been seen as more sustainable compared to the use of fossil fuel sources such as natural gas, there have also been concerns about land occupation and conversion, issues of fertilizer application, and movement of its debris to the water bodies, the use of machinery and transportations involved in maize cultivation (Reid et al., 2020). Furthermore, there are more human health benefits when fossil is replaced or substituted with bioenergy, such as reductions in the atmospheric concentration of fine particles, dust & particulate matter, and other air pollutants that can lead to premature deaths. Nonetheless knowing that some ecosystem services and species would be lost, during the development and deployment of bioenergy. From deforestation and land use change which needs to be put into consideration early enough for mitigatation purposes, Vohra. K. et al., 2021; Jorgensen and Andersen, 2012. These and many more are why the importance of life cycle impact assessment for biogas technologies can never be over-emphasized globally, regionally, and locally.

6.2 Life Cycle Impact Assessment (LCIA)

Impact analysis is where the inventory results are translated into a piece of new information related to impacts coming from the flows to assess their significance both on humans, ecosystem and resources (H.E.R.). In LCIA, a series of factors are applied to the inventory results while generating the impact estimates. A key difference between life cycle impact assessment and other frameworks is its link to a particular functional unit (and, of course, the entire life cycle as a boundary). LCA. & LCIA has two unique features and objectives from other models. Firstly, it evaluates the environmental performance of maize silage production in this study considering raw material productions, transportations, machine manufacturing, and sheds construction. LCA. Also takes into account maintenance, extraction, and final disposal for many other environmental assessment projects, as seen in Pieragostini et al., 2014. The second major benefit is that decision-makers are able to make environmentally friendly choices on bioenergy projects while choosing from alternative processes.

Additionally, LCIA results can be a base for making potential improvements in a product system's environmental performance. This method has informed and derived several activities of a product/service supply chain. The LCIA carried out in this study is able to consider the actual adverse effects from biogas processes on health, ecosystem, and resources, not merely tracking quantities such as tons of emission or liters of fuel consumed during production but also the real environmental effects. The final LCIA results come as indicators (Minu Mohan, 2018). An indicator is a generic word that refers to a clear pointer or signals. For instance, fish dying in the water body could be an indication of eutrophication. Global warming could also be an indication of greenhouse gas emissions.

6.3 The Three Mandatory LCIA Elements

(The compulsory elements considered in this LCIA are three in number, namely, Classification, Selection, and Characterization).

Selection: This is the first mandatory LCIA impact category element. It involves the documentation of the rationale behind the choices sufficiently, which is in line with the stated goal and scope definition of this project. For instance, we said that eutrophication/acidification is an impact category from our model result which affects the ecosystem quality; since we included eutrophication/acidification as our impact category, then there is a need to justify why we selected them considering its relevance in the project design parameters (goal and scope of our study). As a justification, fertilizer and other farm chemicals are used during maize production, which emits acidic elements toxic to the ecosystem and can lead to eutrophication. In this study, we selected Eco indicator, ReCiPe, and TRACI methods in line with the ISO Standard that requires an all-encompassing impact assessment on a comprehensive set of environmental issues. ISO also recommends that the LCIA methods selected should be relevant to the geographical area of the study. This is because a life cycle assessment carried out on a product manufactured in a U.S. factory would not be well-served by using an LCIA method primarily developed in and intended to be applied in Europe alone. Nonetheless, most of the LCIA models have been created only for the U.S. and European locations but can be used elsewhere around the world.

Classification: This is where our results from the inventory are arranged and organized such that they fit into the study framework of the relevant impact categories. It is the first quantitative element of the LCIA. Copying of the inventory items into a number of different piles, where each of them is related to one of the impact categories used by the chosen LCIA method, was done in this classification stage. Therefore, each of our LCIA method had a list of inventory flows connected to the impacts in this study's classification stage.

It is possible that classification has no quantitative effect on the inventory flows other than arranging and creating piles. In addition, the classified list of inventory flows relevant to a chosen LCIA method has different underlying units such as (e.g., kg, g, and tons.). These differences were managed in subsequent elements of the LCIA.

Characterization: This step quantitatively transforms the classified inventory flows through the equivalency factor or characterization factor to create an impact category indicator. These indicators appendix j, are related to health, ecosystem, and resources. The purpose of characterization in this study is to apply scientific knowledge of relative impacts such that all classified flows for an impact can be converted into standard units for comparison.

The characterization methods are the preexisting scientific studies that leverage on the creation of common units. For instance, the impact of climate change example considered in most studies is a characterization method used in IPCC (2013). This IPCC method is well known for creating the global warming potential equivalency values for greenhouse gases, where CO_2 is by definition given a value of 1 and all other greenhouse gases have a factor in equivalent kg of CO_2, also abbreviated as CO_2-equivalent or CO_2e. Similar to other methods, this brings about a weighting factor adjustment for greenhouse gases. The IPCC report actually provides several sets of characterization factors for different time horizons of greenhouse gases in the atmosphere. The factors typically used in LCA and other studies are the IPCC 100-year time horizon values, but values for other number of years are also obtainable. Any classified greenhouse gases or other substances appearing in the list of characterized flows have been analyzed in this study with the 'kg CO_2e/kg of substance' factors to create the characterized value for each inventory flow. The characterization stage is seen as the last of the initial mandatory elements in LCIA, since the remaining elements are optional, and many L.C.A. studies skip all optional elements due to time constraints and sometimes lack of data.

6.4 Impact Assessment Model Category

Many LCIA methods are based on a single category, for example, the global warming potential (GWP) and cumulative energy demand method (C.E.D.). This study applied Eco indicator 99, ReCiPe, and Tool for the reduction and assessment of chemicals and other environmental impacts (TRACI) developed to be used mostly in the U.S. and North America to guide LCIA studies, (Bare, J., 2011 and Bare, J., 2012), ReCiPe method was also used. Eco indicator was applied in this study due to its ability to obtain the total endpoint environmental impact scores and quantify them in three categories, including normalization and weighting. The weighting steps are divided into three; individualist, which excludes and neglect fossil fuel depletion hazards and danger, considers only the extraction of mineral. The Eco indicator hierarchist perspective can be seen as the outlook of an average researcher or scientist. Last but not the least is the egalitarian perception which gives more consideration for future while giving priority to the long-term well-being of the ecosystem quality. To fulfill the study's scope, egalitarian assessment category is chosen as this method deals with the endpoint results and has been widely used for similar studies, Homagain et al., 2015 and Cavalett et al., 2013.

While TRACI was used due to its comprehensive range coverage in the colder regions (Canada and U.S.A.), it was not used in isolation without other methods because of its inability to cover the environmental impacts on land, which is a major aspect of this study. Nevertheless, it serves as a suitable comparison method to the Eco indicator since using a diverse impact method allows us to make relevant comparisons. Comparing across inventory flow helps to credibly analyze whether to choose a product system that releases 3 kg less of nitrate to the water or prefer the one releasing 3kg less of CO_2 to the air considering the location and reason for the assessment. From the literature comparisons, Germany has more nitrate problems compared to Canada, while for GHGs from fossil exploration, Canada may be leading. TRACI also helped to report the end results of this research in a more standardized unit other than using only the eco points or milipoint recorded from the Eco indicator method. Worthy of note is that LCIA may not give precisely quantified damages that had occurred to the environment. For instance, it will not give the height of sea-level rise due to climate change nor give an estimate of the number of destroyed coral reefs. Instead, it will provide valuable and relevant detailed information that will aid and facilitate the decision to protect one environmental medium more than others. Most of the results here are reported from the Eco-indicator after comparing with TRACI and ReCipe methods.

Bioenergy development in the study area 2 (Alberta, Canada)

7.1 Study Area Description and Bioenergy in Canada

With a total area of about 661,848sq. Km, in landmass, sheltering 19 cities, Alberta is situated in the west-central area of Canada, sharing a boundary with British Columbia. The highest elevation point in Alberta is around Mount Columbia, at 3,747m high. Some of the significant rivers are the peace, slave, Milk, Red Deer, and Hay River. The province has its lowest elevation point of 175m in the north-eastern area near the Slave River valley. Their smooth land covered with prairies where maize silage production occurs (Awada, L. et al., 2021 and Guyader .J. et al., 2018) is in the southern and eastern parts of Alberta. The map of Alberta below shows a few features such as the highest point of elevation, the capital city, the river, and the low lands area in figure 11.

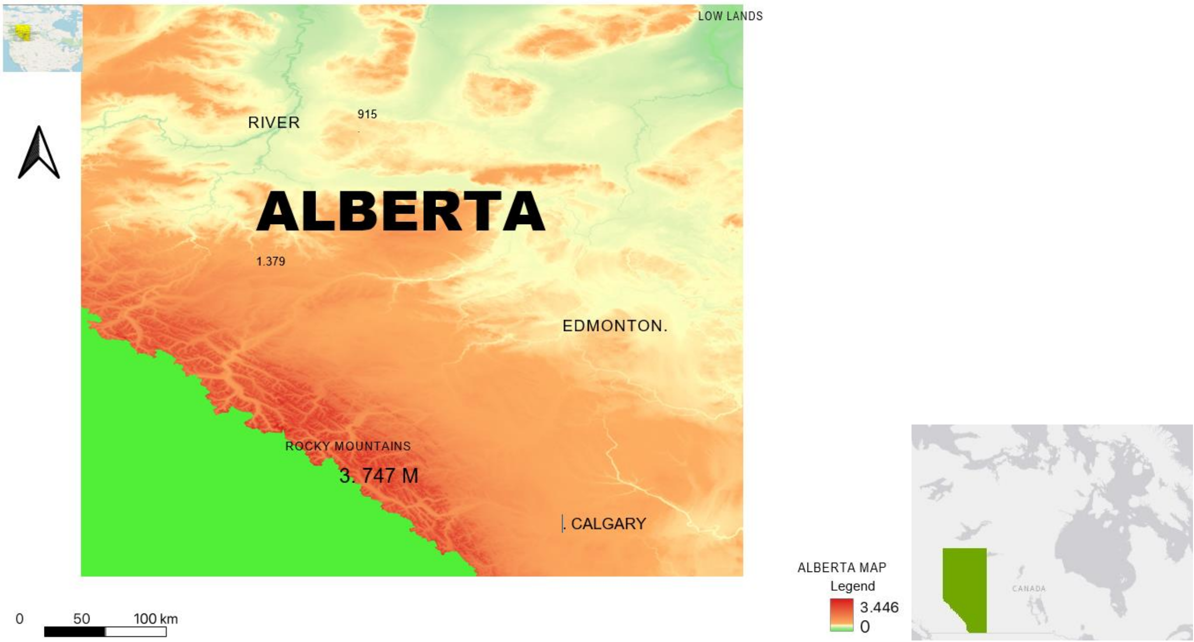

Figure 11. Map of Alberta at the west central part of the country representing few features of the province such as the highest point of elevation, the capital city, river and the low lands area. The highest elevation point from the legend is red, while the lowest point is green.

To acquire the overlay of Alberta, the elevation data of the study area is a crucial requirement for getting this map. The boundary of Alberta is downloaded as a polygon file and using the Shuttle Radar Topography Mission (SRTM) plugin placed on the canvas area through the NASA search engine. The elevation map was downloaded.

The raster tiles were downloaded and merged to form a single file, and different colour codes were assigned to the map using the symbology. This is to indicate regions of distinct elevations on the map, after which the Polygon file was then made transparent. The raster and polygon are merged using the raster extraction function to mask the two layers. This is done to get the exact extract of the Alberta shape of the raster from the polygon. The map layout is then printed, imported, and labeled while adding the legend for use. The map has a coordinate reference system of about WGS 84, while a published paper using Alberta as a case study assumed a coordinate system of (56°21′50″N, 116°47′80″W), Rehman, M. M. et al., 2017.

As an oil-producing province, Alberta runs their energy facilities majorly on natural gas and other fossil product at large, and coal represented almost 87.4% of the energy consumption in 2011, as reported by Statistics Canada, 2012. The province generated around 36% of the country's fossil CO_2 emissions according to Environment Canada, 2013 as Alberta and Ontario have been the most significant emitters since 2005, resulting from oil and gas expansion as reported in the National Inventory Report 1990-2019 as submitted to the United Nations framework convention on climate change, (Environment Canada, 2021). Increasing the share of renewable energy from biomass can reduce air emissions as the region has a substantial amount of untapped feedstock that can support energy transition Weldemichael & Assefa, 2016. Nonetheless, only about 0.04% of the biomass sources are harvested annually until 2014 (Statistics Canada, 2014).

The production of maize silage in the Canadian prairies has increased to about 383,879 hectares as of 2016, and this is due to maize's high yield potential compared to other feedstocks. However, the long cold seasons affect its ability to yield even more than 320-380g kg whole plant dry matter content necessary for ensiling, as cited in Guyader .J. et al., 2018. In the year 2019 alone, Canadian energy consumption was about 8,882,020 Terajoules, of which 2,282,309 terajoules were Albertans' share, according to the Canadian Centre for Energy Information, 2020. As the production of crops contributes about 6.5 percent of the country's emissions, Awada, L. et al., 2021, many scholars have assessed the impacts of bioenergy production in Alberta, Canada, including Bell and Weis 2009; James, G. and Ben, T., 2014; Weldemichael & Assefa, 2016. Nevertheless, evaluating the environmental impacts of maize silage production for bioenergy use with a focus on health, ecosystem, and resources by applying the Eco indicator method across the life cycle pathways still has increased demand. There is no doubt that bioenergy deployment in the Canadian province of Alberta will decarbonize its electricity grids emission significantly. Due to increased fossil fuel production, Alberta has experienced even higher emissions of GHG since 1990, as shown in figure 12 and GHG category by sector is elaborated more in table 7.

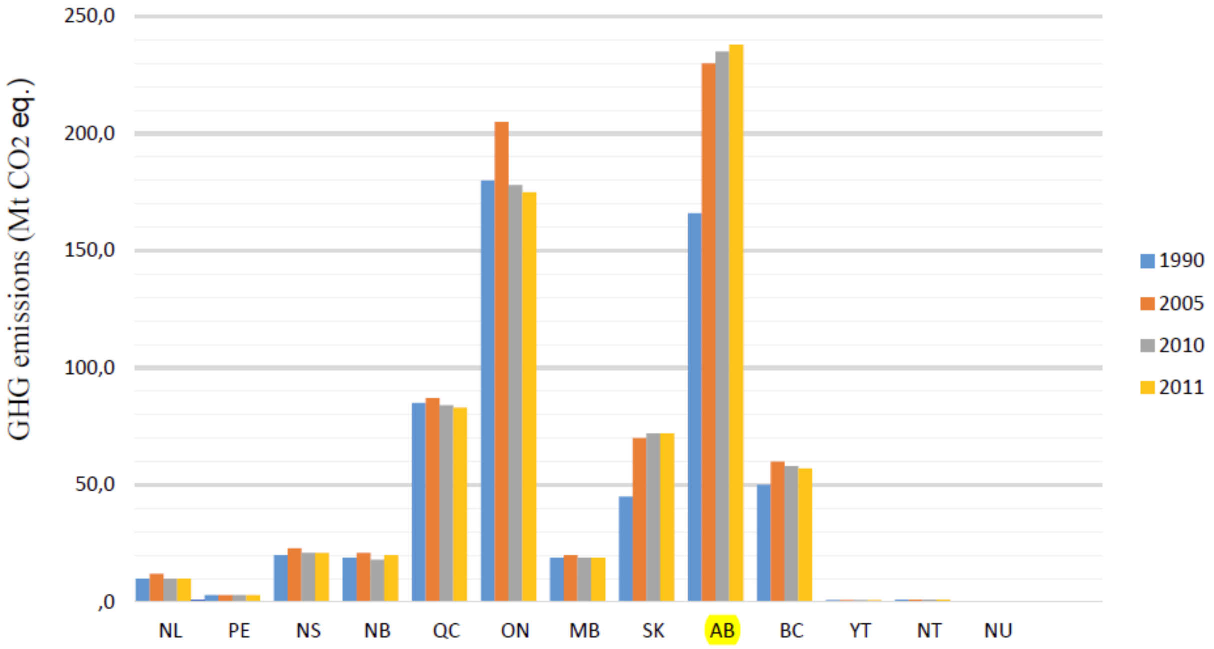

Figure 12. The Canadian GHG emissions from different provinces with Alberta being the highest in the year 2011 as adapted from the Environment Canada, 2013.

Table 7. GHG emissions for Canada by the Intergovernmental Panel on Climate Change (IPCC) with a focus on selected sectors as measured in metric tons CO_2 equivalent 2005-2019.

Sector	Year 2005	Year 2015	Year 2017	Year 2019
Oil & Gas extraction	63 Mt CO_2 eq.	97 Mt CO_2 eq.	97 Mt CO_2 eq.	105 Mt CO_2 eq.
Transport	190 Mt CO_2 eq.	201 Mt CO_2 eq.	207 Mt CO_2 eq.	217 Mt CO_2 eq.
Agriculture	60 Mt CO_2 eq.	58 Mt CO_2 eq.	58 Mt CO_2 eq.	59 Mt CO_2 eq.
Land Use Change & Forestry	8.2 Mt CO_2 eq.	4.0 Mt CO_2 eq.	0.70 Mt CO_2 eq.	9.9 Mt CO_2 eq.

The region generated about 35.7% of the nation's emissions in 2012 alone, which is approximately 249.4 mega tones of the 699 MtCO2 emitted. With over 14,598 MW installed capacity in 2014, more than 80% of the electricity is generated from fossil fuels, as reported in 2015. Currently, few local areas and counties, such as Canmore in Alberta, surrounded by the Canadian Rockie Mountains and environmentally sensitive habitat with a complex land use by-law, have shown how renewable energy transitions plans can be facilitated locally. Although Canmore, like every other city in Alberta, has enough renewable resources such as biomass and land to sustain its bioenergy needs, there are still complete implementation challenges (Jiaao Guo et al., 2020). To really succeed in the ambitious renewable energy targets and cutting down on GHG emission goals, balancing the land-use changes, energy demands, and practicable renewable energy development should be at the forefront. This is because there are factors and regulations that affect the successful implementation of renewable energy projects in Canada. Such factors include technological/engineering limits and barriers, societal or public acceptance, and of course, the market (are people ready to switch from fossils to bioenergy, how many oil industry jobs would be lost?). Recall that Alberta is one of the biggest oil-producing provinces or jurisdictions globally, with over 83% of its electricity approximately coming from non-renewables (Jiaao Guo et al., 2020; Giesy, J.P et al., 2010 and Olmstead, D.E.H. & Ayres, M.J, 2014). However, Canada accounts for about 60% of its total primary energy supply from biomass, hydropower, the solar, wind, and geothermal. Nonetheless, power generation from bioenergy still varies hugely in different municipalities and provinces, Natural

Resources Canada, 2021. A recent paper published in January 2022 suggested that Canada needs to step up more renewable energy policies, plants, and incentives to be able to match up with the biogas front-runners such as Germany, China, the UK, Italy, and Japan, to mention but few. And the anaerobic digestion system has proven to be a suitable method for converting both energy crops and waste to renewable energy (Omid Norouzi and Anime, Dutta, 2022)

7.2 Alberta CO_2 emission per capita

Despite the vast bioenergy resources available in Alberta on a significantly utility-scale, the province is still one of the highest per-capita emitters of fossil carbon dioxide annually at about 62.4 tonnes. Moreover, the province has passed a Renewable Electricity Act to decarbonize this carbon-intensive power system within the province and its municipalities since the year 2017. As a result, the government has committed to having approximately 30% of its electricity generated from renewable resources with the aim of phasing out coal in 2030 and capping oil sand emissions at 100 megatons per annum by Olmstead, D.E.H. & Ayres, M.J, 2014.

While Yemane Weldemichael and Getachew Assefa, 2016, found that total GHG emissions from biomass-based energy generation and use were estimated at about 6.61 $MtCO_2$ eq. in one of their case studies, their case 2 estimated even lesser amount of emission (5.25$MtCO_2$ eq.) for the year 2030 which is an indication that continued use of bioenergy will lower GHG emissions drastically but not wholly. Some other authors argued previously that the province's renewable energy strategies have focused on the development of clean hydrocarbon more than on using the biomass resources presently. However, this will change in the near future as climate change, and reduction of GHG emissions are at the forefront of each country's target following the recent climate conference in Scotland.

7.3 Alberta NO_2 emission

After the application of nitrogen fertilizer, the NO_2 emission is released from the soil to the environment, which is a major contributor of global warming, exhibiting the global warming potential of about 298 times bigger than CO_2 (IPCC, 2013). As mentioned in IPCC (2006), nitrate/NO_2 emissions can be made present from the forest lands through nitrification & denitrification processes in the soil. Nitrogen fertilizer is one of the most commonly found fertilizers in the boreal forest, and it is needed to increase the sapling growth rate of the area (Pukkala, T., 2017; Mahendrappa and Salonius, 1982). This could also be one of the reasons why N fertilizer and atrazine use is still very much allowed in Alberta, Canada, while some countries such as Germany avoid atrazine components where necessary. In the meantime, the gains outweigh the loss as the local bioenergy production, in this case, maize silage as a feedstock, has direct economic and social benefits for the immediate communities and stakeholders (Maier, J.M., et al., 2019 and Müller et al., 2011). It could reduce electricity and heating costs in the future, especially in the remote villages of the province and other off-grid locations, which will lead to independence from crude products and provide local jobs, says Maier, J.M., et al., 2019.

Methodology for the case study two

8.1 The second case study methods

Every study has a laid down procedure followed to achieve the set-out goal and objectives. That said, the method of this study includes the use of openlca software and the Eco-invent data to simulate the impacts of maize production, digestion, and conversion. Also, relevant websites were surfed, and some literature values were adopted. For the literature review, an open search on the topic was carried out on google scholar, web of science, government websites such as Agri-Food Canada, Statistics Canada, and Environment Canada, Canadian Center for Energy Information, 2020, and others where a careful selection of the most relevant and recent studies was made. About 31 related literature were initially reviewed only for this methodology section, 15 out of them were carefully chosen following the 3 LCIA mandatory elements of selection, classification, and characterization. A quality assurance and quality control (QAQC) assessment was carried out to determine where the individual literature values came from and if they meet and can align with the overall scope of this study, some of the literature values were harmonized. For example, (Titaporn et al. 2020). Part of the harmonization was done by converting the different measuring units used in different literature into kg, to match this study. The main focus of the simulation is on Climate change, GHGs, GWP, CO_2, Acidification/eutrophication, Nitrates, Ammonia, Atrazine, and Land use change, all of which made up the flows and impacts categories of this study.

Those selected literature had mass-based functional units for easy conversion from tons to kg for more accurate comparison. Thereafter, the model run was carried out iteratively by using the Eco- indicator, TRACI and ReCiPe methods, which were compared to the inventory results from the contribution tree. Comparison of the different life cycle stages was also carried out to ascertain the most impactful stage between maize production, digestion and conversion processes.

8.2 ISO standards and impact categories

The life cycle assessment method followed the ISO standard principle of goal and scope, inventory, impact assessment, and interpretation, figure 13. The Eco indicator 99 method of the openlca developed by Dutch Pre (Product Ecology Consultants) for the Dutch Ministry of Environment (Filippa et al., 2020) is used majorly to carry out this cradle to gate (Titaporn et al., 2020) assessment of maize silage production. It allows and shows environmental impacts/scores (milipoints) of a product or service in numbers called the eco points. The digestion and conversion processes was also simulated. The Eco indicator unit of measurement called milipoint can be described as the conventional annual load of an average citizen considering the production and consumption capacity in the economy. When the correct inputs are given, the method evaluates 11 environmental damages through its built-in calculation process, Wang, Q.L et al., 2016. The impacts are grouped in three categories as mentioned above, human health using the climate change impact where all the indicators and contributors of climate change such as CO_2 emissions from the full supply chain is assessed and presented as an agent of global warming. This health category checks for example, the number of life that were lost in years and potential human disease impacts due to the environmental degradation arising from the maize silage cultivation, digestion and its conversion to CHP for onward use in homes, and industries, etc. The model analyzed the acidification, eutrophication, and land use impact contributions for the ecosystem quality being the second category assessed. Furthermore, the resource category (fossil fuel & mineral extraction) contribution arises from the depletion of energy and raw material resources, that are measured in terms of surplus energy required to extract lower quality of minerals or energy in the future, Dincer Ibrahim, 2018. The TRACI method of the openlca applied here helped validate the results gotten from the Eco indicator method and describe the eco points in a more standard unit such as the global warming potentials (GWP) of the CO_2 equivalents generated in this study. During the model run, different input quantities and providers were used (just to see the sensitivity as described in the sensitivity analysis part of this study) before the desired result was obtained. For instance, the quantity of input fertilizer and other farm/agrochemicals were initially set at 170 and 3kg per hectare, respectively. However, these numbers were further calibrated and reduced with the most relevant literature reference bearing in mind the research aim, scope, functional units, and system boundary. There was also conversion of different functional units from tons to kilograms for easy and better comparison across the existing studies; the QAQC data used can be found in (appendix m).

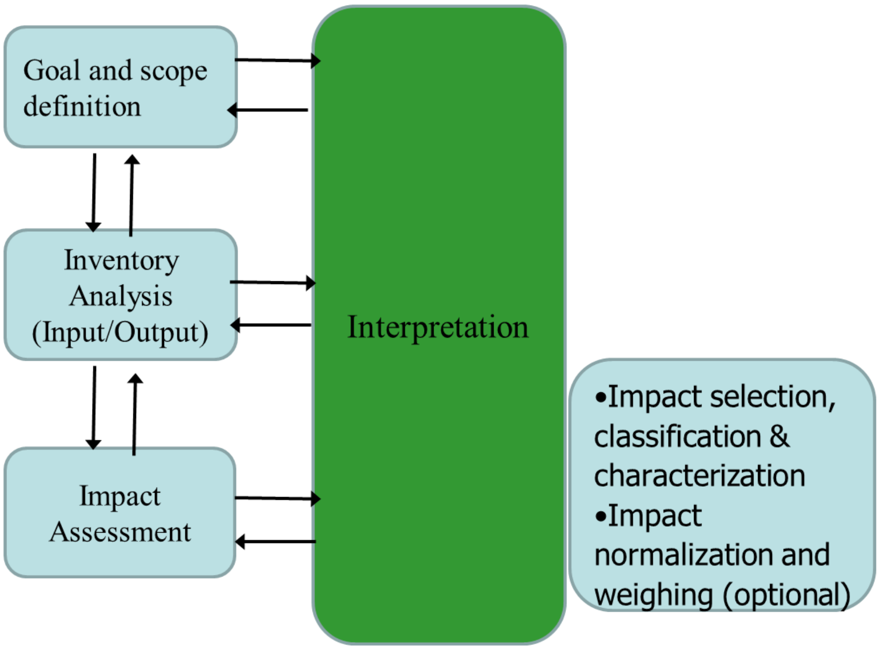

Figure 13. ISO standard 14040, 14044 framework followed in this research

8.3 Description of the dataset used in the second case study for maize production considering the following inputs;

(Tillage, harrowing, by rotary harrow/ ploughing, Self-Loading trailer, fertilizing, harvesting)

The inventory considers the number of agricultural machines and sheds, including the quantity of diesel fuel consumed. Also, it considers the quantity of air emission from the combustion, noise pollution, and emission to the soil from tire abrasion during farming activities and processes. Some preliminary agricultural activities include clearing a parcel of land, say 1 ha surface attaching the adequate machine to the tractor, and uncoupling it at the end of use. This dataset was generated following the Eco-invent quality guidelines, which are still available via the Eco-invent website (http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/). Eco-invent background data is crucial as it is the largest transparent Life Cycle Inventory database globally, according to Gregor Wernet et al., 2016 as referenced in Aleksandra Krol-Badzial et al., 2021. And the Diesel consumption is calculated from primary data and models from the American Society of Agricultural and Biological Engineers (ASABE) published in 2006.

The considered tillage ploughing process represents the service of ploughing 1 ha of the agricultural land with an average of three furrows to height-furrow plough used in loam soil at

15 cm work depth. The dataset includes transfer to field; fieldwork for an area of land of about 1 ha, including turning, idling, and overlapping process, CRAAQ, 2011. The data above also covers for the sowing, and the seeder has a working width of 3 m. Similarly, the amount of emissions to the air from combustion and the emission to the soil from tire abrasion during the work process is taken into consideration. Part of the fuel consumption has been extrapolated from Quebec as Albertan data were missing in some cases, but emissions per kg of diesel used were taken from the original values from the Eco invent global data (GLO). For the complete harvesting process, the dataset represents a service of complete harvesting with the same preliminary activities as in tilling and sowing above.

8.4 Self-Loading trailer and harvesting datasets

A self-loading trailer with a fodder cutter dataset represented here is for transport, cutting, and discharge of the materials being cut such as silage, and fast discharge back to farm for a 1 cubic meter folder. The average working width is 6.9m with a varying number of cuttings per annum and according to the crop type, for example, (1 cut for maize and soybean silage; 3 cuts for a mix of alfalfa and grass fodder). The loading trailer is assumed to be filled up entirely at the average capacity of 65cubic meter. The process also starts with a preliminary work at the farm such as attaching the adequate machine to the tractor. This activity ends with a transfer back to the farm and concluding work, like uncoupling the machine. The inventory includes a transfer of the machine to the field, the loading of 1 m^3 fodder, and a fast discharge of fodder. It takes into account the diesel fuel consumption, the amount of agricultural machinery, and of the shed, which has to be attributed to the fodder loading. Amount of emission to air from the combustion and emissions to the soil and water is also considered.

In general, maize production datasets have been extrapolated to include the land-use change for the Canadian region with the emissions according to the second edition of the Quantis-modified tool developed by Blonk Consultants World Food Life Cycle Assessment DataBase (WFLDB)-adapted-Blonk 2014 direct-land-use-change-assessment-tool, Sebastien Humbert, 2014. The size of the accounted emission depends mainly on the corresponding country-specific land transformations and the relative crop expansion in all other countries where the crop is grown during the last 20 years. Additionally, the current results are based on the average Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data from the year 2011 harvested area as cited in FAOSTAT, 2018.

The weighted average that is applied in this study takes into account relative difference in crop expansion as some crop land can potentially encroach into the primary forest, secondary forest, grassland and perennial land annually in different locations. The activity includes all the upstream and downstream, starting with cultivation and ending at harvesting, ensiling, and delivery to the gate. The dataset includes the inputs of seeds, mineral and organic fertilizers applied, pesticides, and all machine operations and corresponding infrastructure and sheds. Machine operations are for: soil cultivation, transport of seeds, fertilizers, and pesticides to the field (20 km), sowing, fertilization, weed control, pest and pathogen control, plant cutting, loading, transport to farm and discharge into soil. Direct field emissions are also included. Note that there is likely irrigation involved at the global scale, but no data were explicitly collected for the dataset since it is extrapolated from the Quebec geography where no irrigation is applied. The decommissioning and waste management were also not included as they are outside this project's study scope and system boundary.

8.5 Datasets description for the digestion and conversion

The anaerobic digestion inputs with the title (anaerobic digestion plant construction, agriculture, with methane recovery anaerobic digestion plant, agriculture, with methane recovery | Cutoff, U) as stated in the database followed the standard process. The steps involves the plant construction, production, transport and disposal of the main materials for a biogas plant meant for an agricultural feedstock such as maize silage. The procedure refers to an agricultural biogas plant with a capacity of about 500m^3 for each production phase. The used data was sampled from different locations that spanned till the end of the year 2017. The data set were generated following the Eco invent data quality guidelines for a complete lifecycle assessment. The inventory data represent a typical agricultural anaerobic biogas plant with a capacity of 500m^3 and a lifetime of 20 years.

The Conversion process is also the third stage after cultivation and the digestion step, it is titled as (heat and power co-generation unit construction, 160kW electrical, standard components for heat+electricity) in the openlca database. The module summarizes the input and output of the infrastructural components of a cogeneration system or unit. It takes into consideration all the shared components needed for the production of electricity and heat. Included also is the three-way catalytic converter. 1987 January 1 till 2017 December 31 data collection period. Additionally, all the supply chain impacts from the shed, bulbs, wires, aluminum sheets, rods, rubbers, and other electrical appliances for the construction are considered.

8.5.1 Natural gas inventory data description

The natural gas data used in this study represents the Canadian natural gas production on-shore. Some of the flow processes are adapted by using the local data from the study area of Alberta, namely, the air emissions from greenhouse gases (CO_2, CH_4, and N_2O), respectively. At the same time, the criteria for air contaminants or pollutants are the PM2, 5, CO, non-methane volatile organic compound (VOC, NO_x, SO_2), including hydrogen sulfide. The local data have also been used to compute the sour and sweet gas percentage, the quantity flared, burned, and vented in the gas turbine. The percentage of the quantity extracted from sulfur during the sweetening and the production volume is considered.

Drying and sweetening processes have been added, and the sulfur production associated with the desulfurization process is included. The sweetening process, included in the dataset, delivers sweet gas (natural gas, propane), sulfur, and other gases (ethene, butane, and pentane). The activity starts with the exploration and drilling of the wells. The activity ends at the processing plant gate, which is the conversion stage.

The data set contains all the fuels and emissions related to well-rig testing, exploration, extraction, and treatment (sweetening and drying): fugitive emissions, flaring, venting, and the use of gas in turbines. Statistics applied here are an average of the past five years (to 2017). Emissions per cubic meter (m^3) were stable.

Case Study Two Result and Analysis

This analysis has shown how the model is built and simulated to arrive at the desired result, some impacts were analysed considering the individual LCA stages, and others were combined (full system). To perform this LCIA practically with interest on health, ecosystem and resources (H.E.R), climate change and respiratory effect for health impact category is analyzed, acidification/eutrophication and land occupation for the ecosystem impact category were assessed. Fossil fuels and mineral extraction for the resources category were also evaluated and compared across the biogas LCA stages, literature and natural gas in some cases. The flows and impact categories were populated using the LCA selection method from the three impact assessment methods. Averages from each impact were chosen from the three methods used (Eco-indicator, ReCiPe and TRACI). Some of the results were compared with the harmonized data (Part of the harmonization was done by converting the different measuring units used in different literature into kg, tons, etc to match this study´s goal) and literature data such as figure 15, 16 and 20. While, figure 14 shows the most significant maize silage production impact category contributor.

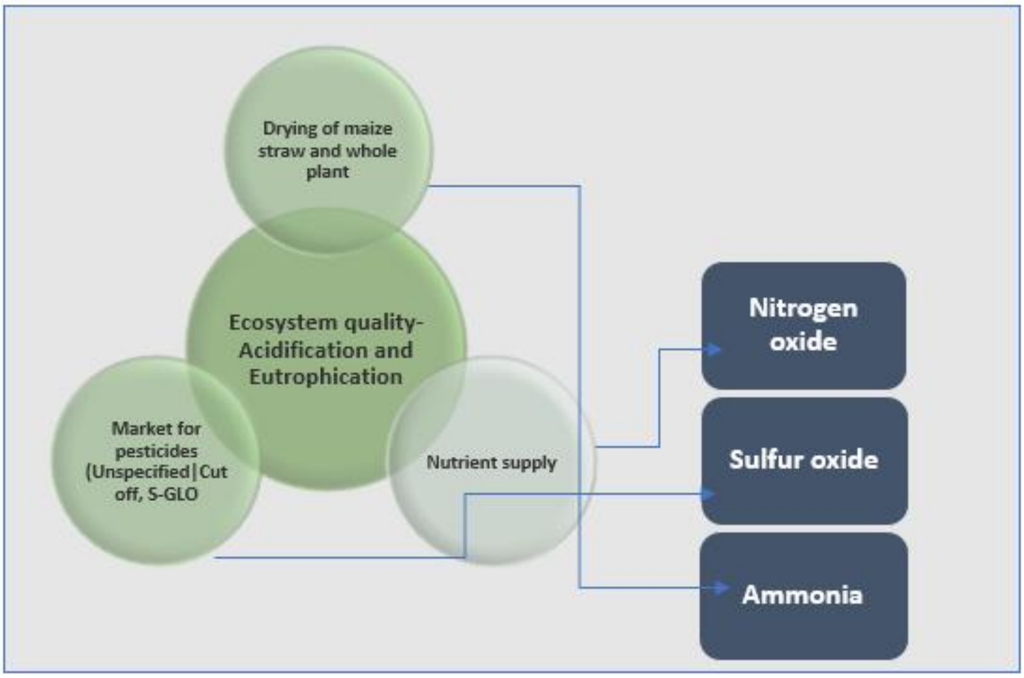

Figure 14. Shows the most significant emission contributors during the cultivation, especially ecosystem quality- acidification and eutrophication categories, emission from drying is leading for tthe maize production stage.

Outlook: What decision-makers should do to maintain environmental protection while swiching to biogas in Alberta is to regulate the use of farm chemicals input, this study recommends about 120 kg of nitrogen fertilizer per hectare as in (Jaroslav et al., 2021; Jayasundara et al., 2014). Since nutrients from farm chemicals and drying for ecosystem quality category is the major contributor as shown in figure 14, it is recommended that maize silage drying should be carried out with hybrid system (biogas and natural gas) to reduce nitrogen, sulfur dioxides and ammonia emissions.

9.1 Maize silage production flow categories Analysis

GHG (CO_2)

The Co_2 emissions arising from the maize production alone were contributed mainly from the drying process and market for pesticide & farm chemicals production and their applications, as also shown in Whitman et al., 2011 with 0,320 kg Co_2 eq/kg of maize produced in Quebec. Freight transport is the third main CO_2 contributor in this LCA stage and this is expected considering the study location where fossil electricity is used for drying and other major farm activities. Canada also has long cold periods, which causes the excessive use of electricity for drying. Large amounts of Co_2 are emitted into the air during this drying process. The obtained result has been compared with other studies, as figure 15 depicts, to gain more confidence and to provide accurate policy recommendation for Alberta. While analyzing from the most significant impact to the smallest, considering the study's assumptions, the research carried out by Titaporn et al., 2020 has the most significant value of 0,351 kgCo_2 eq/kg of maize silage produced in a small county of Thailand. While, our study on the contrary reports 0,132 kgCo_2 eq/kg. In order to reduce the emission, we have assumed that biogas and natural gas (hybrid gas) used to dry the maize silage instead of natural gas, which is popularly used; this will reduce the drying emission in the form of GHG.

Additionally, Jayasundara et al., 2014 who studied the GHG intensity of corn production in Ontario, reported in the ranges of 0, 243 – 0, 353 kgCo_2 eq/kg. In this acidification and eutrophication impacts category, drying is the major contributor as the inventory data includes the energy demand (supplied by burning light fuel oil and consumption of electricity). The infrastructure, including the drying machine for the maize plant at 110-120 degrees Celsius was inventoried as they have the potential to cause climate change.

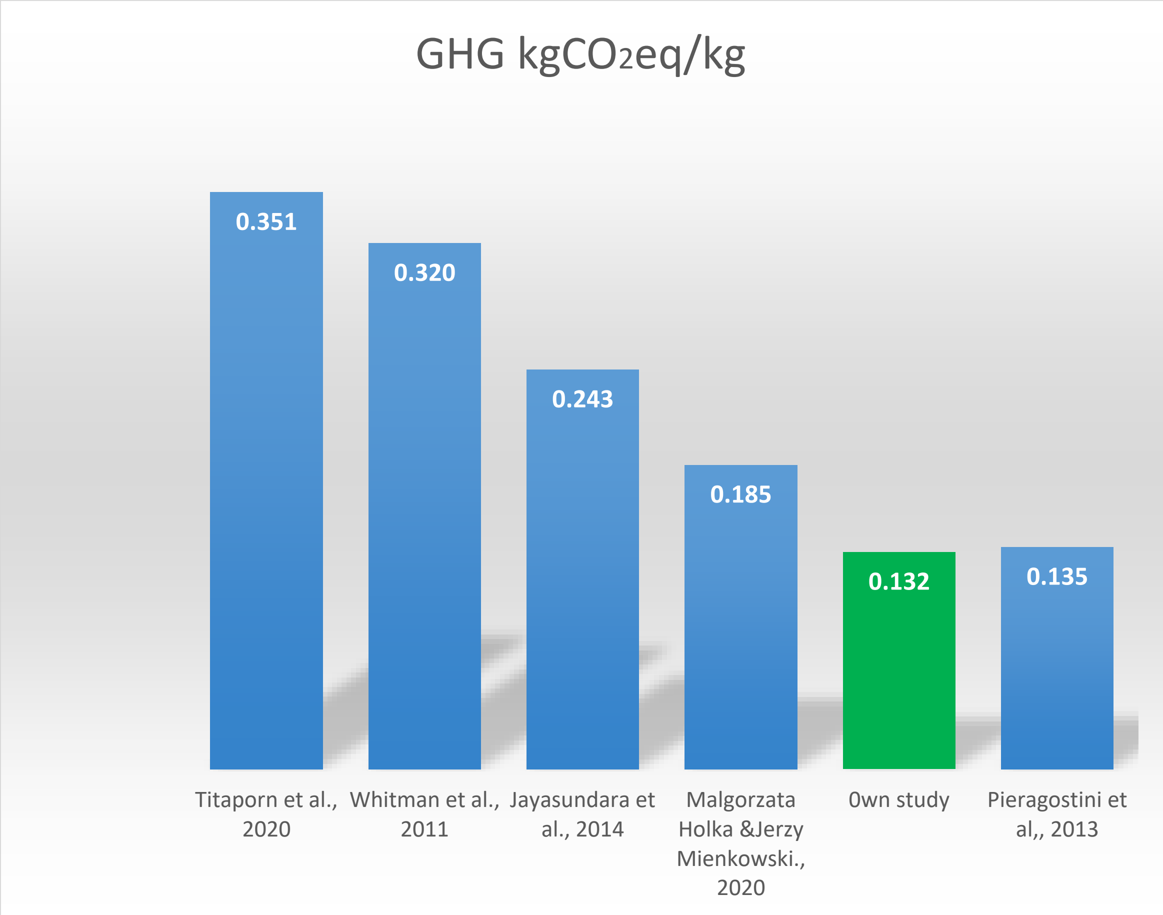

Figure 15. CO_2 comparative LCIA assessment for the production of 1 kg of maize silage in Alberta measured in GHG kgCO_2 eq/kg.

Further analysis show that the maize cultivation process has the highest GHG emission, as reflected in this study's result as well. For example, Adams P.W. et al., 2015 evaluated the GHG produced in the United Kingdom biogas facilities and found that cultivation activities for 4 different maize scenarios have higher emissions than the upgrading and other processes involved in getting the biogas. Whitman, T. et al., 2011 reports the total GHG impact of between 40-and 61%, which is caused mainly by the loss of soil organic content during cultivation in Quebec. At the same time, the nitrate emission is at 31% for the same paper. This research (own study) reports 0.132 kgCO_2 eq/kg as compared to 0.135 and 0.185 kgCO_2 eq/kg reported by Pieragostini, C. et al., 2013 which is the closest to our result and Małgorzata, and Jerzy Bieńkowski., 2020 respectively. Also, 1 ton of maize silage can possibly generate 650 m^3 of biogas, according to Filippa et al., 2020. In their study, the maize cultivation stage has the highest impact compared to other processes, and the majority (63%) of the impact comes from fertilization. While another impact originates from the drying and nutrients delivered to the environment during the cultivation stage.

Outlook: Alberta can have reduced CO_2 emissions by modeling this LCA result in eceosystem services model that shows the most impacted point explicitly, when this is done then drying can be during the summer period to reduce use of fossile gas too.

9.2 Maize production acidification & eutrophication impact categories analysis

For the acidification & eutrophication impacts literature comparison from the study simulation and comparative assessment, Fusi et al., 2016, appears to have the closest and most comparable value of 0,190 kg N eq/kg for the eutrophication potentials in the cultivation process. Other studies such as Pieragostini, C. et al., 2013 and Jayasundara et al., 2014 also compares well with this study's result at 0,260 & 0,130 kg N eq/kg, respectively. Note that Dressler et al, 2012 has the lowest eutrophication because they avioded atrazine components. Market (supply chain) for pesticides and other farm chemicals gathered from all the upstream and downstream activities are responsible for this study's eutrophication potential. On the other hand, the acidification impact category of this study's Eco-indicator result (0,184kgSO_2 eq/kg) has its major contribution from agricultural support activities such as drying, which emits sulfur dioxide, hydrogen chloride, nitrogen oxides, and some amounts of ammonia to an unspecified area in the air and to a high population density regions. The study's acidification result compares well with the harmonized acidification value of a recent paper by Jaroslav et al., 2021 and that of Jayasundara et al., 2014 at 0,205 & 0,151 kgSO_2 eq/kg, respectively, as evidenced below in Figure 16. Jayasundara et al., 2014 (151 kgSO_2 eq/kg of maize) despite being almost same location as own study still has .3kg lower to this study due to the 5 years research gap (more fertilizers may have been used now than in 2014).

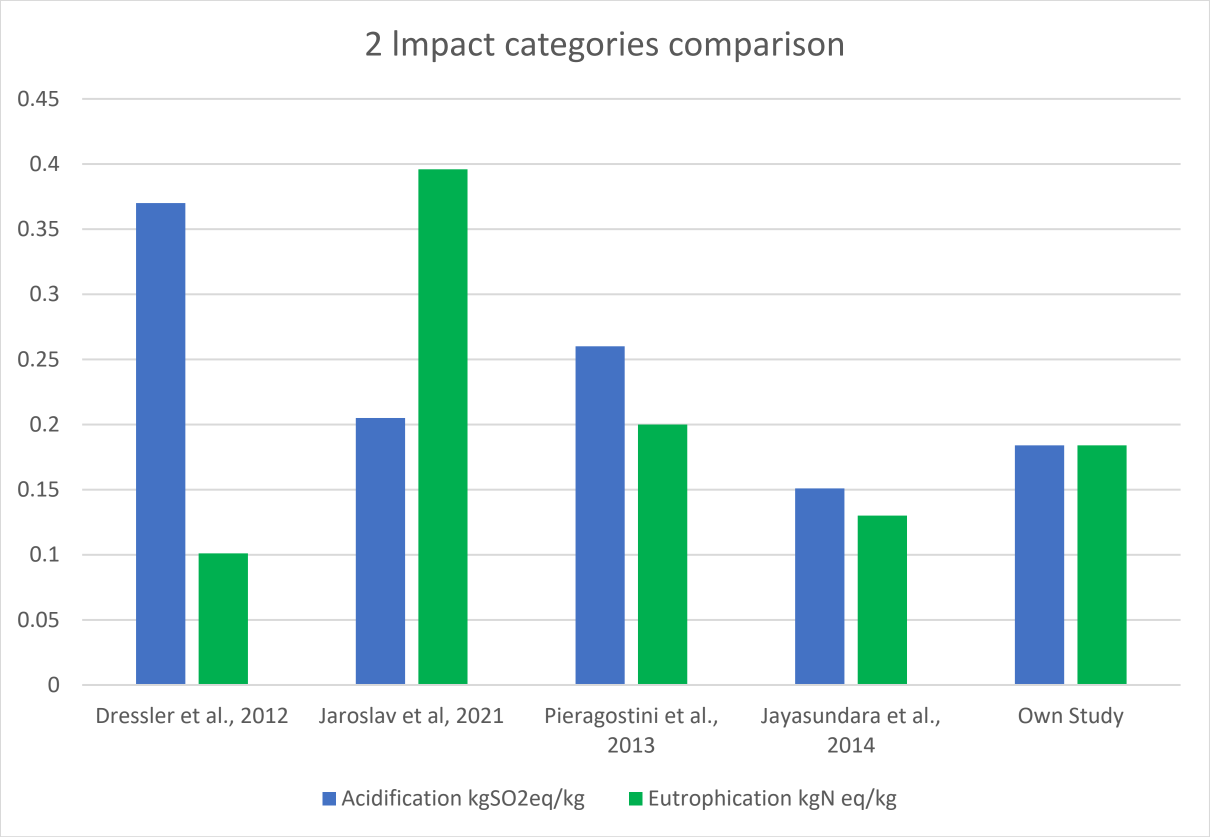

Figure 16. Maize production acidification and eutrophication impact category comparison with the harmonized literature data for example, (conversion of the FU from 1 ton to 1kg).

Outlook: How are water ecosystem services affected when producing biogas in Alberta compared to the literature in figure 16?

Pesticides and other farm chemicals production & use are responsible for this study's water eutrophication, which has damaging effect on water quality as an ecosystem service and aquatic lives generally. Eutrophication/acidification can reduce the services Albertans get from water ecosystem if neglected.

The differences from the compared literature value is due to varied locations, assumptions, and methods used, the closest result to our own result is an Ontario study for the acidification potential. Using an ecosystem services model such as InVEST will give more insights that helps to figure out more details in a spatially resolved form presented in a colour map (For more information on how to model this LCIA result in an ecosystem service model see the last section-11.3). And finding the most affected areas will help decision-makers proffer legal solutions that can protect this part of the ecosystem more from the others (for example, making it a law to use less atrazine in herbicides production and use as in Germany) and all the stakeholders including the farmers would be aware of this for implementation.

9.3 LCA stages impact category analysis between eutrophication, acidification & climate change

Comparing the impact categories within the life cycle stages helped to see which pathway contributes more to the environmental burdens of the process, flow, and project & product system under study. The inventory result indicates that eutrophication & acidification (0, 184) and climate change (1,181) potentials are high for maize production, followed by the anaerobic digestion activities at 0,981, and the conversion to heat and power has the most negligible values/impact in figure 17. While acidification arising from the anaerobic digestion stage is higher (at 0,628 $kgSO_2$ eq. /kg) than in maize cultivation and conversion process at 0,057 $kgSO_2$ eq. /kg of maize silage produced. The bulk of the climate change potential impacts are emissions from carbon dioxide fossil and methane from fossil production. The farm support activities especially the use of machines and electricity for drying icreased the climate impact including the transportation of goods to the farm gate. To reduce this negative impact from drying, a hybrid system is recommended to reduce the use of natural gas that is currently state of the art in Alberta, Canada.

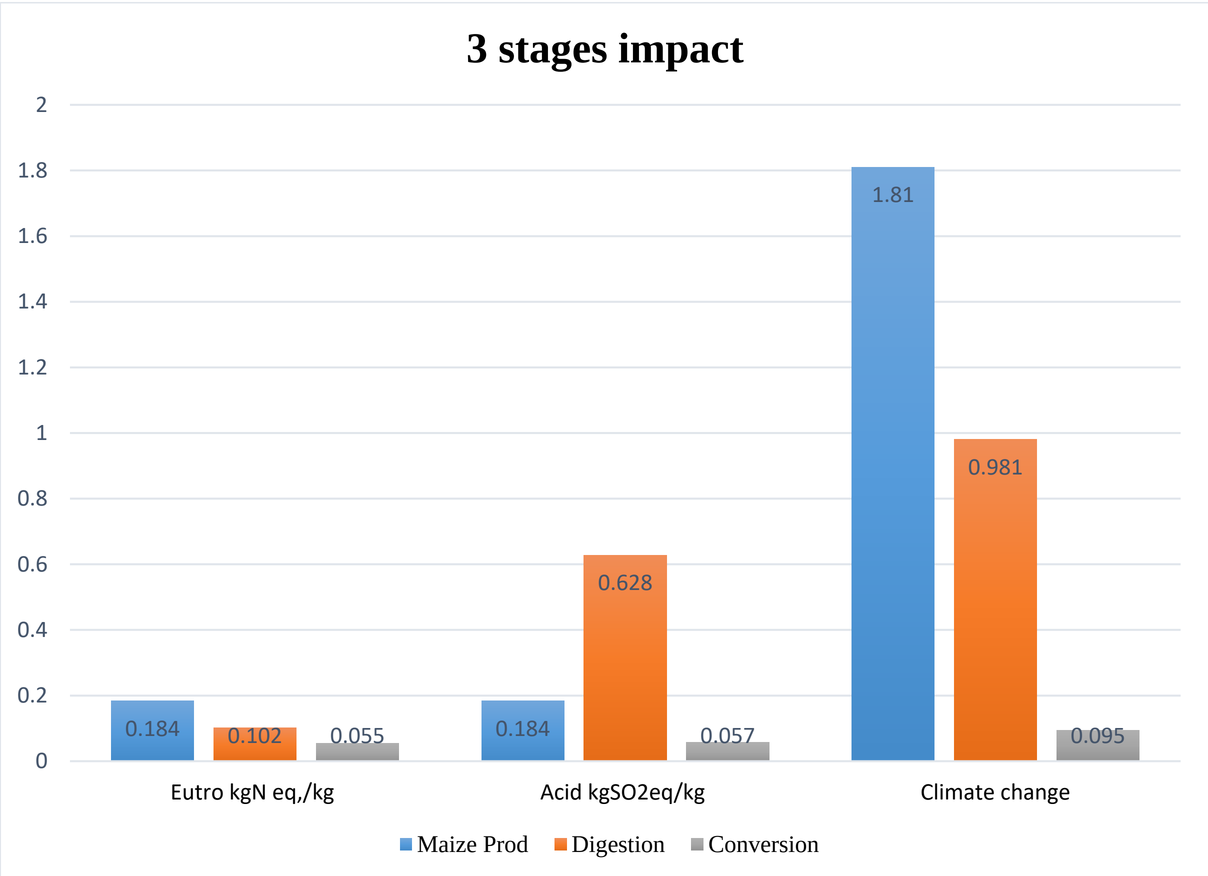

Figure 17. Comparison of the life cycle stages (maize production, digestion and conversion) impact categories assessment for acidification, eutrophication and climate change.

9.3.1 Comparing CO_2 and the climate change impact within the LCA stages

Maize silage production CO_2 emission value is 0,132 kg CO_2 eq/kg from the inventory results of the three assessment methods applied in this study (Eco-indicator, TRACI, and ReCipe). The second highest CO_2 after the digestion stage being the first is at 0,132 kg CO_2 eq/kg recorded from this study maize production stage considers the following inputs; clearing, tilling, sowing, weeding, harvesting, drying, and ensiling. At the same time, the climate change impact from cultivation is as high as 1, 81 milipoints (0,693kg) making it the highest potential impact in the biogas LCA three major stages but comparable with Filippa et al., 2020 who recorded 1, 52 mpts. Note that climate change impact is considered in all the supply chain involved in getting 1 kg of maize silage. The second-largest climate change impact is from the anaerobic digestion processes with a value of 1,17 kg CO_2 eq/kg, while the digestion stage has the highest CO_2 emission in this category at 0,981 kg CO_2 eq/kg when a kg of maize silage is digested. Conversely, the heat and power conversion process contributes little to the CO_2 and climate impacts. The result further shows that the climate impact arising from the digestion and conversion stages is lower than their CO_2 emissions value in, contrary to the maize cultivation stage. This is because CO_2 is only a single indicator contributor among many other emissions (e.g., sulfur dioxide & other flared gases) that has climate change potentiality when maize is used for biogas. Other emissions, such as emissions from methane leakages, still count to make up for the GHG emissions that can cause climate change. Further analysis on why the CO_2 for maize production is lower than that of digestion and conversion is stated in the digestion section (Note; anaerobic digestion plants construction and conversion site needs high heat, and its combustion activities emit a lot of CO_2). Although maize cultivation process generates lesser CO_2 in this study, its climate change potentiality is still higher when compared to other life cycle stages, figure 18.

The 1. 81 points recorded from the Eco-indicator´s maize production stage climate change show (0,693 kgCo_2 eq/kg) from the TRACI method using the same input data, and this 1. 81 points from our study compares well with Filippa et al., 2020 that reported 1, 52 millipoints from Eco-indicator assessment method also. Using same fomular above, climate change for digestion stage is converted from points to kgs as 0,981* 0, 38 is 0,376 and conversion stage at 0,009 * 0, 38 at 0,004 kg respectively.

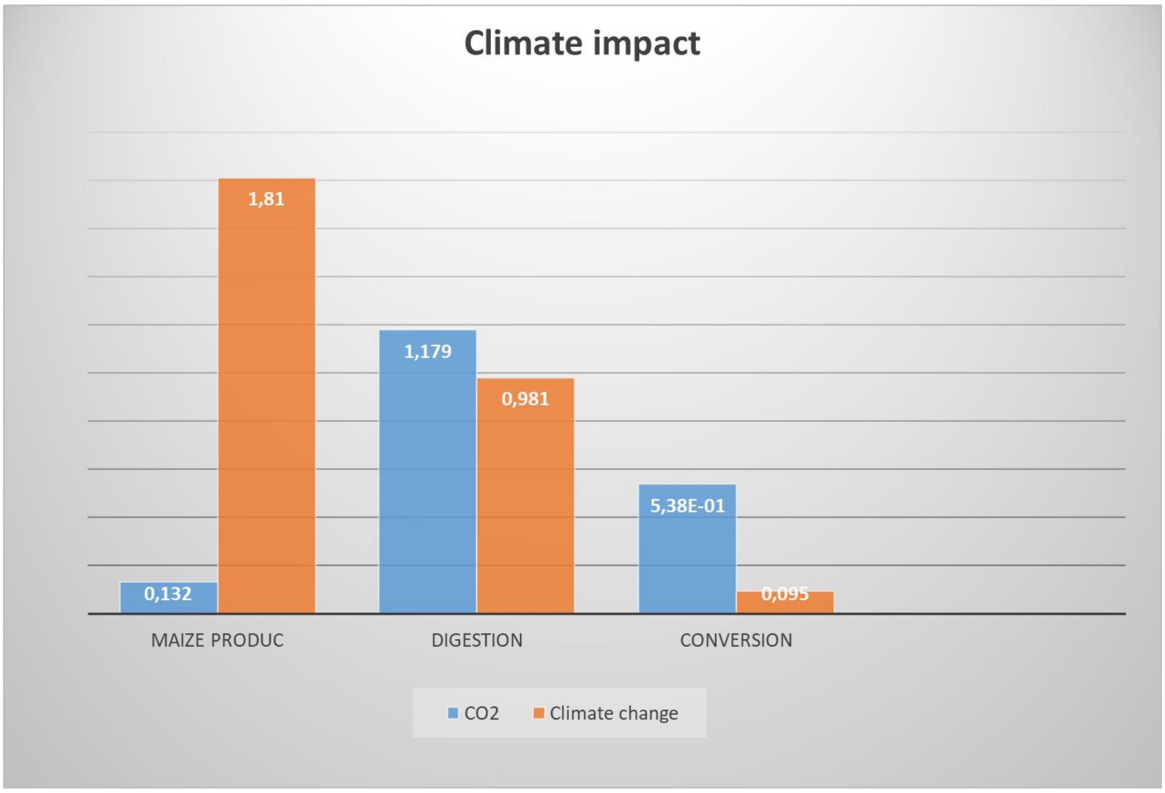

Figure 18. Contribution analysis of CO_2 in kgCO_2 eq/kg of maize silage produced and the climate change impacts across the LCA stages.

Outlook: In Alberta specifically, here is the peculiarity in impacts and why in relation to ecosystem services.

Co_2 emissions arising from the maize cultivation were contributed mainly from the drying process in Alberta. Electricity from natural gas is used for drying while other literature focusing on Germany sun dried their maize silage. This emission will reduce if the maize is dried in summer with a hybrid (biogas & natural gas) systems.

Climate change impact from cultivation is as high as 0,693 kgCo_2 eq/kg of maize silage produced from TRACI method & 1, 81 milipoints from Eco-indicator making it the highest impact in the biogas pathway and comparable with Filippa et al., 2020 who recorded 1, 52 mpts (no drying). 0,132 kg CO_2 eq/kg is recorded from the cultivation stage in this study because, CO_2 is only a single indicator contributor among many other emissions (e.g., sulfur dioxide & other flared gases) that has climate change potentiality. Further assessment on why the CO_2 for maize production is lower than that of digestion and conversion shows anaerobic digestion plants construction and conversion needs high heating system, and its combustion activities emit a lot of CO_2

9.4 Flow analysis (Nitrates, atrazine, ammonia) for maize cultivation compared to other life cycle stages

For the selected flow categories (nitrate, ammonia and atrazine), the most significant contributors during the cultivation stage have been seen to be nitrates 0,117, ammonia 0,018, and atrazine 0,028kg/kg of maize silage produced. This result from the cultivation process alone has been compared with other LCA stages (i.e., digestion and conversion processes), as depicted in figure 19. The emissions from nitrate 0,117kg/kg is the highest flow category coming more from drying and farm nutrients or chemicals production and use as represented in appendix j. Also, atrazine, the second-highest from maize, arises from the production and farm application of herbicides and has a negative impact on water. Ammonia output is from all the agricultural activities such as machine use that releases emission into the air or water unspecified area with nitrate still leading other impacts from the maize production stage. Note that the major pollutant released to the environment from the farm chemicals and drying process are nitrogen oxides and sulfur dioxides. In this flows analysis across the life cycle pathways, the digestion process ammonia emission is significant compared to other stages. Because the model accounted for any impact, the digestate output (slurry) may cause in the future when used as manure and digestate leakage from the digestion plant into the environment, which has high eutrophication potential. Therefore, the lowest impact in this LCA stage flows analysis comes from the digestion & conversion stages atrazine emission, as shown in figure 19. Atrazine content is not directly needed in the other life cycle pathways except for the maize cultivation stage; hence, it is justifiable that atrazine impact is insignificant for conversion and digestion stages.

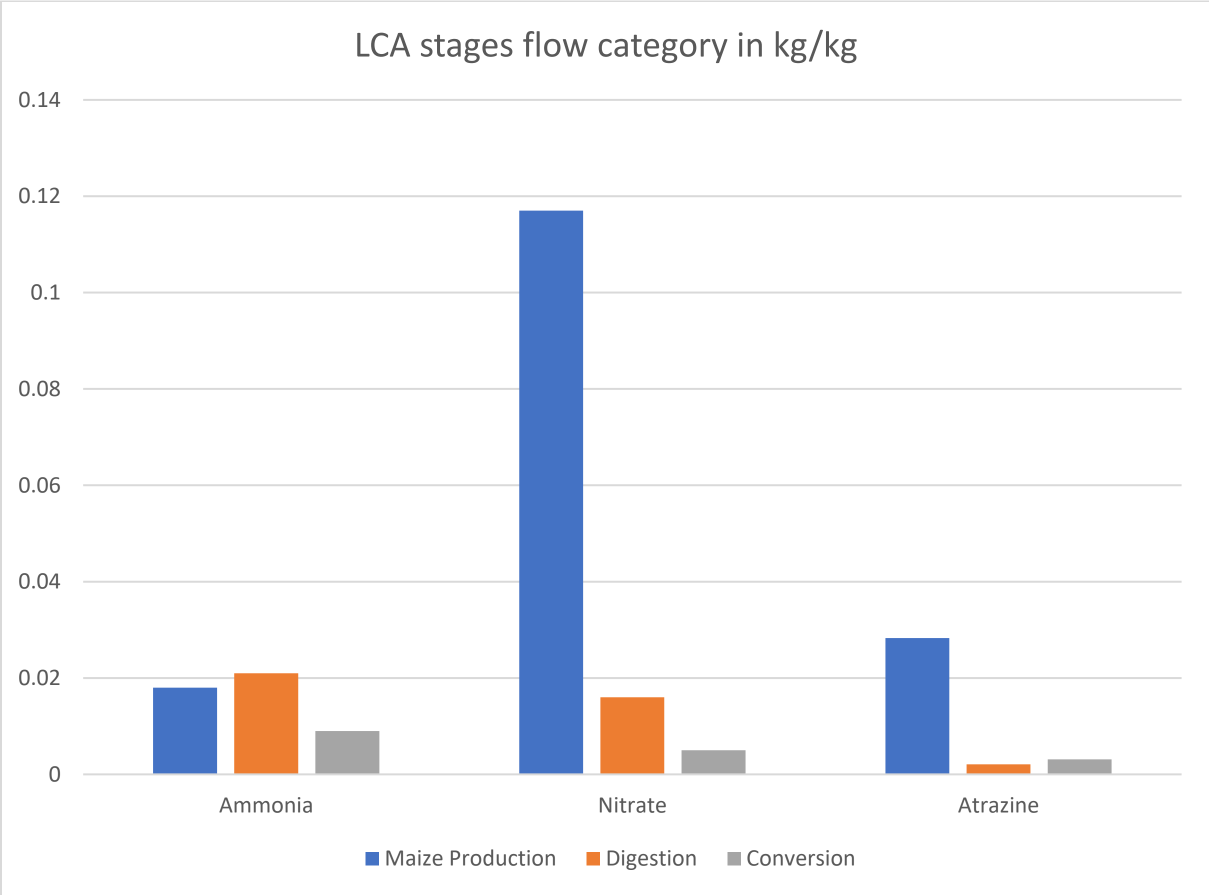

Figure 19. Flow category analysis for the production of maize compared with other LCA stages (digestion and conversion LCA stages) in kg/kg of maize silage produced

Outlook: The emissions from nitrate 0,117kg/kg is the highest flow category coming more from drying and farm nutrients or chemicals production and use as represented in figure 19, appendix j. Ammonia output recorded from all the agricultural activities such as the use of agro machine that releases emission into the air or water. The digestion process ammonia emission is significant compared to other stages, because the model accounted for any impact the digestate output (slurry) may have in the future when used as manure or digestate leakage from the digestion plant into water, which has high eutrophication potential. This can be avoided by siting the anaerobic plant far from any water body.

9.4.1 Literature comparison with this study's flow categories

The flow categories nitrate, ammonia, and atrazine results is compared with the literature flows to gain more confidence and for validation purposes using a few studies such as Dressler et al., 2012 whose ammonia value is higher than this study due to the use of digestate as farm manure in their research which now added more nutrient to the water. However, they avoided atrazine components that some countries still use to produce farm protective chemicals. The nitrate emission from Whiteman et al., 2014 and Jaroslav et al., 2020 compares well with this study. Titaporn et al., 2020 also report a similar ammonia value as this research, as seen in figure 20. However, Atrazine which is still in use in Canada has the lowest score across the board but it is already banned in some countries such as Germany to reduce its eutrophication potential in water ecosystems. Additionally, our nitrate is at 0,117kg/kg of maize silage produced, which is comparable to Jaroslave et al., 2020, who recorded 0,112kg/kg, while Whitmann et al ., 2014 is 0,083 after the conversion from tons to kg.

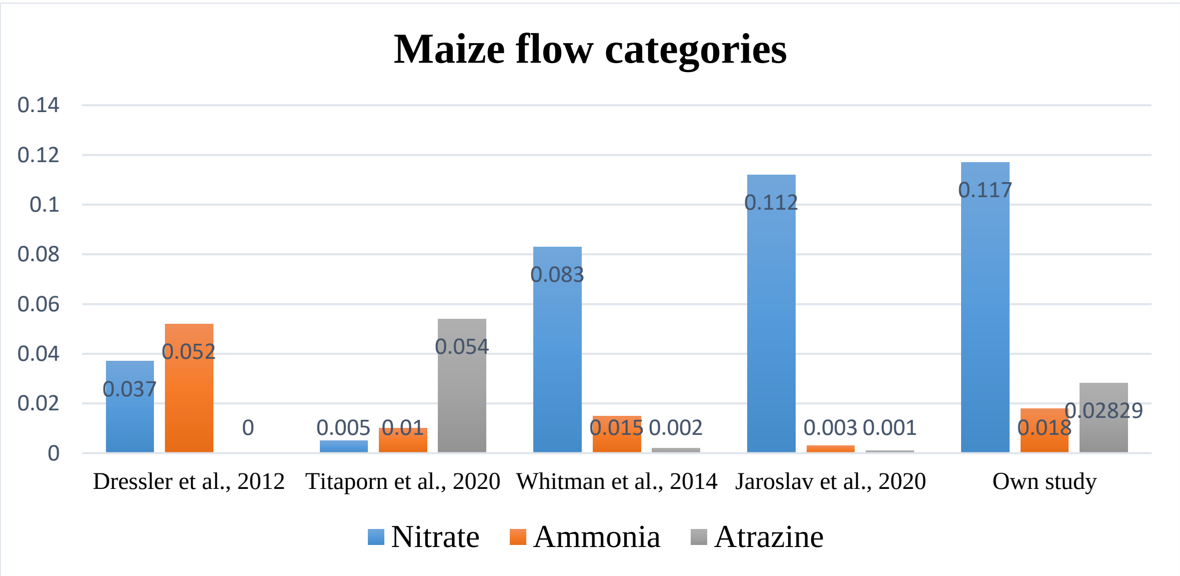

Figure 20. Literature comparison for the studied flow categories (nitrate, ammonia and atrazine), with own studies nitrates looking similar to Jaroslav et al., 2020.

Outlook: Dressler et al., 2012 has 0 atrazine due to its ban in Germany for the use of farm protective chemicals.

This study´s significant nitrate emission is due to high use of farm chemicals in Alberta where atrazine is still in use.

9.5 Comparing the full system's acidification, eutrophication & GHG impact categories with the natural gas one

The analysis shows that the entire biogas system or three LCA stages (maize production, digestion, and conversion stages) has more eutrophication potentials with less acidification and GHG which is an agent of global warming. This is because fertilizer which is an agent of eutrophication is not needed for natural gas processing. As expected, natural gas production and processing have more greenhouse gas emissions from methane compared to when maize is cultivated, digested, and converted into heat and electricity. There is more sulfuric acids emission that can lead to acidification compared to nitrates emission in the natural gas production pathway, and that justifies why natural gas production has almost no eutrophication potential impact. However, it has higher GHG and acids in the air, figure 21.

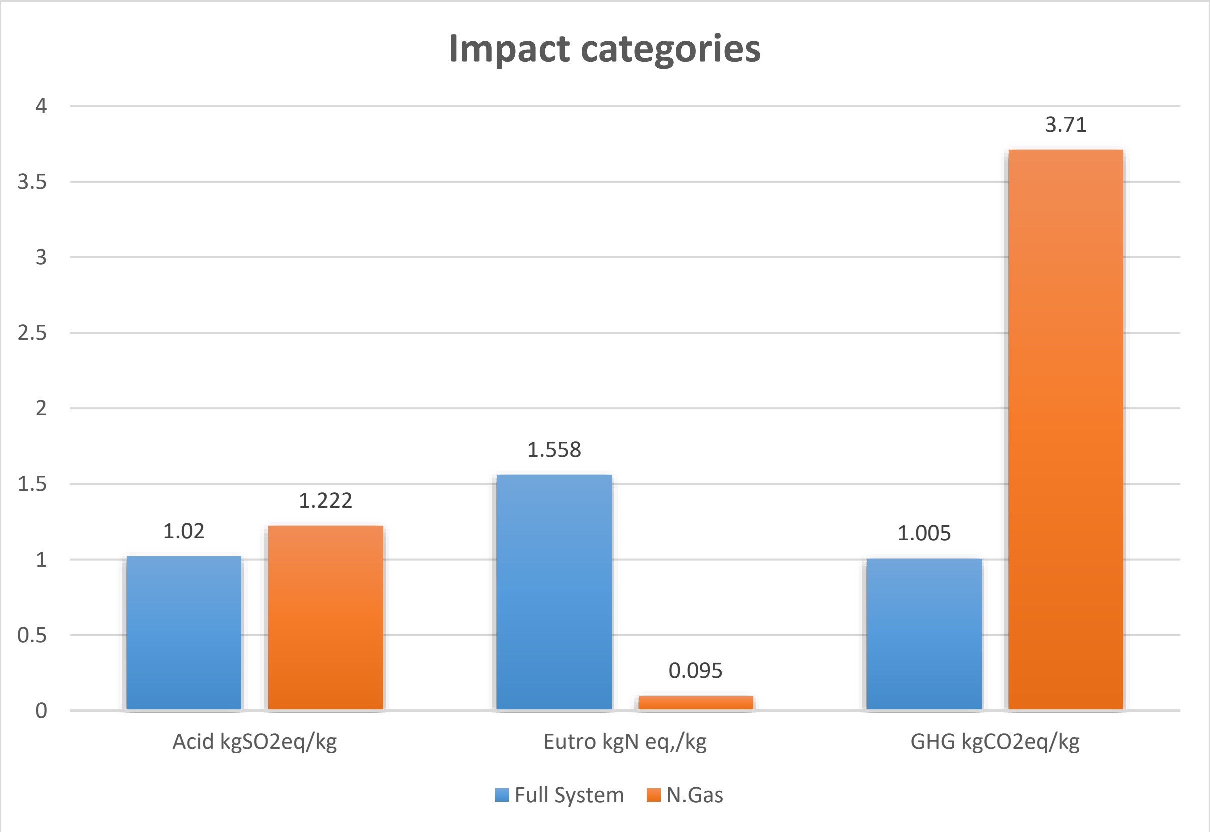

Figure 21. Impact categories comparison between the full system (biogas pathway) and the natural gas production and processing

9.5.1 Flow categories contribution analysis for the full system compared to natural gas

The production of natural gas has little or no significant impact on the flow categories analysis compared to the biogas full system for nitrate, ammonia, and atrazine. This is explainable owing to the fact that fertilizers and other farm chemicals are not needed in the natural gas processes evidenced in figure 22. These chemicals' production and application are the main contributors to the emission understudy, and they are more significant for consideration during the cultivation stage.

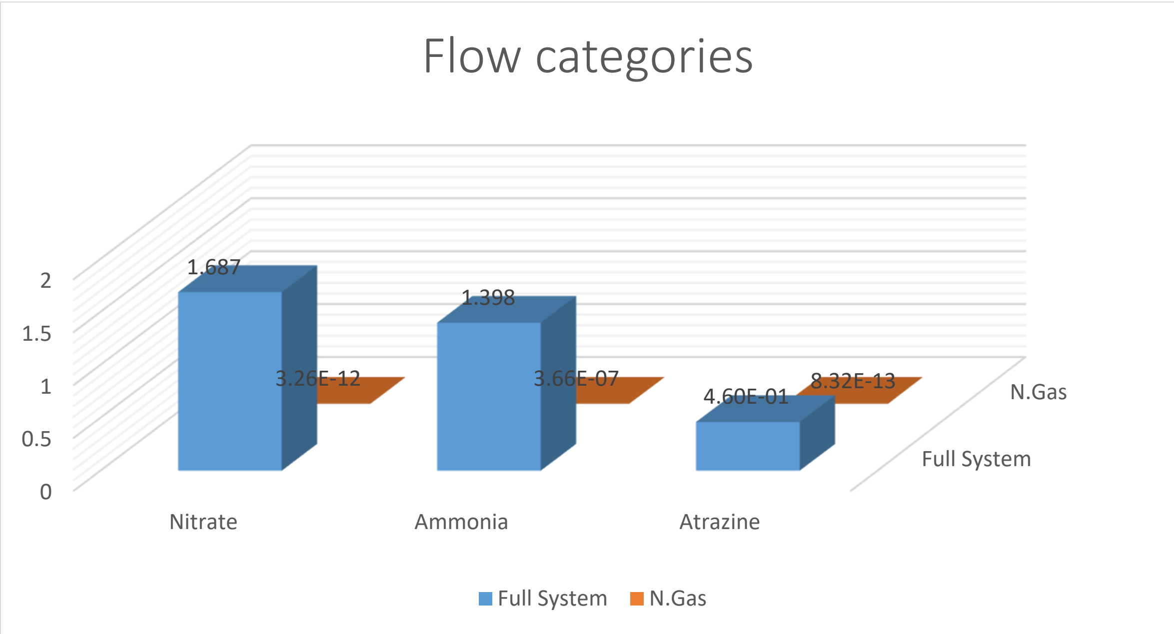

Figure 22. Comparing the biogas pathway nitrate, ammonia and atrazine emissions (flows category) with that of natural gas production.

9.5.2 Comparing natural gas production against the LCA stages impact categories, GWP and climate change, eutrophication/acidification.

The study observed that eutrophication has the lowest impact on natural gas production, followed by the acidification impacts because only the cultivation process has significant eutrophication potential compared to other biogas pathways and natural gas too. Recall that nitrate is also low for the natural gas impact in figure 22, compared to the three LCA stages. Conversely, the global warming potential (GWP) is significant across the pathways, which is an agent of climate change and automatically increases the climate potential for both the biogas and natural gas processes. Natural gas production has the most significant climate change potential, followed by the maize cultivation phase in this study. While, the maize production stage has the lowest GWP, followed by conversion & digestion stage processes, as the natural gas production has the highest GWP & climate impact, evidenced in figure 23 below. The comparison of biogas impacts with their fossil fuel counterpart is observed in a recent study (Jan Lask et al., 2020), where the fossil reference scored higher in the GWP than in this study. They also observed the same pattern in Wagner et al., 2019 and Kiesel et al., 2017. This an indication that fossile fuel still has more impacts than biogas in general, despite the eutrophication impacts biogas has recorded, this makes biogas a better option.

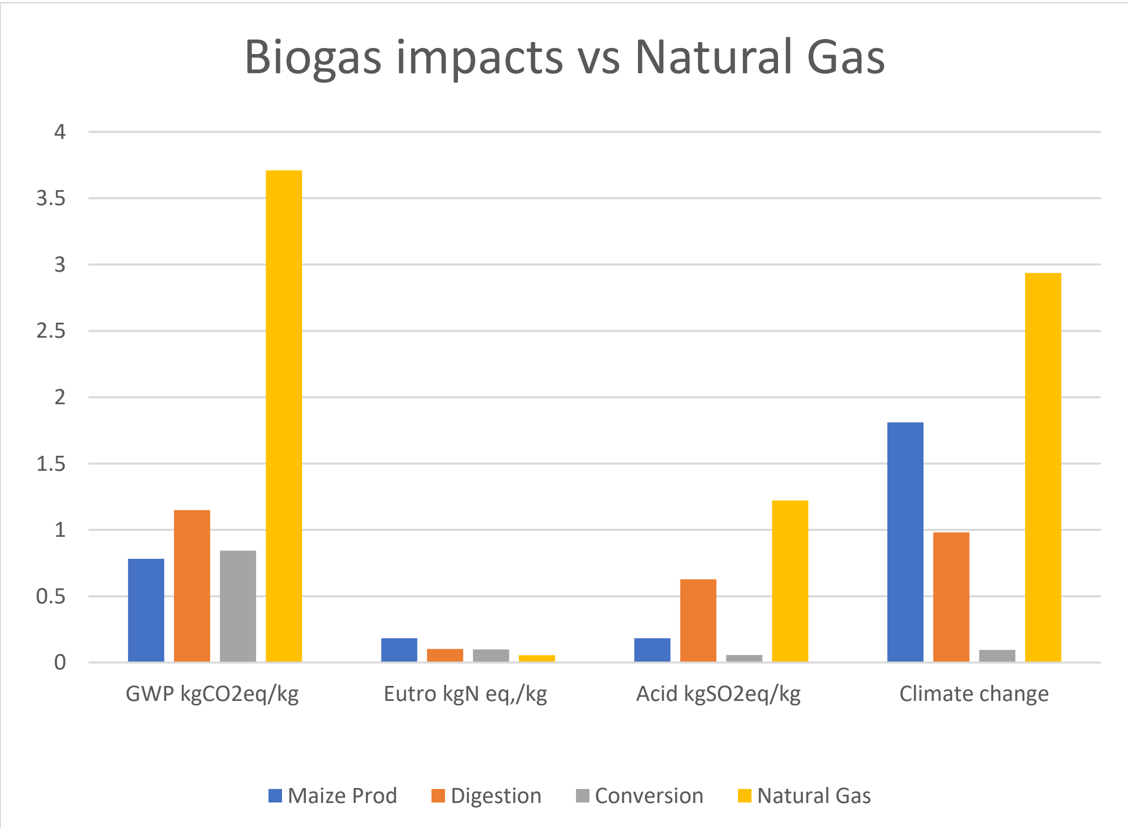

Figure 23. Impacts category analysis of the LCA stages (biogas pathway) compared to the natural gas processes.

Outlook: How are the land, air and water ecosystems affected when switching from Natural gas to biogas in Alberta?

Natural gas has more impacts on GWP, acidification and climate change with lesser impact on eutrophication potentials as seen in figure 23. Natural gas production has the most significant climate change potential, followed by the maize cultivation phase in this study. While, the maize production stage has the lowest GWP, followed by conversion & digestion processes. In general, there will be a shift in impacts as air emissions will reduce while water pollution through euthrophication will increase. However, with the moderate use of farm chemicals (e.g 120kg of N fertilizer per hectare), there will be a balance between biogas production and environmental protection.

Other impact contributors, such as emissions from methane gas leakages, still count to make up for the GHG emissions that causes high climate change impact and other acidification processes that affects the ecosystem services.

9.6 Land occupation and transformation analysis

Due to complication and lack of data, many studies do not consider land-use change when assessing the environmental impacts of maize production in LCA, Changqi Liu, et al., 2018. However, this study finds it very important as land occupation, transformation and conversion have their own associated challenges that can negate the positivity in bioenergy production and the whole energy transition goal (González-García, S. et al., 2013). This study's initial result from the Eco-indicator and ReCiPe assessment methods for the land occupation impact category indicates 0,124 & 0,186 milipoints, respectively, while the third assessment method used (TRACI) does not account for a land-use impact category. The above result corresponds well with Filippa et al., 2020, whose total single-year land-use impact from maize cultivation scored 0,155 milipoints. The percentage contribution shows that the sowing stage, tiling, and harvesting have the highest scores for both methods (Eco-indicator and ReCiPe) at 57% and 78%. This study's initial model run assumes the average of 68% for the land occupation impact category, which is in line with other studies such as Pieragostini C. et al., 2014 whose impact from corn seed production contributed 67% to the land use category, which is attributed to conventional tillage. Figure 24 depicts the land use percentage contribution of maize production and the impact from other life cycle stages (cultivation, digestion and conversion) compared to the natural gas production land transformation and occupation. The production of maize is also the most relevant process among other stages here when analyzing land-use change impact; this research adopted about (0,124 points) or 68% out of 100% land use impact for the maize production stage as in other studies. While, the digestion scored 18% (0,019), and conversion is at 14% (0,015), using the following conversion formular 68 of 0,155 is 0.68 multiply by

0,155 = 0, 1054, 18 of 0,019 is 0, 18 multiply by 0, 1054 = 0,019 and 14 of 0,015 is 0, 14 multiply 0, 1054 = 0,015. To reduce or evade the competition between food and energy as noted in literature such as (Filipa et al., 2020; Mehmood, M.A., et al., 2017 and Carlsson, G., et al 2017), scholars concluded that it is better to grow maize on abandoned land that is degraded. Which has the potential to reduce carbon debt and loss of biodiversity's that results from the direct clearing of farmlands on a long-term basis, as in González-García, S. et al., 2013. Another school of thoughts also noted that the arable land occupation for maize cultivation is responsible for the 94% contribution of the land competition; according to Jan Lask et al., 2020, intensification of land already in use has 65% as land transformed from other uses into cropland is at 34%. Malgorzata Holka et al., 2017 analyzed land use for maize production in Poland and other EU countries. They reported land-use indicators as 0,141 and 0,146 ha t per annum for the country (Poland) and the continent of Europe, respectively. Another researcher reported land use and climate change result as having a 100% impact on the environment and added that because the category results are expressed in different units, their results cannot be compared with each other. This 100% is the highest result in a given benchmark category, Chłopek, z., & Samson-bręk, I. (2017). While, Vera, I et al., 2022 metioned that using land to produce dedicated energy crops increases food price but difficult to determine all other impacts both on food supply and land-use.

The average percentage gotten from the ReCiPe and the Eco-indicator methods is compared with the digestion and conversion life cycle stages and also with the natural gas production land occupation to test the sensitivity of each stage in a different model run with varied input values in appendix d.

Additionally, understanding the use of land for crops is very vital as the population growth and increased demand for energy come with an inevitable need for more land occupation and transformation. The land-use change analysis comprises the environmental impacts of reshaping, occupying, transforming, and management of land that lead to it deterioration and degradation from its original naturalness. For the above reason, land use is at the heart of a few scholars focusing on energy crops for biogas systems, Hijazi. O. et al., 2016 and Hartman, 2006, as it is in this case study too.

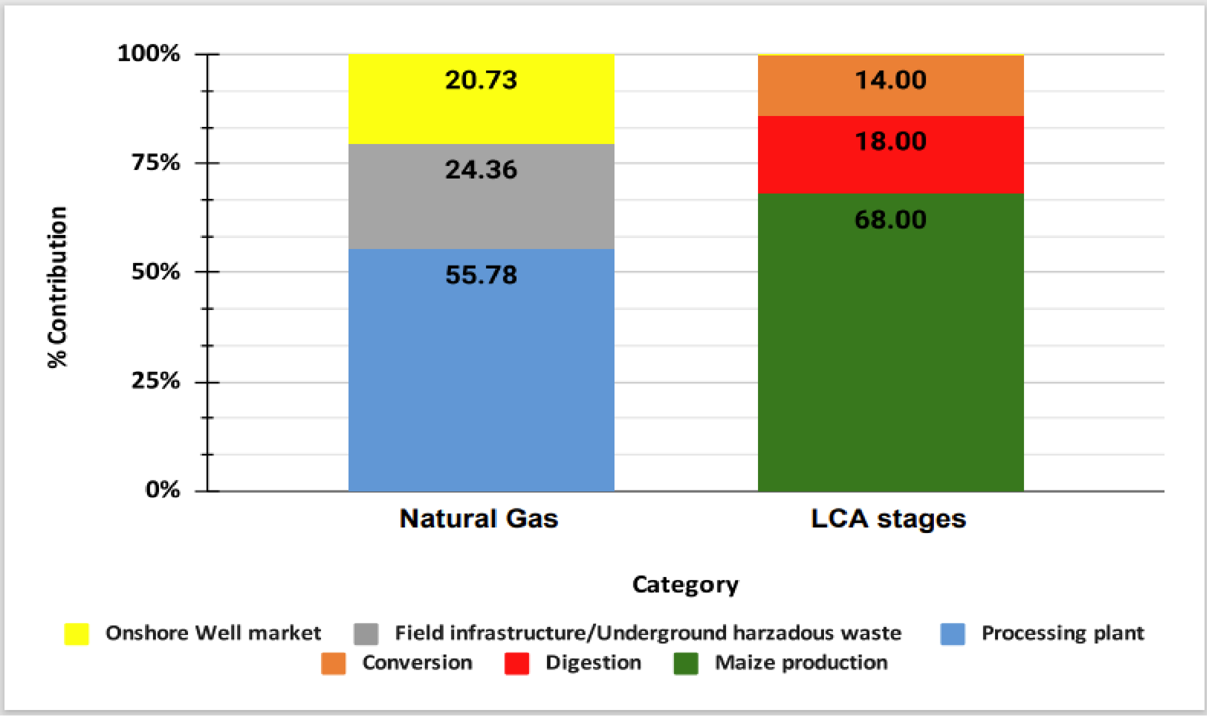

Figure 24. Land use percentage contributions for maize production, digestion and conversion compared with the natural gas processes.

Outlook: Figure 24 depicts the land use percentage contribution of the biogas pathways compared to the natural gas production land transformation and occupation. Cultivation stage recorded 68% or 0,124-0,186 milipoints averaged to (0,155) mpts, digestion 18% (0.019), and conversion at 14% (0,015). To safeguade Alberta land ecosystem and its services, and to reduce competition between food and energy systems, decision makers and stakeholders should encourage reusing already used land for cultivation. When this is done then the land use impact would reduce by half when switched to biogas/biofuel.

The digestion and conversion stages for the land occupation impacts are lesser than that of maize cultivation, as seen from figure 24 above, because, at this stage, the land is mostly used for building of sheds and the digestion/conversion plant construction, which is not land intensive. Also, the natural gas exploitation process and building of the gas production plant (for sweetening and purification) after the exploration activities or (seismic operations) on the ground needs land surface but not as much as maize cultivation do. Initial land use analysis with different input data (sensitivity) is shown in appendix k. Table 8 depicts land use percentage contribution in percentage for the biogas pathway and natural gas.

Table 8. Shows land use percentage contributions for maize production, digestion and conversion compared with the natural gas processes.

LCA stages	% contribution		Natural Gas	% contribution
Maize production	68		Processing plant	55,78
Digestion	18		Field infrastructure/Underground hazardous waste treatment	24,36
Conversion	14		onshore Well market	20,73

9.7 Comparing all the 11 Eco-indicator impact categories for the production of maize

In general, this is an overview of all the 11 impact categories using the Eco-indicator method of the openlca reports, though this study scope is focusing on the three categories necessary for biogas pathways. It is interesting to know that the fossil fuels category has the most significant impact for this stage in figure 25, followed by respiratory effects with climate change and carcinogenic effects looking similar. While the ionization effect appears to be the most minor impact here, land occupation under the ecosystem quality impact is also minute at 0,124 milipoints or 68% as stated in the percentage contribution in figure 24 above. This is expected considering Albertan's huge land mass. This result also shows that Eco-toxicity is high compared to eutrophication and acidification for the ecosystem impacts. While carcinogenic effect is significant for the health impact, which means apart from the fact that the climate is changing, there is a risk of increased number of lung cancer or other respiratory sickness patients in the hospitals, which needs to be considered when making a decision for energy transition in Canada. That said, impact from fossil fuels emission still scores (10, 163 milipoints) the highest as expected in Alberta and 0,005 mpts the lowest from the ionizing radiation.

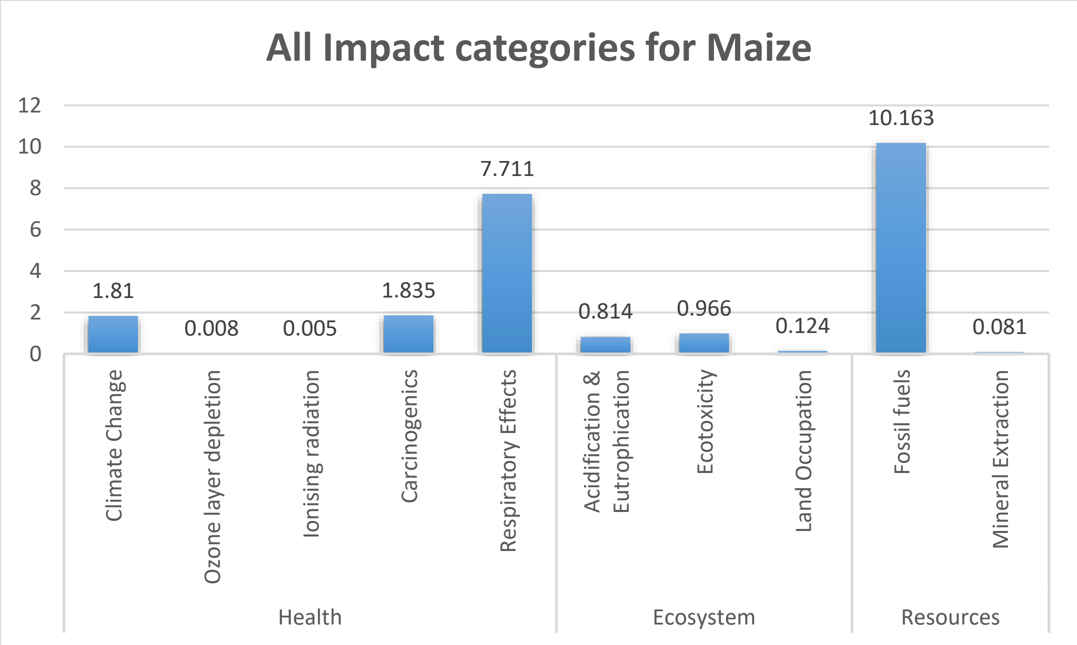

Figure 25. All impact categories analysis (Ecosystem, Health and Resources) from Eco-indicator method

9.8 Maize silage production sensitivity analysis & comparison

It is not surprising to encounter some uncertainties while presenting the analysis of an energy and environmental systems assessment, especially from the LCIA; the reason for this is because there are several ways of modeling or mimicking reality, as revealed in Goedkoop et al., 2008. Moreover, there are many assumptions, subjective choices, and opinions affecting the end results, such as location, functional units, system boundaries, etc., that can significantly impact and influence the outcome. In this study, vital parameters were changed, simulated, and remodeled to see their effect on key assumptions, which fulfilled the sensitivity analysis requirement. For this study's sensitivity analysis, the input data were manipulated following the eco invent data and tons of reviewed literature with different functional units, boundaries, time of data collections, and publications, including varied geographical locations. The result below shows that our model simulations with different runs followed by different assessment methods and different input values work well.

Starting from the more impactful to the less impactful flow category contribution for the life cycle impact assessment methods, the Co_2 emission from the flow contribution tree is at 66.1% generated from all the supply chains involved in getting out the 1kg of maize silage and transporting it to the anaerobic digestion plant gate. Appendix e shows the model platform with the title (2021_Maize silage production2) used for this sensitivity simulation and analysis, while the model graph generated directly from the openlca tool is seen in appendix j.

The impact category from the contribution tree result shows the mineral extraction category as the highest in the maize silage production stage with a percentage of 91.9%, mostly from natural resources acquisition and other precious minerals mining associated with the supply chain of maize production. Fossil fuels impact follows this extraction with 83.9% (0.83%) of the overall environmental impacts recorded for maize silage production as against 46.6% reported in Filippa et al., 2020. The high values from extraction and fossil is expected because Canada is an oil-rich country with a lot of oil exploration and exploitation activities going on in the boreal forest of the province of Alberta, according to Hebblewhite, Mark 2017. This drilling process affects biodiversity and poses a threat to endangered species.

This sensitivity analysis considered the health impacts from the respiratory effect at 79.4% under maize out of the general impact. At the same time, the climate change impact stands at 75.7% (0.75.7%), which can be attributed to Canada being a high Co_2 and other greenhouse gas emitter. Conversely, a study concluded in Italy shows that the climate change impact category scored 0.94% from the production and the use of fertilizer at 61 percent, Filippa et al., 2020. Additionally, the impact on ecosystem services based on the eutrophication/acidification category is 76.6%. When fertilizers and plant protective chemicals are used on the farm, the nutrient easily washes down to the nearby river and causes an accumulation of substances that suffocates or kill aquatic creatures, as reported in Pal, Nandini, 2020. The conversion, transformation, and occupation of the land ecosystem have 33.3% of the overall impact of this process. This lesser value for land occupation is understandable considering that Canada has a large landmass that may not have very significant or adverse effects when more maize is planted. However small the impact on the environment appears to be, it worth having a close look at before sitting energy projects. In this analysis of sensitivity, mineral extraction, fossil fuel impacts scored highest, followed by drying, manufacturing of pesticides, fertilizer, and other agrochemical products is the highest input contributor in the supply chain, as well as the the support activities to agriculture and post-harvest events involved in the maize cultivation processes. Figure 26 indicates the impact categories result from sensitivity (when the input numbers are manipulated or changed) in percentages on H.E.R.

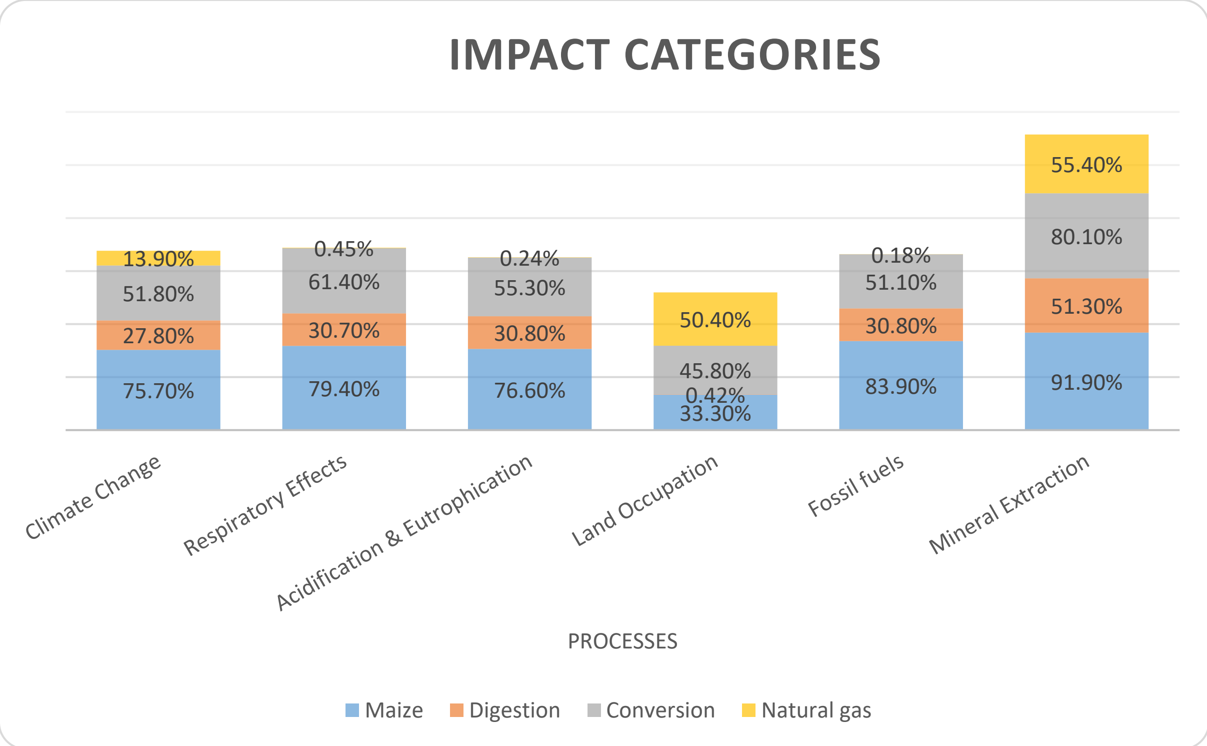

Figure 26. The sensitivity analysis of the LCA stages impact categories in comparison with the natural gas

Additionally, another simulation was carried out with smaller inputs. The focus here is on land occupation at 0.3, eutrophication/acidification with 4.5 eco points, the respiratory effect at 44.9, climate change at 8.2, mineral extraction at 1.9, and last but not least is the fossil fuel with 74.8 eco points being the highest for this run. From this maize silage production eco point's result, the land occupation has the most minor point in the province and country at large, which the large land area could explain. Since Canada is a nation with abundant land resources, it will not cause significant environmental damage to cultivating maize, building digesting, and conversion plants in the near future. On the other hand, fossil fuel has the second-highest impact from maize silage production section because of all the environmental degradation involved in extracting the fuels used for farm machines, transportation, agrochemicals production, etc. as Alberta, the second study area, is a major producer, and there is always a direct environmental impact on the immediate ecosystem.

In analyzing the total emission going into the environment from the production of maize silage, some of the impactful elements have been investigated. As an interpretation recommended by Curran, 2012, if 100% represented by (180kg) of nitrogen fertilizer has been used to produce 1kg of maize silage, it means that 95.9% of that nutrient is washed down to the nearby surface water. Nitrogen or nitrate emission is an essential element in this study since the use of fertilizers and plant protective chemicals are inevitable for maize cultivation, and its contribution stands at 95.9% emissions to the environment. This means that only about 5% of the applied chemicals (fertilizer and herbicide were used up by the plant, the remaining 95% ended up in the environment. Atrazine has 99.95%, and Ammonium ion emission to an unspecified area in water is at 98.31% when the input value for farm chemicals is high. Many LCA studies, such as Fusi et al., 2016 do not consider land emissions due to lack of data and because the maize is grown on land already dedicated for feedstock production. However, studies such as Carlsson, G. et al., 2017 considered the impact on land and land-use change, occupation, and transformation as this current study did in figure 27.

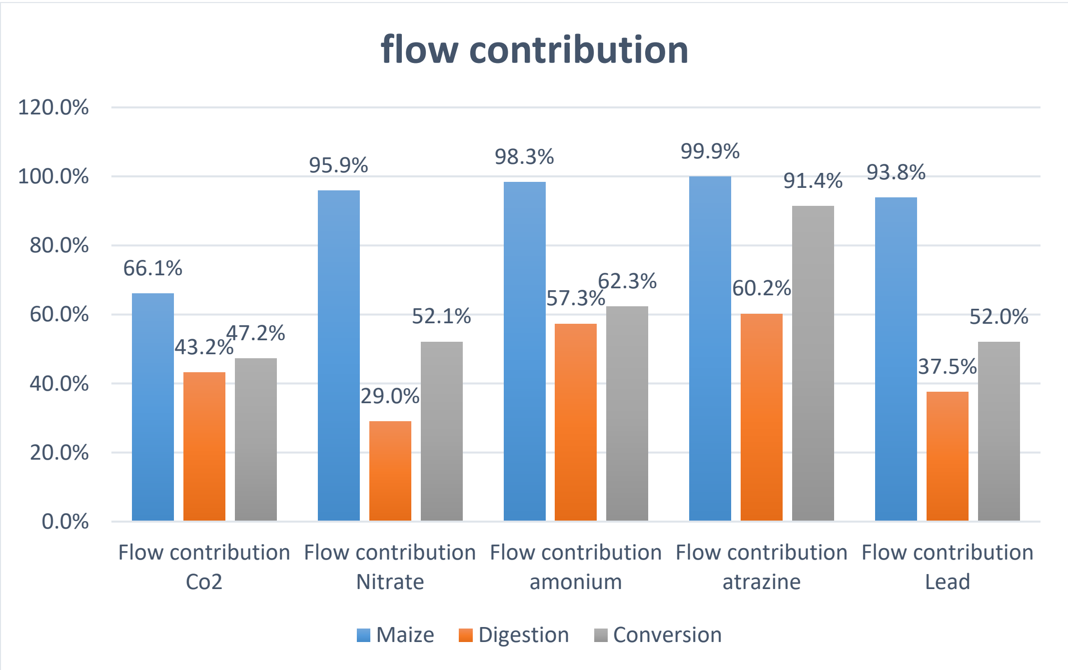

Figure 27. Percentage flow contribution of the LCA stages from the sensitivity analysis.

Note that most of the sensitivity analysis for maize production are carried out in this study to test the model robustness and accuracy when input values are manipulated as found in the appendix f.

9.8.1 Digestion process sensitivity analysis

For the anaerobic digestion process, CO_2 emission to the air contributes 43.2% of the total examined emission, arising primarily from the market for concrete and from the supply chain of used steel during the plant construction phase. Also, from the reinforcing steel production, the market for glued laminated timber, synthetic rubber production, and aluminum alloy starts with the arrival of aluminum input and other additives, which are preheated, at the induction furnace. From the cradle, that means including all downstream and upstream activities. This activity ends with the casting in ingot by direct chilled vertical casting and cooling. The dataset includes material and energy-related to the alloy production and casting: scrap and primary metal input, preheating, induction melting, alloying, degassing, water use, and ingot casting).

For the digestion processes under the resources impact category, mineral extraction has the highest impact of about 51.3%, emanating from reinforcing steel production, metallic matrix composite, concretes, and laminated timber. However, its fossil fuels counterpart is at 30.8%. The second-largest impact for this digestion is the eutrophication/acidification under the ecosystem category standing at 30.8%. While land occupation seemed really small at -04.2%, the land needed for the anaerobic digestion plant construction is not significant compared to land needed for the cultivation and mineral extraction considering Canada's colossal landmass. The health impact category saw respiratory effect at 30.7%, which is understandable as there will be some dust particles flying around the construction site, and finally, the climate change impact that may arise from emissions while construction and operating the plant contributes 27.8% of the total impact. The data used here represents the aluminum alloy, metallic matrix composite manufacturing process. More dataset descriptions and representations are found in appendix g.

9.8.2 Conversion (CHP) stage sensitivity analysis

The combined heat and power stage sensitivity result from the contribution tree reports that the carbon dioxide emission from fossil to air (unspecified area) amounts to 47.2% in the conversion (cogeneration) process of this LCIA project. The main contributors are the facility's building, the heating processes, the concrete production, and the steel production process. The most needed materials used for the building of this cogeneration heat and power facility include chromium steel, copper, electronic components, plastics, insulation, and fluid. The dataset also consists of the energy required for the construction and the disposal of the device. The unit includes an electricity generator, a compressor, a condenser, tubes, and pipes for thermal oil distribution within the cycle. The boiler is connected to a biomass burning boiler with 5000kWth capacity that produces about 1000kWel. It starts with the reception of all components at the factory gate. The used data is from the cradle, i.e., including all upstream activities; this activity ends with the disposal of the device at the end of its lifetime. However, decommissioning and waste management are not considered here as it is out of the research scope.

For the H.E.R categories, the contribution result for resources shows about 80.1% coming from the mineral resource, making it the highest for the conversion stage of the LCIA. 51.1% from fossil fuel. The respiratory effect of the health category is at 61.4%, and climate change amount to 51.8% coming from the cogeneration heat and construction phase sensitivity analysis. Acidification/eutrophication and land occupation are at 55.3 and 45.8%, respectively. Further details about the conversion process considered in this project are presented in Kolb et al., 2019.

9.8.3 Natural gas sensitivity analysis

The natural gas production flow category from the contribution tree shows that about 52.5% of the CO_2 emission is majorly from the extraction, processing activities, and market for chemicals/ field infrastructures. Ammonium emission to water contributed 41% coming from the natural gas processing plants, hazardous chemicals, and the landfilled waste from infrastructure. Nitrates, 49.7%, Lead to an unspecified location is 38.7%

The extraction of mineral resources has an impact factor of 55.4% or 0.55% in the resource category of natural gas, making it the largest for this group, while fossil fuel, on the contrary, is as little as 0.1.8%.

Surprisingly, land transformation, occupation, and conversion played a significant role in natural gas production under the ecosystem impact category at 50.4%, making it one of the highest impact values coming from land-use change in this study. It is worthy of note that Alberta, Canada, produces a massive amount of natural gas and the exploration facilities occupy a lot of land space across the province. The land is needed starting from building a shed to produce the seismic machines and the seismic activities themselves. Deploying the materials to the oil rig/field, damaging or degrading the land while creating the seismic lines, and other exploitation/exploitation activities are all land-intensive. Eutrophication/acidification has 0.2.4% being the lowest eutrophication value in this analysis since fertilizers and other farm chemicals are not used in natural gas production, and there are no nearby water bodies to be contaminated from nutrient delivery. The high number of contributions from land occupation is also linked to different processes such as all the upstream activities, materials, land, and energy requirements of a natural gas production and or its processing facility all upstream activities. Material, land, and energy requirements of a natural gas production plant.

For climate change under the health impact category, it has about 13.9% impact factor contributed from the separation process with climate change potentials. Additionally, the market for solvent, market for onshore well, oil/gas, and some other hazardous chemical emissions played a role. The respiratory effect is at 04.5%, contributed by the treatment of mineral oil and other particles.

The reviewed studies on natural gas emissions show a variety of values ranging up to 380kgCO_2 eq/MWNG for cradle to gate emissions, considering both emission intensities and harmonized results. Few studies have reported Co_2 emission for natural gas as from 168 to 351 kgCO_2 eq/MWhNG, as in O` Donoghue et al., 2014, and 214 to 330 kgCO_2 eq/MWhNG according to Heath et al., 2014. The latter also used the 2014 5th Assessment of the IPCC Report to harmonize other studies as stated in Kolb et al., 2021 reports a minimum value of about 214kgCO_2 eq/MWhNG for the emission intensity of 0.53%, which is based on the quantity of natural gas produced. Our contribution tree results show that (0.0044kg or 52.5%) converted to 0.52% CO_2 emission is released to an unspecified direction on air, which is similar to 0.53% Kolb et al., 2021 reported. Additionally, other scholars such as Barkley et al., 2017 and Clark et al., 2012 also have similar numbers.

Discussion for the Canadian case study

10.1 General discussion on the LCIA outputs

The second case study has examined the total supply chain impact of producing 1 kg of maize silage, processing it via anaerobic digestion, and converting it into heat and power for further use. The result is then compared with the fossil natural gas emissions in Alberta, Canada. The end result shows that maize production has more impact during the cultivation stage compared to other life cycle stages assessed. Emissions from fertilizer and pesticide components are the major contributors to this analysis, especially emission from drying and other support activities (nutrient supply, market for pesticides) that consumes fossil electricity as seen in the model output graph. To account for these emissions that are to be quantified, the mode of application, climatic condition, and the ecosystem service of the cultivated area are taken into account. Although, it is not very easy to get these data when conducting an LCA in detail, Fusi et al., 2016. It is assumed that a good percentage of the applied farm chemicals components from (fertilizer and pesticides) are retained in the soil; say, for instance, out of the 100% of the total quantity applied, the plants use up 45%, and the rest of the % is washed down to the nearby water body where it will have a more adverse effect. This assumption has also been made by other scholars, such as Fantin et al., 2015 and Falcone et al., 2015 as was recommended by (Curran, 2012).

As mentioned above, this study estimated that the highest environmental impacts are experienced during the maize production process, especially for the nitrate being an agent of eutrophication problems, as illustrated in figure 19 above with the title (flow category analysis for the production of maize compared with other LCA stages). Also, similarly recorded in Abbas A. et al., 2021 who studied sustainable corn farming in Pakistan. From the overall assessment and the sensitivity analysis result, as well as the input manipulations for the fertilizer show that the largest impacts arise from its production and extreme use as reported in previous studies such as Sadeghi S. M. et al., 2018 and Kiesel et al., 2017. However, drying of the maize silage plays a significant role in this study due to its excessive use of electricity during this operation as against other studies such as Abbas A. et al., 2021 whose irrigation processes played more role in the environmental damage when maize is used as energy feedstock. Yemane Weldemichael and Getachew Assefa 2016 estimated Alberta's biomass resources at 458 PJ whereas agricultural biomass, of which maize silage is included ranks the most reliable for the energy transition. They added that about 39-40 percent of the province's heat supply from fossil fuels could be substituted with biomass resources, and this can help in climate change mitigation plans. Using three different assessment methods helped to view the results from different perspectives with more standardized units such as kg other than eco points alone. For the eco points, it is recorded as human health and ecosystem endpoint level indicator depicted in appendix m, represented as disability-adjusted life-years (DALYs), and all the dataset results applied fulfills the LCA ISO standard for data quality description as displayed in table 9. And a sample of the LCA platform showing the input data is shown in appendix l.

Table 9. Shows that the input data were duely selected following the LCA data quality standard of reliability, completeness, and temporal correlation, geographical and technological correlation.

Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Verified data based on measurements	Representative data from all sites relevant for the market considered, over an adequate period	Less than 3 years of difference to the time period of the data set	Data from area with similar production conditions	Data from enterprises, processes and materials under study
Verified data partly based on assumptions or non-verified data based on measurements	Representative data from > 50% of the sites relevant for the market considered, over an adequate period	Less than 6 years of difference to the time period of the data set	Average data from larger area in which the area under study is included	Data from processes and materials under study (i.e. identical technology) but from different enterprises
Qualified estimate (e.g. by industrial expert)	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Less than 10 years of difference to the time period of the data set	Data from area under study	Data on related processes or materials
Non-verified data partly based on qualified estimates	Representative data from only one site relevant for the market considered		Data from unknown or distinctly different area (GLO instead of CA)	

The DALY's are the cumulative estimate of cumulative years whereby some human lives may have been threatened due to environmental stressors, pollution, or contamination arising from these energy projects. The DALY's characterizes and quantifies the severity of the disease, Homagian, K. et al., 2015. It also gives an account of morbidity and mortality, which is the lifetime with an illness at the hospital that lowers the life quality of someone, and mortality is, off course, losing life to premature deaths due to the impact coming from the production and use of 1 kg of maize silage for biogas. The ecosystem damage is measured and represented in a potentially disappeared fraction (PDF), which includes the loss of species, endangered species, and other ecological species that are threatened by the energy project supply chain in a particular area and time. For instance, if our human health impact (climate change and respiratory effects) scored 1 DALY's during our analysis, it means that the average loss of years of life (time spent in the hospital) from the overall population of Alberta is also one and not necessarily that one person died, Humbert S. et al., 2012. When it comes to ecosystem quality, which is paramount in this study, the LCA unit used in describing it is the PDF (potentially disappeared fraction) of specie in a specific location and period. Some of these ecosystem and ecosystem services damages are caused mainly by toxic emissions, including eutrophication, acidification effects, and land conversion or occupation. The unit may be represented as (PDF.m2.yr). Just as an interpretation, if 1 m^2 of land is cultivated in one year for a product or service with an ecosystem quality score of 0.1 PDF.m^2.yr, the implication is 10% of the species could also be the endangered species lost on a 1 m^2 of the cultivated earth surface (Homagian, K. et al., 2015). Mineral extraction and exploitation are the major cause of resource depletion and damage for the fossil fuel impact categories. The climate change CO_2 analysis was carried out and reported as GWP, which is how to relatively measure the quantity of greenhouse gas heat that is trapped over a specific period in the atmosphere. This study has assessed the overall (upstream and downstream) impact of feedstock production and the use of which nitrogen fertilizer is one of the essential nutrients for plant growth. Additionally, the provision of this fertilizer and other plant protective chemicals are energy-intensive, thus leading to fossil fuel emissions which decision-makers need to be aware of for proper energy transition legislation that favours environmental safety and protection. Note that the TRACI impact category mothed is used to also compare the eco-indicator results. This is suitable as the TRACI method that was originally developed by the US EPA to serve as a guide to the sustainability practitioners focuses more on the US regulations and policies. TRACI is not sufficient to be used alone for this analysis since it lacks data on land transformation and occupation that exists in eco-indicator method. Land resources is not only an important element for ecosystem impact assessment, but it is one of the first requirements for the cultivation of bioenergy crops, in this case, maize. Eco-indicator is one of the widely used assessment methods in LCA, as mentioned in Homagian, K. et al., 2015 and Cavalett et al., 2013 to evaluate endpoint results. Though, in reality, the impact assessment methods are created precisely to deal with significant inputs and convert the detailed inventory information into estimates of associated impacts. This study has made a valuable and useful highlight of some research gaps which has been fulfilled in this project and has proposed further steps for improvement and integration of LCIA results into an ecosystem services valuation and tradeoffs model and vice versa.

Similarly, several LCA studies concluded that bioenergy produced from biomass performs well when it comes to climate change and GHG emission issues when compared with fossil fuel energy systems, and the more the environmental impacts are assessed even before deployment (for instance, impact on human health or ecosystem) the more the benefits (Gu and Bergman, 2017; Maier, J.M et al., 2019 and Boschiero et al., 2016)

11. Conclusion, Outlook and Recommendation for the Models Integration

11.1 Conclusion

In the first case study, there was less precipitation between the years 1980-2010 than we have now, and we will even have more wet periods in the years 2036-2065, as the climate model shows in figure 10 under the section where modifications of climate data took place. This is an indication that the climate is changing which is important to be considered before choosing biogas as an alternative source of energy. SustainableGas presented in the first case study is contributing to German energy independence & sustainability with the proposed RGP's combination. The final result from the InVEST model shows that nutrient load will reduce drastically by the year 2050 if the set-out process is implemented (use of power to X from the year 2045). This is compared to the reference state where more biogas RGP's powered with maize is in use, and higher nutrients are delivered to the water bodies. After the analysis of the first case study, it is right to conclude that the InVEST model is a suitable tool for assessing ecosystem services in an energy project, as found in this study. However, the NDR model calibration was the most difficult and complex due to the unique nature of the model that requires simple parameterization during the simulation. The reason for this complex process is because there are different environmental conditions, such as (different soil types, variations in rainfall patterns, different land-use types and so on) across the study area.

Additionally, bio-methane RGP's is a short-term remedy, while Power to Gas and Power to Hydrogen can be long-term options in transforming the German gas sector. Although most Power to X plants are not technologically ready or may still be in the pilot stage, their environmental impacts are yet to be uncovered. It is important to note that renewable energy system analysis should consider the local availability of feedstock to avoid more ecosystem damage in the future. In general, residues, manure, and maize-powered RGP's have been identified to play a major role in the nearest future and would make an impact in reaching the -40% emission reduction in the German energy sector. The sustainable scenario was finally chosen as the best environmentally acceptable development, suggesting that environmental prosperity should be put ahead of any energy project. The scenario (sustainable) also saw a reduction of demanded biomass by 46 percent in other to create a balance between technological demand and ecological sustainability. Furthermore, the CO_2 price increment compared to the current rate is implemented in the selected green scenario (Kolb, S., et al. 2019), and this will even aid the heavy emitters to consider transiting to a greener option that the proposed RGP's represents, Kolb, S., et al., 2021. Since Germany is in the Nitrate vulnerable zones, as stated in the European Union nitrate vulnerable zones chart, it was also considered in this study to reduce eutrophication. We conclude that by the year 2050, there will be a reduction of nutrients being delivered in the rivers, which is one of the reasons we chose this as the green scenario with less environmental impact for the German case study. Further investigation using a life cycle impact assessment tool such as Openlca is implimented to evaluate our feedstock production's cradle to grave environmental impacts. Lastly, changes in habitat quality by modeling with InVEST the number of terrestrial or aquatic species impacted or to be affected in the future if more RGP's are built are recommended as it is not included in this first case study.

11.2 Integrating LCIA output data of this study into the InVEST ecosystem services model and vice versa

In recent times, many scientists have used different scientific processes and diverse assessment methods, Cavalett et al., 2013. In some cases, multiple models are used to arrive at more accurate and concrete results in solving environmental problems, such as in Chaplin-Kramer et al., 2017 and the study carried out by Souza, D. M., et al., 2015. The former showed that spatially explicit data from InVEST of the ecosystem services could be applied to the LCA in large-scale predictive modeling in their new approach called Land-use Change Improved (LUCI)-LCA. Nonetheless, due to the complications and the problematic nature of this integration, authors mostly identify major gaps in analyzing the ecosystem services within the LCA framework and provide recommendations on how to tackle methodological challenges (Rugani, B. et al., 2019) but not performing the standard LCA with ecosystem data or verse vice. This study's LCIA presents results from different methods (Eco-indicator, ReCipe and TRACI) using the openLCA tool and now making recommendations for further studies to ensure the use and integration of two different modeling tools, their result presentation & interpretation as one. Furthermore, multiple LCIA methods are often applied in different studies to evaluate and assess whether different approaches agree and correspond on the severity of the chosen impacts. When this is done, it helps to report and interpret the endpoint results or the damages that are considered as impacts within the supply chain. We recall that the destruction of coral reefs, rising of the sea level, unusual longer warm/cold degree days, and many other extreme events related to the global environmental change could be attributed to the midpoint damages for the global warming and climate change impact categories. Also, for the conventional pollutants, endpoints may be human health effects due to increased exposure to concentrations, such as an increase in asthma cases or hospital admissions (respiratory or carcinogenic effects), while the death of fishes could be from the eutrophication potentials or can be attributed to it.

When simulating LCIA outputs in the InVEST nitrate delivery ration (NDR) model, specifically for the eutrophication potential being one of the major ecological problems for the water ecosystems pertinent to maize cultivation globally, the data needs to first and foremost appear in a spatially explicit form (e.g., vector, raster, shp, or tiff files readable in ArcGIS) to be able to work well in the ecosystem model (InVEST). One other possible and the novel way would be to run the openlca with the details found in table 9 (fertilizer, herbicide, and pesticide) being the major farm chemicals that contribute to eutrophication during maize cultivation processes both in Alberta and globally. The output result of this simulation (in numbers) can now be used in InVEST NDR model for the inputs Subsurface Critical Length (Nitrogen) and Subsurface Maximum Retention Efficiency (Nitrogen). By way of description, these data show how critical and the maximum nitrate that is delivered and retained in the water ecosystem at a particular time and area.

This process of (integrating the LCA values from table 10 into the InVEST NDR) will give an estimate and interpretation of the quantity of nutrients retained in water or underground water with its eutrophication potential when 1kg of maize silage is produced. The outcome will aid policy decision-making to reduce some farm chemicals' excessive use and maintain environmental sustainability. It is important to note that only the Subsurface Critical Length (Nitrogen) and the Subsurface Maximum Retention Efficiency (Nitrogen) data are not enough to perform the simulation in the InVEST NDR model. However, the following data (DEM, Land Use, Nutrient Runoff Proxy, Watersheds, Biophysical Table, Threshold Flow Accumulation, and Borseli k Parameter) are also needed of which a default value for the study area of Alberta, Canada can also be obtained from the natural capital project directly (the developers the InVEST model) and used for a start.

Table 10. Proposed LCA input data needed to run the InVEST NDR model for the eutrophication impacts category.

INPUT	VALUES	UNITS	CATEGORY	PROVIDER	ASSUMPTION
Herbicide	1.5	kg	Elementary flows/Emission to soil/agricultural		Assumed for production of 1kg per ha
Nitrogen fertilizer P fertilizer	120 75.3	Kg	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics and synthetic rubber in primary forms/2012:Manufacture of fertilizers and nitrogen compounds	market for nitrogen fertiliser, as N_nitrogen fertiliser, as N | Cutoff, U - CA	1 ton of grain for 1 ha 1 hectare of cultivated area &1 ton of grain
Pesticide	1.0	kg	202:Manufacture of other chemical products/2021:Manufacture of pesticides and other agrochemical products	market for pesticide, unspecified pesticide, unspecified Cutoff,	

Since fertilizer production, its application and the maize silage drying process contributes more in the assessed LCIA processes, (The maize silage is currently dried with electricity from natural gas in Alberta). This study therefore recommends that; the drying of the maize silage be carried out with biogas and natural gas mix (hybrid) to reduce the electricity fossil fuel emissions. While the use of bio manures from waste products and or forest residues is recommended instead of using only the synthetic fertilizer during the planting stage to reduce environmental impacts arising from the conventional fertilizer use as manure.

11.2.1 Additional process for integrating the LCIA data into the InVEST model

In order to run the sedimentary delivery ration (SDR) and the nutrient delivery ration (NDR) suites, the following spatial data, as mentioned above, is needed from the study area of Alberta, Canada. For example, the raster file (tiff) of the digital elevation model (DEM), the watersheds, a vector shapefile is also needed. Also, the nutrient runoff proxy raster file, land use raster, biophysical table (CSV) file that describes all the biodiversity in the study area (Alberta) is important, and finally, the subsurface critical length, subsurface maximum retention efficiency (nitrogen), threshold flow accumulation and Borseli k parameter would be needed. The sediment delivery ratio model will need all of the above in addition to the rainfall erosivity index raster file (tiff), soil erodibility maximum SDR value, and Borselli IC0 parameter. The land use land cover map for Alberta is also crucial for this step to determine the different types of land use currently available. Once these are correctly loaded into the InVEST model and successfully simulated, the output map can now be viewed, interpreted, and arranged in the ArcGIS for proper result presentation.

11.3 Further process to integrate the InVEST data into the LCIA models (second or reversed option)

From the reviewed literature, it is almost impossible or challenging to integrate ecosystem spatially explicit (i.e a measure of the smallest ecological impact) output on land use into a standard LCIA model, Jane Bare, 2010. However, with some improvements, modifications, and developed framework, the ecosystem modeling results can be used as key inputs to model in LCA tools such as the openlca using the same assessment methods as in this study (Eco-indicator, TRACI, and ReCiPe). Some of the existing studies with a similar approach includes Rugani, B. et al., 2019 and Chaplin-Kramer et al., 2017. Few of the inputs needed to integrate the InVEST data into the LCIA with their sources are shown in table 11, while the InVEST model platform or interface sample for NDR and SDR models are found in appendix h. Using the input values earlier mentioned, the InVEST model would be simulated with the Canadian data in order to gather the key results to be fed into the LCA model. This InVEST rerun is necessary to get a location-specific data and results, which is more accurate than using the European or German data applied in the first case study of this thesis as part of (SustainableGas). To check for the validity and accuracy of the results against uncertainties, especially for the SDR model, the model output will be calibrated with other existing literature such as Kalu et al., 2021 and Ureta, J. et al., 2020.

Table 11. Description of some InVEST input data, sources of data required for the model set-up, resolutions and assumptions needed from Alberta in a spatially explicit form.

Input data	Sources of data (e.g. Natural capital project database)	Description/assumptions
(Digital Elevation Model) The DEM is a GIS raster file. We made sure the DEM is corrected by filling in sinks. To ensure proper flow routing which helps to determine the slope.	Alberta/Canada/North American DEM	Or. Resolution: User Res.: 250 m
(Rainfal erosivity index) GIS raster which variables depends on the duration & intensity of rainfall in a location. The higher the rain stom, the greater the erosion potentials.	Alberta/Canada/North American Rainfal erosivity index	Time period: 1981-2010 or 2050
(Soil erodibility); K is a measure of the soil particle susceptibility to detachment & transported by runoff and rainfall. The unit index values are ton·ha·(ha·MJ ·mm)−1	Alberta/Canada/North American Soil erodibility	Or. Res.: 500 m User. Res.: 250 m
(land use land cover); Is a GIS raster file, the integer code is LULC for each cell (e.g. 11= maize in kalu et al ., 2021). It shows different land use classes of an area	Alberta/Canada/North American current land use map (from Albertan land use map, Geography dept)	Or. Res.: 1 km grids/year User. Res.: 250 m
(river network)	Alberta/Canada/North American shape file	
(Precipitation) is s GIS raster dataset with a non-zero value for average annual precipitation for each cell. The precipitation values should be in millimeters.	Alberta/Canada annual precipitation	
	Canadian weather service	Or. Res.: 1 km grids/year User. Res.: 250 m Period: 1981-2010
Reference Evapotranspiration (reference evapotranspiration); is the potential loss of water from soil by both evaporations from the soil and transpiration by healthy plant (or		Or. Res.: 1 km grids/year

grass) if sufficient water is available. The reference evapotranspiration values should be in millimeters & it is a raster dataset too.		User. Res. 250 m Period: 1991-2010
(Depth to root restricting layer); Root restricting layer depth is the soil depth at which root penetration is strongly inhibited because of chemical or physical characteristics. It is a GIS raster dataset valuing each cell.	Alberta/Canada Depth to root restricting layer	Or. Res.: 250 m grid User. Res. 250 m
(Plant available water fraction); is the fraction of water that can be stored in the soil profile that is available for plants' use. PAWC is a fraction from 0 to 1. Also, a raster file.	Plant available water fraction from Canada	Or. Res.: 250 m grid User. Res. 250 m
(land use map)	University of Calgary Geography department	Or. Res.: 1 km grids/Jahr Benutz. Res.: 250 m
(Watersheds) Shape file; Is a layer of watersheds that shows what each watershed contributes to a point of interest where water quality will be analyzed? It is a file of polygons	Vigiak et al. 2012	Or. Res.: 1 km grids/Jahr user. Res.: 250 m
Biophysical table; Is a csv table of LULC classes in an excel format with water quality coefficients data showing attributes of each class rather than showing individual cells in a raster map	Hamel P., Chaplin-Kramer, R., Sim, S., Mueller, C., 2015. A new approach to modelling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 166–177.	

In order to successfully utilize and integrate the ecosystem services output from InVEST into the standard LCA model or the other way round, for the simulation of eutrophication potentials, there are a few things to keep in mind;

The modeling of a spatially explicit nutrient loss has an influence on the nitrate leaching from the farm that affects the eutrophication potentials.

The InVEST model result in the loss of nitrogen is based on the total amount of feedstock required to meet the final product's demand (biogas).

Eco-invent database for maize nitrate emissions are based on the emission factor of about 32% of N coming from the nitrogen fertilizer alone based on a field measurement carried out following the procedure stated in Randall et al., 2003.

Standard life cycle inventories assessments are based on single yield figures and nitrogen application rates; for instance, this study considered 120kg of N fertilizer. While the InVEST and other ecosystem models use spatially differentiated yield and nitrogen application relationships that are climate-dependent and need to be harmonized. Most of the InVEST results are represented in maps where colour codes show low or high impacted areas.

Finally, the nitrogen export value from the InVEST NDR model can be substituted into the openlca in place of the nitrate emission value to water in the inventory (output) section.

The above-recommended steps will help curb the disparaging effect of climate warming and its environmental effects on ecosystem services that are unequivocal, especially in the twenty-first century biogas projects. As issues surrounding environmental sustainability and sustainable development for a sustained future can never be over-emphasized locally, regionally, and globally. Assessment of renewable energy opportunities and their challenges while considering their environmental impacts has always been one entity that supports decision-making. The overall costs of the energy transition process and potential environmental (land-use) impacts have remained scarce. Nonetheless, such data are vital, as they constitute crucial input for new investments in energy infrastructure and policy decision-making in the country's bioenergy sector. This LCIA study has attempted to cover most attributes/aspects of the natural environment, human health, and resources using the eco-indicator method, including a wide range of potential environmental impacts on the product life (supply chain). It has also applied a systematic & iterative approach to identify, check, evaluate and present information based on the study goal and scope, as the LCA is seen as a powerful tool to ensure environmental sustainability during the energy transition process.

This LCA case study is considered a cradle to gate analysis since it covers maize, cultivation, silage production, digestate processing, conversion of the biogas into heat and power, and the final emissions to the ecosystem, resources & health impact. It does not cover the decommissioning and final waste disposal from the biogas plants. This is out of the scope of the research, and it is not considered a limitation. However, further studies can elaborate on those. The study ensures that the selected technology is environmentally suitable since bioenergy development and deployment have the ability to mitigate climate change but may also have an impact on the environment generally if care is not taken from the project conception stage. Additionally, this research has exposed us to the importance of sustainable renewable energy development both for human survival and saving the environment from further damage. Moreover, the production of energy from alternative technologies powered by biomass sources, solar, and manure is expected to play a major role both now and in future energy systems. Therefore, it is imperative to uncover the environmental implications of alternative energy technologies bearing in mind that the intensity of the impacts varies from location, source, and type of technology to GHG emissions in relation to climate warming. So far, climate change is perceived as an agent of environmental change with obvious evidence such as a rise in sea level, longer cooling degree days, and increased heating degree days. These changes suggest that the current warming of the climate has a drastic effect on numerous aspects of the ecological communities, including competition level, species abundance, assembly pattern, population dynamics, and ecosystem services. Due to anthropogenic activities such as massive deforestation for farming of energy crops (land-use change), species interaction with temperature is predicted to have changed owing to climate conditions. Worthy of note is that there is always an environmental consequence that goes with the way energy is generated and used, although renewable energy is perceived as being totally harmless by many schools of thought which is not entirely true. So far, detailed assessment of the benefits and costs of alternative gas production technologies with a focus on Albertan biogas eutrophication challenge, GHG emissions, the regional process of the energy transition, and potential environmental (land-use) impacts have remained scarce. The study bridges this knowledge gap by fulfilling the stated obligation using an Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) and the life cycle assessment as the modeling tools. The result of the study helps to quantify and inform public (stakeholder) perceptions of and expected heterogeneity preferences for alternative energy generation pathways in the light of a sustainable environment.

Addition of Life cycle costing (economics) to all the LCA stages recommended.

For more inclusive and holistic LCIA, it will be necessary to include a life cycle cost analysis (Whole-life costing) to the overall goal of achieving a comprehensive life cycle impact assessment, since renewable energy delevopment cannot be completely isolated from the economic improvement of a nation. This is because economic activities play an important role in production, Neugebauer, S. et al., 2016 and, usage of goods and services of which biogas is one of them. The cost of each LCA stage will generate the economics involed for example, the cultivation stage being the most impactful stage for euthrophication.

Implimenting a life cycle cost analysis will not only yield monetary value but will also trigger a culture of conserving the envirionment more independently by the heavy emitters. Additionally, if an individual knows the ecosystem services cost implication of using electricity from biogas before hand, it will inform his decision on the actual cost of his energy demand both environmentally and economically. The life cycle costing analysis can be carried out by the same way the environmental impact or endpoint analysis has been perfomed in this study. However, the LCA method to be chosen is the LCC (life cycle costing) instead of the Eco-inidicator used as the life cycle impact assessment method in the openlca framework. This is after creating the flows, product system and process, connecting them to the cost impact category result according to Özlem Duyan and Andreas Ciroth, 2013.

Lastly, having assessed the environmental impacts of biogas feedstock production and use in Germany and the upstream and downstream implications for the biogas full LCA stages in Alberta, futher analysis that includes a life cycle costing is recommended to be simulated in openLCA. After this, then the output can be spatially resolved to be fit for the InVEST model run readable in ArcGIS. When this is done then, a cost value will be attached to the ecosystem services that are or can be affected when maize is used for biogas production. This life cycle costing will be necessary for all the LCA stages considered in this thesis namely, maize silage production, anaerobic digestion and the conversion stages.

Papers/posters presented during the PhD program & some conferences attended,

EGU poster presentation, Vienna Austria

Regional leadership summit Quebec, Canada

AbbyNet summer schools, Bayern and Alberta

SustainableGas project meetings/seminar, Nuremberg

International Conference on Sustainable Development Goal, USA

Acton university conferences, Munich

Tag der Hyrologie, Garching

Author contributions for the published research paper in the case study one

Amarachi Kalu: Manuscript preparation, Validation/ Updating, Formal analysis, Gathering of data, Visualization, Writing and Editing. **Janja Vrzel**: Modeling, Calibration, Draft, Software management. **Sebastian Kolb**: Analysis, Simulations, Data curation. **Philip Marzahn:** Framing, Correcting, Methods, Administration. **Juergen Karl**: Framing, Conceptualization. **Fabian Pfaffenberger**: Suggestions, Supporting. **Ralf Ludwig**: Supervision, Methods, Resources, Conceptualization, Framing, Drafting, Corrections**.**

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Conflicts of interest

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References

A Technical Mapping Guide for Local Government" *ISPRS International Journal of Geo-Information* 9, no. 5: 324. https://doi.org/10.3390/ijgi9050324

A.I.M. Aly and R.A Hussein. (2014). Environmental Impacts of Nuclear, Fossil and Renewable Energy Sources: A Review available online at https://www.researchgate.net/profile/Rasha_Hussien4/publication/303767454_Environmental_Impacts_of_Nuclear_Fossil_and_Renewable_Energy_Sources_A_Review/links/575167d508ae17e65ec14e06/Environmental-Impacts-of-Nuclear-Fossil-and-Renewable-Energy-Sources-A-Review.pdf Accessed 14/02/2021.

Abbas, A.; Zhao, C.; Ullah, W., Ahmad, R.; Waseem, M.; Zhu, J. (2021). Towards Sustainable Farm Production System: A Case Study of Corn Farming. *Sustainability 13, 9243.* https://doi.org/10.3390/ su13169243

Abu-Rayash, Azzam, and Ibrahim Dincer. (2019). "Sustainability assessment of energy systems: A novel integrated model." *Journal of Cleaner Production* 212: 1098-1116.

Adams, P.W.R.* & Mezzullo, W.G. & McManus, M.C. (2015). Biomass sustainability criteria: Greenhouse gas accounting issues for biogas and biomethane facilities. *Energy Policy*, vol. 87, December 2015, Pages 95-109

Alberta Innovates Biosolution (2014) .http://bio.albertainnovates.ca/media/68546/biological_solutions_forum_2014_final_program_oct_1-2__2014_edmonton_ab.pdf Available online at Alberta Innovates - Bio Solutions business plan - Open Government. Accessed on 14.03.2022.

Aracil, C., Haro, P., Giuntoli, J. and Ollero, P., (2017). Proving the climate benefit in the production of biofuels from municipal solid waste refuse in Europe. *Journal of cleaner production*, 142, pp.2887-2900.

ASABE Technical Library: Publications Included: (2006). CSBE/SCGAB, Edmonton, AB Canada, July 16-19, 2006 *ASABE Technical Library*. Available online at ASABE - American Society of Agricultural and Biological Engineers > Home, accessed on 15.01.2022

Awada, Lana, Cecil Nagy, and Peter WB Phillips. (2021). "Contribution of land use practices to GHGs in the Canadian Prairies crop sector." *PloS one* 16, no. 12: e0260946.

Arvidsson, R. (2021). Inventory Indicators in Life Cycle Assessment. In Life Cycle Inventory Analysis (pp. 171-190). *Springer*, Cham.

Bacenetti, J., Lovarelli, D., & Fiala, M. (2016). Mechanisation of organic fertiliser spreading, choice of fertiliser and crop residue management as solutions for maize environmental impact mitigation. *European Journal of Agronomy*, 79, 107-118.

Bach, Martin., (2012). Stickstoff-Bilanzierungen Notwendigkeit harmonisierter Ansätze.

Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., (2013). A comparative assessment of decision-support tools for ecosystem services quantification and valuation. *Ecosyst. Serv*. 5, 27–39. doi:10.1016/j.ecoser.2013.07.004

Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

Bare, J., TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0EXITEXIT EPA WEBSITE. Clean Technologies and *Environmental Policy* 2011, 13, (5)

Barkley ZR, Lauvaux T, Davis KJ, Deng A, Miles NL, Richardson SJ, Cao Y, Sweeney C, Karion A, Smith M, Kort EA. (2017). Quantifying methane emissions from natural gas production in north-eastern Pennsylvania. *Atmospheric Chemistry and Physics*. Nov 23;17 (22):13941-66.

Bell, J. & Weis, T. (2009). *Greening the Grid: Powering Alberta's Future with Renewable Energy*, Pembina Institute.

Bioenergy In Germany Facts And Figures (2019). Available Online: Http://Www.Fnr.De/Fileadmin/Allgemein/Pdf/Broschueren/Broschuere_Basisdaten_Bioenergie_2018_Engl_Web_Neu.Pdf#:~:Text=Domestic%20biomass%20will%20contribute%20substantially%20to%20the%20energy,Unused%20potentials%20from%20biogenic%20residual%20and%20waste%20materials (accessed on 18 February 2021).

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R. and Sabater, S., (2014). Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. *Science of the Total Environment*, 470, pp.567-577.

Boone, L., De Meester, S., Vandecasteele, B., Muylle, H., Roldán-Ruiz, I., Nemecek, T., & Dewulf, J. (2016). Environmental life cycle assessment of grain maize production: An analysis of factors causing variability. Science of the Total Environment, 553, 551-564.

Borselli, L., Cassi, P. and Torri, D., (2008). Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. Catena, 75(3), pp.268-277.

Boschiero, M., Cherubini, F., Nati, C., Zerbe, S., (2016). Life cycle assessment of bioenergy production from orchards woody residues in Northern Italy. *J. Clean. Prod*. 112, 2569–2580. https://doi.org/10.1016/j.jclepro.2015.09.094

Bouguerra, S. and Jebari, S., (2017). Identification and prioritization of sub-watersheds for land and water management using InVEST SDR model: Rmel river basin, Tunisia. Arabian Journal of Geosciences, 10(15), p.34

Bouguerra, S., Jebari, S. and Tarhouni, J., (2020). Spatiotemporal analysis of landscape patterns and its effect on soil loss in the Rmel river basin, Tunisia. Soil and Water Research, 16(1), pp.39-49.

Busico, G., Mastrocicco, M., Cuoco, E., Sirna, M., & Tedesco, D. (2019). Protection from natural and anthropogenic sources: a new rating methodology to delineate “Nitrate Vulnerable Zones”. *Environmental earth sciences*, 78(4), 104.

Canadian Centre for Energy Information, (2020). Get started: Canadian Centre for Energy Information (canada.ca), https://energy-information.canada.ca/index-eng.htm

Carlsson, G.; Mårtensson, L.M.; Prade, T.; Svensson, S.E.; Jensen, E.S. (2017). Perennial species mixtures for multifunctional production of biomass on marginal land. *GCB Bioenergy* 2017. 9, 191–201. [Google Scholar] [CrossRef]

Cavalett O, Chagas MF, Seabra JEA, Bonomi A (2013). Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *Int J Life Cycle Assess* 18:647–658

Chaplin-Kramer, Rebecca, Sarah Sim, Perrine Hamel, Benjamin Bryant, Ryan Noe, Carina Mueller, Giles Rigarlsford (2017). "Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services." *Nature communications* 8, no. 1 1-8.

Chen, C., Xue, B., Cai, G., Thomas, H., & Stückrad, S. (2019). Comparing the energy transitions in Germany and China: Synergies and recommendations. *Energy reports*, 5, 1249-1260.

CHŁOPEK, Z., SAMSON-BRĘK, I. (2017). Analysis of the ecological effects of biogas use of to supply the internal combustion engine in the electricity generation process – result of LCA analysis. Combustion Engines. 171(4), 134-139. DOI: 10.19206/CE-2017-422

Clark CE, Han J, Burnham A, Dunn JB, Wang M. (2012). Life-cycle analysis of shale gas and natural gas. Argonne National Lab. (ANL), Argonne, IL (United States); Jan 27.

ClimEx. https://www.climex-project.org/ (Accessed 14.02.2021).

Cucchiella, F., Gastaldi, M., & Trosini, M. (2017). Investments and cleaner energy production: A portfolio analysis in the Italian electricity market. *Journal of Cleaner Production*, 142, 121-132.

Curran, A. M. (2012). Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products. New Jersey: John Wiley & Sons and Scrivener Publishing.

Daniel-Gromke, J., Rensberg, N., Denysenko, V., Stinner, W., Schmalfuß, T., Scheftelowitz, M., Nelles, M. and Liebetrau, J., (2018). Current developments in production and utilization of biogas and biomethane in Germany. *Chemie Ingenieur Technik*, 90(1-2), pp.17-35.

Dincer I. Comprehensive energy systems. (2018). Elsevier; Feb 7. First edition, university of Ontario institute of technology, Oshawa, ON, Canada. Life Cycle Assessment of Energy. Comprehensive Energy Systems, 1042–1084 | 10.1016/B978-0-12-809597-3.00134-6 Available online at (sci-hub.se) accessed on 16.04.2021

Dressler, Daniela, Achim Loewen, and Michael Nelles. (2012) "Life cycle assessment of the supply and use of bioenergy: impact of regional factors on biogas production." The International Journal of Life Cycle Assessment 17, no. 9, 1104-1115.

Ekka, A., Pande, S., Jiang, Y., & der Zaag, P. V. (2020). Anthropogenic modifications and river ecosystem services: A landscape perspective. Water, 12(10), 2706.

Environment Canada (2013). National Inventory Report 1990–2012: Greenhouse Gas Sources and Sinks in Canada. Environment Canada 2013, *National Inventory Report 1990–2012:* Greenhouse Gas Sources and Sinks in Canada. - Google Search

Environment Canada (2021). National Inventory Report 1990-2019. Available online at Greenhouse gas sources and sinks: executive summary 2021 - Canada.ca accessed on 10. 03. 2022.

European Soil Data Centre (ESDAC), (2019). European Commission, Joint Research Centre https://esdac.jrc.ec.europa.eu/tmp_dataset_access_req_17702#tabs-0-filters=2

Falcone, G., Strano, A., Stillitano, T., De Luca, A., Iofrida, N., and Gulisano, G. (2015). Integrated sustainability appraisal of wine-growing management systems through LCA and LCC methodologies. Chem. Eng. Trans. 44, 223–228. doi:10.3303/CET1544038

Fantin, V., Rondini, I., Righi, S., Pasteris, A., Coatti, F., Passerini, F., et al. (2015). "Environmental assessment of wheat and maize production in an Italian farmer's cooperative," in Proceedings International Conference LCA for Feeding the Planet and Energy for Life, Stresa.

Federal Ministry for Economic Affairs and Energy, Energy Data. (2019)

Filippa, F., Panara, F., Leonardi, D., Arcioni, L., & Calderini, O. (2020). Life cycle assessment analysis of Alfalfa and corn for biogas production in a farm case study. Processes, 8(10), 1285.

FNR-Agency of the renewable resources Fachagentur Nachwachsende Rohstoffe e.V., (2017)

FNR-Agency of the renewable resources Fachagentur Nachwachsende Rohstoffe e.V., (2017)

Fusi A, Bacenetti J, Fiala M, Azapagic A. (2016). Life cycle environmental impacts of electricity from biogas produced by anaerobic digestion. *Frontiers in bioengineering and biotechnology*. 2016 Mar 11;4 : 26.

German Renewable Energy Sources Act (2017). Available online at, https://www.bmwi.de/Redaktion/EN/Artikel/Energy/res2017.html#:~:text=The%202017%20Renewable%20Energy%20Sources%20Act%20therefore%20restricts%20the%20expansion,a%20bid%20to%20reduce%20this.

Giesy, J.P. (2010). Anderson, J.C.; Wiseman, S.B. Alberta Oil Sands Development. *Proc. Natl. Acad. Sci*. USA

Goedkoop M. (1999). Adamage oriented method for life cycle impacts assessment. In: Eco-Indicator 99;

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R (2013). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint level. *Dutch Ministry of Housing, Spatial Planning and Environment* (VROM), The Hague

Goglio, P., Smith, W. N., Worth, D. E., Grant, B. B., Desjardins, R. L., Chen, W., ... & Burgess, P. (2018). Development of Crop. LCA, an adaptable screening life cycle assessment tool for agricultural systems: A Canadian scenario assessment. *Journal of Cleaner Production*, *172*, 3770-3780.

González-García S, Bacenetti J, Negri M, Fiala M, Arroja L. (2013). Comparative environmental performance of three different annual energy crops for biogas production in Northern Italy. *Journal of cleaner production*. Mar 1;43:71-83.

Google Search-(http://www.ecoinvent.org/database/ecoinvent-version-3/reports-of-changes/)

Government of Canada (2021). Available online at https://agriculture.canada.ca/en/agricultural-programs-and-services/agricultural-climate-solutions-farm-climate-action-fund-0

Grafius, D.R., Corstanje, R., Warren, P.H., Evans, K.L., Hancock, S. and Harris, J.A., (2016). The impact of land use/land cover.

Grassi, A., Carvalho, M.D.G., Helm, P., Scarlat, N., (2019) Eds.; ETA-Florence *Renewable Energies*: Lisbon, Portugal, pp. 1863–1868.

Gu, H., Bergman, R., (2017). Cradle-to-grave life cycle assessment of syngas electricity from woody biomass residues. *Wood Fiber Sci*. 49, 177–192.

Guyader J, Baron VS, Beauchemin KA. (2018). Corn forage yield and quality for silage in short growing season areas of the Canadian prairies. *Agronomy*. Sep; 8 (9):164.

Hamel, P., Falinski, K., Sharp, R., Auerbach, D.A., Sánchez-Canales, M. and Dennedy-Frank, P.J., (2017). Sediment delivery modeling in practice: Comparing the effects of watershed characteristics and data resolution across hydroclimatic regions. *Science of The Total Environment*, 580, pp.1381-1388.

Hartmann, J.K. (2006). Life-cycle-assessment of industrial scale biogas plants. Fakultät für Agrarwissenschaften der Georg-August-Universität Göttingen. Dissertation zur Erlangung des Doktorgrades; 2006.

Heath GA, O'Donoughue P, Arent DJ, Bazilian M. (2014). Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation. *Proceedings of the National Academy of Sciences*. Aug 5;111 (31):E3167-76.

Hebblewhite, Mark. (2017) "Billion dollar boreal woodland caribou and the biodiversity impacts of the global oil and gas industry." *Biological Conservation* 206 102-111.

Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M. (2016). Review of life cycle assessment for biogas production in Europe. Renewable and Sustainable Energy Reviews, 54, 1291-1300.

Holka, Małgorzata, and Jerzy Bieńkowski. (2020). "Carbon footprint and life-cycle costs of maize production in conventional and non-inversion tillage systems." Agronomy 10, no. 12 1877.

Holka, Małgorzata, Jerzy Franciszek Bieńkowski, Janusz Jankowiak, and Radosław Dąbrowicz. (2017) "Life cycle assessment of grain maize in intensive, conventional crop production system." *Romanian Agricultural Research* 34 1-10.

Homagain, K., Shahi, C., Luckai, N., & Sharma, M. (2015). Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario, Canada. *Journal of Forestry Research*, *26*(4), 799-809.

Homagain, K., Shahi, C., Luckai, N., & Sharma, M. (2015). Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario, Canada. *Journal of Forestry Research*, 26(4), 799-809.

https://www.maiskomitee.de/Fakten/Statistik/Deutschland/Fl%C3%A4chenertr%C3%A4ge Accessed on 18.02.2021.

Humbert S, Schryver AD, Bengoa X, Margni M, Jolliet O. (2012). Life cycle assessment IMPACT 2002+ User Guide.

Hauschild MZ, Huijbregts MAJ (2015). Life cycle impact assessment. In: Klöpffer W, Curran MA (eds) LCA compendium – the complete world of life cycle assessment. *Springer*, Dordrecht

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017). ReCiPe 2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22(2):138–147

Intergovermental Panel on Climate Change (IPCC). (2014) Fifth assessment report of the intergovernmental Panel on climate change. Genf; 2014.

IPCC (2006). N2O emissions from managed soils, and CO2 emissions from lime and urea application. Geneva: IPCC

IPCC (2013). Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Intergovernmental Panel on Climate Change 2013.

ISO, (2018a) ISO 14000 family — Environmental management systems.

ISO, (2018b). ISO 14001:2015 - Environmental management systems -- Requirements with guidance for use. URL https://www.iso.org/standard/60857.html.

James, G. & Ben, T. (2014). Power to Change: How Alberta Can Green its Grid and Embrace Clean Energy, *The Pembina Foundation and the Pembina Institute, Canada*.

Jaroslav Bernas; Tereza Bernasová; Pedro Gerstberger; Jan Moudrý; Petr Konvalina; Jan Moudrý Jr. (2021). Cup plant, an alternative to conventional silage from a LCA perspective.

Jayasundara, Susantha, Claudia Wagner-Riddle, Goretty Dias, and Kumudinie A. Kariyapperuma (2014). "Energy and greenhouse gas intensity of corn (Zea mays L.) production in Ontario: A regional assessment." *Canadian Journal of Soil Science* 94, no. 1. 77-95.

Jørgensen, M.S. & Andersen, B.H. (2012). "THE CONTROVERSIES OVER BIOENERGY IN DENMARK:'BIO' IS NOT THE SAME AS' SUSTAINABLE, *Environmental Engineering & Management Journal* (EEMJ), vol. 11, no. 11.

JRC, (2018). http://eusoils.jrc.ec.europa.eu/Library/Themes/Erosion/Erodibility/Data/Index.cfm (500 m resolution).

Kalu, Amarachi, Janja Vrzel, Sebastian Kolb, Juergen Karl, Philip Marzahn, Fabian Pfaffenberger, and Ralf Ludwig. (2021). "Considering the Environmental Impacts of Bioenergy Technologies to Support German Energy Transition" *Energies 14*, no. 6: 1534. https://doi.org/10.3390/en14061534 Available online at https://www.mdpi.com/1996-1073/14/6/1534

Karp, A. and Shield, I. (2008). Bioenergy from plants and the sustainable yield challenge. New Phytol. 179: 15_32.

Kiesel, A., Wagner, M., & Lewandowski, I. (2017). Environmental performance of Miscanthus, switchgrass and maize: Can C4 perennials increase the sustainability of biogas production? *Sustainability*, *9* (1), 5. https://doi.org/10.3390/su901 0005

Kolb, S., Plankenbühler, T., Frank, J., Dettelbacher, J., Ludwig, R., Karl, J. and Dillig, M., (2021). Scenarios for the integration of renewable gases into the German natural gas market–A simulation-based optimisation approach. *Renewable and Sustainable Energy Reviews*, 139, p.110696.

Kolb, S., Plankenbühler, T., Pfaffenberger, F., Vrzel, J., Kalu, A., Holtz-Bacha, C., Dillig, M. (2019). Scenario-based analysis for the integration of renewable gases into the German gas market.

Kolb, S., Plankenbühler, T., Homfann, K., Bergerson, J., & Karl, J. (2021). Life cycle greenhouse gas emissions of renewable gas technologies: A comparative review. *Renewable and Sustainable Energy Reviews, 146.* https://dx.doi.org/10.1016/j.rser.2021.111147

Król-Badziak, A., Pishgar-Komleh, S. H., Rozakis, S., & Księżak, J. (2021). Environmental and socio-economic performance of different tillage systems in maize grain production: Application of Life Cycle Assessment and Multi-Criteria Decision Making. *Journal of Cleaner Production*, 278, 123792. Available online at Environmental and socio-economic performance of different tillage systems in maize grain production: Application of Life Cycle Assessment and Multi-Criteria Decision Making - ScienceDirect. Accessed on 20.02.2022

Kühn, M., Ask, M., Juhlin, C., Bruckman, V.J., Kempka, T. and Martens, S., (2016). Interdisciplinary Approaches in Resource and Energy Research to Tackle the Challenges of the Future. *Energy Procedia, 97*, pp.1-6.

Lakhani, R., Doluweera, G. and Bergerson, J., (2014). Internalizing land use impacts for life cycle cost analysis of energy systems: A case of California's photovoltaic implementation. *Applied energy, 116*, pp.253-259.

Lars Häggmark, Karl-Ivar Ivarsson, Stefan Gollvik & Per-Olof Olofsson (2000). Mesan, an operational mesoscale analysis system, Tellus A: *Dynamic Meteorology and Oceanography*, 52:1, 2-20, DOI: 10.3402/tellusa. v52i1.12250.

Lask, Jan, Alejandra Martinez Guajardo, Jan Weik, Moritz von Cossel, Iris Lewandowski, and Moritz Wagner. (2020) "Comparative environmental and economic life cycle assessment of biogas production from perennial wild plant mixtures and maize (Zea mays L.) in southwest Germany." GCB *Bioenergy 12*, no. 8: 571-585.

Leh, M.D., Matlock, M.D., Cummings, E.C. and Nalley, L.L., (2013). Quantifying and mapping multiple ecosystem services change in West Africa. Agriculture, *ecosystems & environment, 165*, pp.6-18.

Lindenmayer, D. B. and Fischer, J. (2006). *Habitat fragmentation and landscape change*. An ecological and conservation synthesis. CSIRO Publishing Melbourne, Australia.

Liu, Changqi, Yaji Huang, Xinye Wang, Yang Tai, Lingqin Liu, and Hao Liu. 1 (2018). "Total environmental impacts of biofuels from corn stover using a hybrid life cycle assessment model combining process life cycle assessment and economic input–output life cycle assessment." *Integrated environmental assessment and management 14*, no. 139-149.

Mahendrappa MK, Salonius PO. (1982). Nutrient dynamics and growth response in a fertilized black spruce stand. *Soil Sci Soc Am J 46(1)*: 127-133.

Maier, J. M., Sowlati, T., & Salazar, J. (2019). Life cycle assessment of forest-based biomass for bioenergy: A case study in British Columbia, *Canada. Resources, Conservation and Recycling*, 146, 598-609.

Martens, S., Hangx, S., Juhlin, C., Kühn, M. and Kempka, T., (2017). *Energy, Resources and the Environment*: Meeting the challenges of the future.

McIntyre, S. and Hobbs, R. (1999). A framework for conceptualizing human effects on landscapes and its relevance to management and research models. *Conservation Biology*, Vol. 13 (1999), 1282–1292.

Mehdi, B., Ludwig, R. and Lehner, B., (2015). Evaluating the impacts of climate change and crop land use change on streamflow, nitrates and phosphorus: a modeling study in Bavaria. *Journal of Hydrology*: Regional Studies, 4, pp.60-90.

Mehmood, M.A.; Ibrahim, M.; Rashid, U.; Nawaz, M.; Ali, S.; Hussain, A.; Gull, M. (2017). Biomass production for bioenergy using marginal lands. *Sustain. Prod. Consum*. 9, 3–21

M. Antrop, V. van Eetvelde, (2000). Holistic aspects of suburban landscapes: visual image interpretation and landscape metrics, Landscape and Urban Planning, Vol 50, pages 43-58.

M.J. Metzger, M. Rounsevell, L. Acosta-Michlik, R. Leemans and D. Schröter, (2006). The vulnerability of ecosystem services to land use change. Agriculture, *Ecosystems and Environment*, Vol. 114, pages 69- 85

Minu Mohan, Chapter 14 - Perovskite Photovoltaics: Life Cycle Assessment, (2018). Editor(s): Sabu Thomas, Aparna Thankappan, Perovskite Photovoltaics, *Academic Press*, Pages 447-480, ISBN 9780128129159, https://doi.org/10.1016/B978-0-12-812915-9.00014-9. (https://www.sciencedirect.com/science/article/pii/B9780128129159000149).

Moore, R.V., Morris, D.G. and Flavin, R.W., (1994). Sub-set of UK digital 1: 50,000 scale river centre-line network. NERC, *Institute of Hydrology*, Wallingford.

Müller, S., Brown, A., Ölz, S., 2011. Renewable energy: policy considerations for deploying renewables information paper. *Renew. Energy* 72. https://doi.org/10.1016/S0960-1481 (00)00187-7.

N. Euliss, L. Smith, W. Duffy, S. Faulkner, R. Gleason and S. Eckles, (2011). Integrating estimates of ecosystem services from conservation programs and practices into models for decision makers, *Ecological Applications*, Vol. 21(3) pages 128-134.

Natural Resources Canada, (2021). Renewable Energy Facts. Available online: https://www.nrcan.gc.ca/sciencedata/data-analysis/energy-data-analysis/energy-facts/energy-and-greenhouse-gas-emissions-ghgs/20063 (accessed on 15 January 2022).

Norouzi, O. Dutta, A. (2022). The Current Status and Future Potential of Biogas Production from Canada's Organic Fraction Municipal Solid Waste. *Energies*, 15, 475. https://doi.org/10.3390/en15020475.

Neugebauer, S., Forin, S., & Finkbeiner, M. (2016). From life cycle costing to economic life cycle assessment introducing an economic impact pathway. *Sustainability*, *8*(5), 428.

O' Donoughue PR, Heath GA, Dolan SL, Vorum M. (2014). Life cycle greenhouse gas emissions of electricity generated from conventionally produced natural gas: systematic review and harmonization. *Journal of Industrial Ecology*. Feb; 18 (1):125-44.

Olmstead, D.E.H.; Ayres, M.J. (2014). Notes from a Small Market: The Energy-Only Market in Alberta. *Electr. J.* 27, 102–111.

Pal, Nandini. (2020) "Eutrophication-An Ecological Menace." *Biotica Research Today* 2, no. 7: 559-561.

Özlem Duyan and Andreas Ciroth, (2013). Life Cycle Costing Quick Explanation Two different methods to perform Life Cycle Costing in openLCAAcessed on 20.04.22, available online at https://www.openlca.org/wp-content/uploads/2015/11/How-to-perform-Life-Cycle-Costing-in-openLCA.pdf

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L. and Alewell, C., (2015). The new assessment of soil loss by water erosion in Europe. *Environmental science & policy*, 54, pp.438-447.

Pessacg, N., Flaherty, S., Brandizi, L., Solman, S., & Pascual, M. (2015). Getting water right: A case study in water yield modelling based on precipitation data. *Science of the Total Environment*, 537, 225-234.

Pieragostini, C., Aguirre, P., & Mussati, M. C. (2014). Life cycle assessment of corn-based ethanol production in Argentina. *Science of the Total Environment*, *472*, 212-225.

Piyathilake, I.D.U.H., Sumudumali, R.G.I., Udayakumara, E.P.N., Ranaweera, L.V., Jayawardana, J.M.C.K. and Gunatilake, S.K., (2020). Modeling predictive assessment of soil erosion related hazards at the Uva province in Sri Lanka. *Modeling Earth Systems and Environment*, pp.1-16.

Pndolfi, J. M., S. R. Connolly, D. J. Marshall, and A. L. Cohen. (2011). Projecting coral reef futures under global warming and ocean acidification. Science 333:418–422. *American Association for the Advancement of Science*.

PRé Consultants. SimaPro Life Cycle Analysis version 7.2 (software). Amersfoort, The Netherlands: PRé Consultants; 2017

Pukkala, T., (2017). Optimal nitrogen fertilization of boreal conifer forest. *Forest Ecosystems*, 4(1), pp.1-10.

Quebec Reference Center for Agriculture and Agri-food (CRAAQ), (2011). Available online at CRAAQ | Cultivating expertise. Sharing knowledge. Accessed on 11.03.2022

Rahman, M.M.; McDermid, G.J.; Strack, M.; Lovitt, J. (2017). A New Method to Map Groundwater Table in Peatlands Using Unmanned Aerial Vehicles. *Remote Sens. 9*, 1057. https://doi.org/10.3390/rs9101057

Randall, G.W., Vetsch, J.A., Huffman, J.R., (2003). Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by time of nitrogen application and use of nitrapyrin. *J. Environ. Qual*. 32, 1764–1772.

Redhead, J.W., May, L., Oliver, T.H., Hamel, P., Sharp, R. and Bullock, J.M., (2018). National scale evaluation of the InVEST nutrient retention model in the United Kingdom. *Science of the Total Environment*, 610, pp.666-677.

Reid, W.V.; Ali, M.K.; Field, C.B. (2020). The Future of Bioenergy; Stanford University: Stanford, CA, USA, [CrossRef]

Rugani, Benedetto, Danielle Maia de Souza, Bo P. Weidema, Jane Bare, Bhavik Bakshi, Blane Grann, John M. Johnston et al. (2019) "Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology." *Science of the Total Environment* 690: 1284-1298.

Sadeghi, S.M.; Noorhosseini, S.A.; Damalas, C.A. (2018). Environmental Sustainability of Corn (Zea Mays L.) Production on the Basis of Nitrogen Fertilizer Application: The Case of Lahijan, Iran. *Renew. Sustain. Energy Rev*. 95, 48–55.

Sebastien Humbert, (2014). World Food LCA Database Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Available online at https://www.academia.edu/24589302/World_Food_LCA_Database_Methodological_Guidelines_for_the_Life_Cycle_Inventory_of_Agricultural_Products. Accessed on 10.03.2022

Shapouri, H., Duffield, J. A. and Wang, M. (2002). The energy balance of corn ethanol: An update. *Agricultural Economic Report 813*. US Department of Agriculture, Washington, DC.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N. and Vigerstol, K., (2016). InVEST+ VERSION+ User's Guide. *The Natural Capital Project*.

Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D.,Fisher, D., Glowinski, K., Griffin, R., Guannel, G., Guerry, A., Johnson, J., Hamel, P., Kennedy, C., Kim, C.K.,Lacayo, M., Lonsdorf, E., Mandle, L., Rogers, L., Toft, J., Verutes, G., Vogl, A. L., and Wood, S. (2020). InVEST 3.8.5.post0+ug.gdd887c5.d20201118 User's Guide. *The Natural Capital Project*, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Souza, D. M., Teixeira, R. F., & Ostermann, O. P. (2015). Assessing biodiversity loss due to land use with Life Cycle Assessment: are we there yet? *Global change biology*, 21(1), 32-47.

Statistics Canada (2013). Table 25-10-0020-01 Electric Power, Annual Generation by Class of Producer 2013. Available online at: Electric power, annual generation by class of producer (statcan.gc.ca) https://doi.org/10.25318/2510002001-eng . Accessed on 26 January 2022)

Strzalka, R., Schneider, D. and Eicker, U., (2017). Current status of bioenergy technologies in Germany. *Renewable and Sustainable Energy Reviews*, 72, pp.801-820.

Supasri, Titaporn, Norihiro Itsubo, Shabbir H. Gheewala, and Sate Sampattagul. (2020). "Life cycle assessment of maize cultivation and biomass utilization in northern Thailand." Scientific Reports 10, no. 1 1-13.

Tallis, H., Rickets, T., Guerry, A., Wood, S., Sharp, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, E., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lons, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., (2014) InVEST 3.0.1 User's Guide: Integrated Valuation of Environmental Services and Tradeoffs.

Tamanini, J., Bassi, A., Hoffman, C. and Valenciano, J., (2014). Global Green Economy Index: Measuring National Performance in the Green Economy. United Nations: Washington, DC, USA.

Terrado, M., Acuña, V., Ennaanay, D., Tallis, H. and Sabater, S., (2014). Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin. Ecological Indicators, 37, pp.199-209.

Thran, D., Schaubach, K., Majer, S., & Horschig, T. (2020). Governance of sustainability in the German biogas sector—adaptive management of the Renewable Energy Act between agriculture and the energy sector. *Energy, Sustainability and Society*, 10(1), 1-18.

U.S. Life Cycle Inventory Database (2012). National Renewable Energy Laboratory, 2012. Available online at https://www.lcacommons.gov/nrel/search. Accessed on July 13, 2021

Ureta, J. C., Clay, L., Motallebi, M., & Ureta, J. (2020). Quantifying the Landscape's Ecological Benefits—An Analysis of the Effect of Land Cover Change on Ecosystem Services. *Land*, 10(1), 1-1. https://doi.org/10.3390/land10010021

Verkerk, P. J., Fitzgerald, J., B., Datta, P., Dees, M., Hengeveld, G. M., Lindner, M., Zudin, S., (2019). Spatial distribution of the potential forest biomass availability in Europe. *Forest Ecosystems*. 6. 1–11. DOI:

Vera, I., Wicke, B., Lamers, P., Cowie, A., Repo, A., Heukels, B., & van der Hilst, F. (2022). Land use for bioenergy: Synergies and trade-offs between sustainable development goals. *Renewable and Sustainable Energy Reviews*, 161, 112409.

Vigiak, O.; Borselli, L.; Newham, L. T. H.; McInnes, J.; Roberts, A. M. (2012). Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. Geomorphology.

Vohra, Karn, Alina Vodonos, Joel Schwartz, Eloise A. Marais, Melissa P. Sulprizio, and Loretta J. Mickley (2021) "Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem." *Environmental Research* 195: 110754.

von Trentini, F., Leduc, M. and Ludwig, R., (2019). Assessing natural variability in RCM signals: comparison of a multi model EURO-CORDEX ensemble with a 50-member single model large ensemble. *Climate Dynamics*, pp.1-17.

Wagner, M., Mangold, A., Lask, J., Petig, E., Kiesel, A., & Lewandowski, I. (2019). Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. GCB Bioenergy, 11(1), 34–49. https://doi.org/10.1111/gcbb.12567

Walston, L. J., Li, Y., Hartmann, H. M., Macknick, J., Hanson, A., Nootenboom, C., & Hellmann, J. (2021). Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. *Ecosystem Services*, *47*, 101227.

Wang, Q. L., Li, W., Gao, X., & Li, S. J. (2016). Life cycle assessment on biogas production from straw and its sensitivity analysis. *Bioresource technology*, 201, 208-214.

WCRP CORDEX (Coordinated Regional Climate Downscaling Experiment .https://cordex.org/ (Accessed 14.02.2021).

Weber, G. and Cabras, I., (2017). The transition of Germany's energy production, green economy, low-carbon economy, socio-environmental conflicts, and equitable society. *Journal of Cleaner Production*, 167, pp.1222-1231.

Wei Yang, Johan Andréasson, L. Phil Graham, Jonas Olsson, Jörgen Rosberg, Fredrik Wetterhall; (2010). Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrology Research* 41 (3-4): 211–229. doi: https://doi.org/10.2166/nh.2010.004

Weldemichael, Y., & Assefa, G. (2016). Assessing the energy production and GHG (greenhouse gas) emissions mitigation potential of biomass resources for Alberta. *Journal of Cleaner Production*, *112*, 4257-4264.

Wernet, G., Bauer, C., Steubing, B. et al. (2016). The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Whitman, T., Yanni, S. and Whalen, J., (2011). Life cycle assessment of corn stover production for cellulosic ethanol in Quebec. *Canadian Journal of Soil Science*, 91(6), pp.997-1012.

World Food and Agriculture - Statistical Pocketbook (2018). (fao.org) Available online at FAOSTAT data (Food and Agriculture Organization Corporate Statistical Database) for the 2011 harvested area - Google Search

Woznicki, S.A., Cada, P., Wickham, J., Schmidt, M., Baynes, J., Mehaffey, M. and Neale, A., (2020). Sediment retention by natural landscapes in the conterminous United States. *Science of The Total Environment*, 745, p.140972.

Case study 1 appendix

Appendix a

Description of InVEST input data, data sources required for the model set-up/calibration and their resolutions in case study one.

Input data	**Sources**	**Description**
(Digital Elevation Model) The DEM is a GIS raster file. We made sure the DEM is corrected by filling in sinks. To ensure proper flow routing which helps to determine the slope.	COPERNICUS (DEM E4030+E4020) http://land.copernicus.eu	Or. Resolution.: User Res.: 250 m
(Rainfal erosivity index) GIS raster which variables depends on the duration & intensity of rainfall in a location. The higher the rain stom, the greater the erosion potentials.	JRC https://esdac.jrc.ec.europa.eu/ (Roose, 1996): http://www.fao.org/docrep/t1765e/t1765e0e.htm	Time period: 1981-2010
(soil erodibility); K is a measure of the soil particle susceptibility to detachment & transported by runoff and rainfall. The unit index values are ton·ha·(ha·MJ ·mm)−1	JRC: http://eusoils.jrc.ec.europa.eu/Library/Themes/Erosion/Erodibility/Data/Index.cfm (500 m resolution)	Or. Res.: 500 m User. Res.: 250 m
(land use land cover); Is a GIS raster file, the integer code is LULC for each cell (e.g. 11= maize). It shows different land use classes of an area	CORINE 2012	Or. Res.: 1 km grids/year User. Res.: 250 m
(river network)	http://www.mapcruzin.com/free-germany-arcgis-maps-shapefiles.htm	
(Precipitation) is s GIS raster dataset with a non-zero value		

for average annual precipitation for each cell. The precipitation values should be in millimeters.		
	Deutsche weather service (https://www.dwd.de)	Or. Res.: 1 km grids/year User. Res.: 250 m Period: 1981-2010
Reference Evapotranspiration (reference evapotranspiration); is the potential loss of water from soil by both evaporations from the soil and transpiration by healthy plant (or grass) if sufficient water is available. The reference evapotranspiration values should be in millimeters & it is a raster dataset too.		Or. Res.: 1 km grids/year User. Res. 250 m Period: 1991-2010
(Depth to root restricting layer); Root restricting layer depth is the soil depth at which root penetration is strongly inhibited because of chemical or physical characteristics. It is a GIS raster dataset valuing each cell.	German federal ministry for geosciences and raw materials (BGR) (https://geoviewer.bgr.de/mapapps/) CITATION TITLE Physiologische Gründigkeit der Böden Deutschlands **eng-US** Title translated: Soil depth in Germany ALTERNATE TITLES PhysGru1000_250 CREATION DATE 2014-04-09 PUBLICATION DATE 2015-08-03 EDITION 1.0 EDITION DATE 2014-04-09 PRESENTATION FORMAT mapDigital UNIQUE RESOURCE IDENTIFIER VALUE 3650b770-8d14-11e5-9984-8851fb422c62 RESPONSIBLE PARTY - AUTHOR INDIVIDUAL'S NAME Bug, Jan Fabian, Dr. ORGANIZATION'S NAME Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Or. Res.: 250 m grid User. Res. 250 m
(Plant available water fraction); is the fraction of water that can be stored in the soil profile that is available for plants' use. PAWC is a	German federal ministry for geosciences and raw materials (BGR) (https://geoviewer.bgr.de/mapapps/)	Or. Res.: 250 m grid User. Res. 250 m

fraction from 0 to 1. Also, a raster file.	CITATION TITLE Nutzbare Feldkapazität im effektiven Wurzelraum in Deutschland **eng-US** Title translated: Available water capacity in the rooting zone of German soils ALTERNATE TITLES NFKWe1000_250 CREATION DATE 2014-06-14 PUBLICATION DATE 2015-08-03 EDITION 1.0 EDITION DATE 2014-06-20 PRESENTATION FORMAT mapDigital UNIQUE RESOURCE IDENTIFIER VALUE 0b25c1a6-61c0-4674-a332-3c52cf7d282c RESPONSIBLE PARTY - AUTHOR INDIVIDUAL'S NAME Duijnisveld, Wilhelmus, Dr. ORGANIZATION'S NAME Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	
(land use map)	CORINE 2012	Or. Res.: 1 km grids/Jahr Benutz. Res.: 250 m
(Watersheds) Shape file; Is a layer of watersheds that shows what each watershed contributes to a point of interest where water quality will be analyzed? It is a file of polygons	Vigiak et al. 2012	Or. Res.: 1 km grids/Jahr user. Res.: 250 m
Biophysical table; Is a csv table of LULC classes in an excel format with water quality coefficients data showing attributes of each class rather than showing individual cells in a raster map	http://www.fao.org/geonetwork/srv/en/main.home . Hamel P., Chaplin-Kramer, R., Sim, S.,Mueller,C.,2015. A new approach to modelling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 166–177.	

Appendix b

Calibration Data and Sources

Model	Input data	Data Sources	Description
SDR	(Soil erosion map)	European Soil Data Centre (ESDAC), European Commission, Joint Research Centre https://esdac.jrc.ec.europa.eu/tmp_dataset_access_req_17702#tabs-0-filters=2	Or. Res.: 100 m user. Res.: 250 m
WYM	Durchschnittlicher jährlicher Nettoabfluss Water content) (1990-2010),simulated with LISFLOOD-Modell.	EC-JRC LISFLOOD model output 1990-2014 (De Roo, 2014) (Average annual net runoff (freshwater availability) (1990-2010), simulated using the LISFLOOD model.)	Or. Res.: 5 km User. Res.: 250 m
NDR	different Regional NDR-Model	Bach, M., 2015. Stickstoff-Bilanzierungen Notwendigkeit harmonisierter Ansätze. http://docplayer.org/64047928-Stickstoff-bilanzierungen-notwendigkeit-harmonisierter-ansaetze.html	Municipality

Bioenergy in Germany Facts and Figures 2017 and cover scale on modelling urban ecosystem services. Landscape Ecology, 31(7), pp.1509-1522.

Germany 2020 energy policy review. Available online at https://www.iea.org/reports/germany-2020**.** Accessed on 20.01.2021

Case study two appendix

Appendix c

Part of the data used for the QAQC before the harmonization/conversion process to match our functional unit.

			Maize Cultivation Inputs									ize Transp	Maize Properties						
Reference	System Boundary	Functional Units	Maximum Fertilizer (kg N/ha)	Fertilizer used (kg N/ha)	Phosphorus Fertilizer (P2O5) [kg P2O5/ha]	Potassium Fertilizer (K2O) [kg K2O/ha]	Herbicides (kg/ha)	Fuel (L/ha)	Irrigation (mm/m2)	Maize Yield (dt FM/ha)	Direct nitrous oxide emissions (%/kg N)	Transport Distance (km)	Dry Matter (%/kg fresh matter)	Organic Matter (%/kg dry matter)	Biogas Yield (lN/kg organic matter)	Methane Content (%/mN3 biogas)	Power Requirement [%/kWh generated power)	Heat Requirement [kWh/mN3 biogas)	Electrical Power (kWh)/GJ Mg grain
Dressler et al., 2012	radle to Grav	1 kg fresh matter of maize; 1 kWh of electricity produced	180,000	68-83	51-55	73-82	1,500	66.4-82.9	None - 610	398.1-468.8	1,000	20,000	33,000	96,000	650,000	52,000	7,000	0,256	255,000
Filipa et al.,	company gate	biogas from AD	220,000	220,000	80,000			215,000	400 m3	20 (ton DS /ha)			20 (ton DS /ha)		650 for tons ODS	55-75	0,000	0,000	0,000
Titaporn et a	cradle to gate	1 kg of maize grain	312.50	93.75 kg/ha	104,000	104,000	43497,000	68.75 L/ha		3420 - 4,400 kg/ha									
Lijo et al., 20	Cradle to gat	100kWel	170 kg / ha	135 kg	0.32	0.32	0,000	0.33	0.67 m3 water	0,000	0,000	0.7							
Whitman et al., 2011		corn stover	123.5	114,000	36,000		1.9kg/ha	17 L/ha	0,000	6.1 t/ ha		20,000			280L /t dry stover				
Jaroslav et al	Cradle to farm gate	matter & 1 ha	120,000	70-85	0.34 kg	1.25 kg	1.25kg		300,000	17.6/55 per ha		10 km							
Fusi et al., 2	cradle to gra	1 kWh of electricity	130,000	60 kg/ha urea	0,000	0,000	0,000	120 kg/ha	4400 m3 / ha	21.41 - 53.3 tons/ha		35 km	10.7 %	3.40 kg/day m3		52.1%		1.1 MWh	7972 MWh/a
C. Pieragostini et al	cradle to gat	corn-ethanol	0.489	0.489	8.667E-05 kg			127kg/ha	4440 m3/ha	7726 kg/ha		30,000							
Jayaundara et al., 2014	Cradle to gat	1 Mg of grai	120,000	91-146	6,95 MJ kg P2O5	3.73 kg	1.89kg	0.47-17.0	0,000	7.6 -10.6	0.0115-0.013	30,000							0.15
Malgorzata Holka	Cradle to gat	One hectare of	143.8	129.2	75.3	97.7	0.2-07	87 kh/ha	0,000										
Liu et al., 2017	unit of well-to-wheels	1 MJ of biofuel	137.66		0,000	0,000	35.5	24,000	0,000	10.35 t/ha	8.99E-02	30,000							

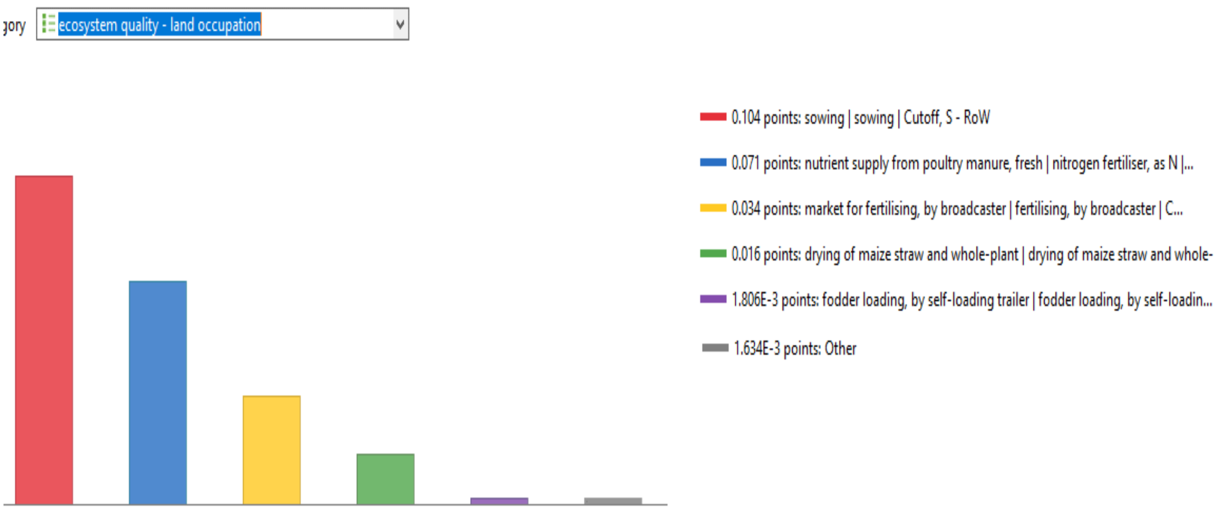
QAQC Literatures showing their functional units, boundaries and method used.

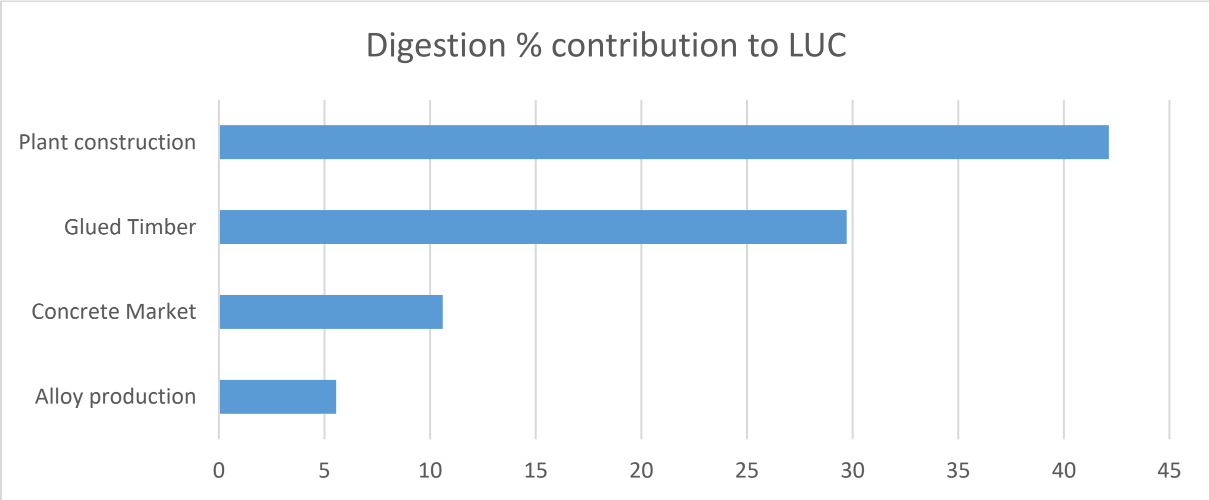
QAQC Literature	System Boundary	Functional Units	Maximum Fertilizer (kg N/ha)	LCIA Method Used
Dressler et al., 2012	Cradle to Grave	1 kg fresh matter of maize; 1 kWh of electricity produced in a combined heat and power generation plant (CHP) using biogas.	180,000	CML baseline
Filipa et al., 2020	birth to company gate	1 m3 of biogas from AD	220,000	Simapro/ Eco-indicator/IPCC GWP
Titaporn et al., 2020	cradle to gate	1 kg of maize grain	312.50	ReCipe
Lijo et al., 2014b	Cradle to gate	100kWel	170 kg / ha	CML baseline
Whitman et al., 2011		1 ton of dry corn stover	123.5	Process-based LCA in MS Excel
Jaroslav et al., 2021	Cradle to farm gate	1 ton of dry matter & 1 ha	120,000	SimaPro/ ReCipe Midpoint
Fusi et al., 2016	cradle to grave	1 kWh of electricity	130,000	CML 2001
C. Pieragostini et al., 2013	cradle to gate	1 MJ of corn-ethanol	0.489	Eco indicator/ReCipe

Jayaundara et al., 2014	Cradle to gate	1 Mg of grain	120,000	
Malgorzata Holka &Jerzy Mienkowski., 2020	Cradle to gate	One hectare of maize cultivation area and one ton of grain	143.8	CML
Changqi Liu et al., 2017	functional unit of well-to-wheels	1 MJ of biofuel	137.66	TRACI

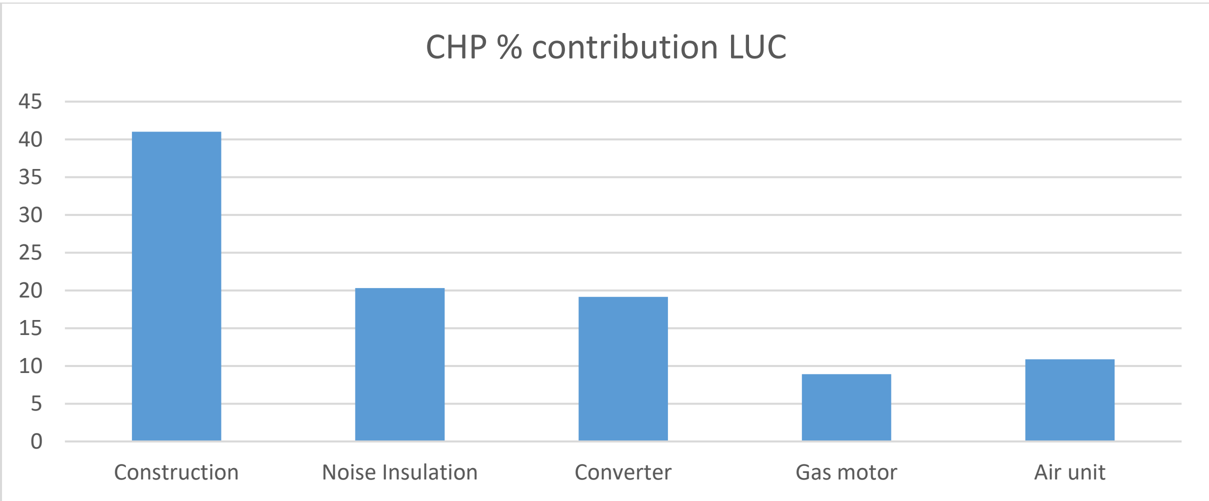
Appendix d

Maize silage production %contribution to LUC

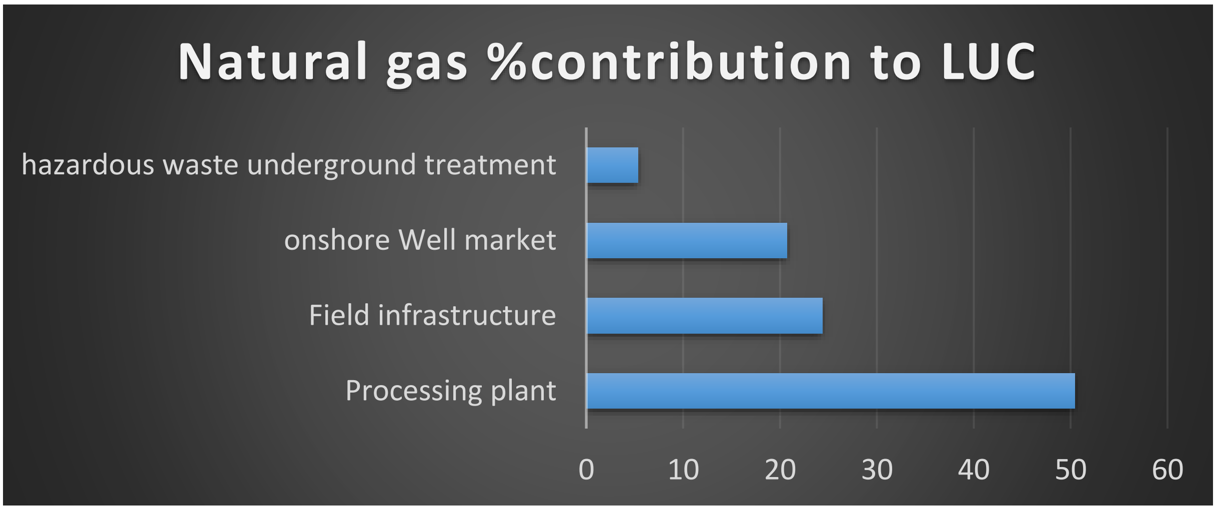




Part of the sensitivity analysis for the digestion stage



Part of the sensitivity analysis for the conversion stage



Part of the sensitivity analysis for natural gas

Appendix e

2021_Maize silage production2

(●) Flow — Carbon dioxide, fossil - Emission to air/unspecified

( ) Impact category — total - total

Contribution	Process	Amount	Uni
100.00%	2021_Maize silage production - CA-...	84.61180	kg
66.19%	market for pesticide, unspecified | p...	56.00608	kg
20.22%	nutrient supply from poultry manur...	17.10942	kg
08.23%	drying of maize straw and whole-pl...	6.96345	kg
03.43%	sowing | sowing | Cutoff, S - RoW	2.89966	kg
01.78%	market for fertilising, by broadcaste...	1.50889	kg
00.09%	fodder loading, by self-loading trail...	0.08032	kg
00.04%	market for maize grain | maize grain...	0.03519	kg
00.01%	harvesting, by complete harvester, ...	0.00540	kg
00.00%	transport, freight, lorry >32 metric t...	0.00260	kg
00.00%	tillage, rotary cultivator | tillage, rota...	0.00079	kg

The contribution analysis showing the percentage of carbon dioxide emission based on different processes.

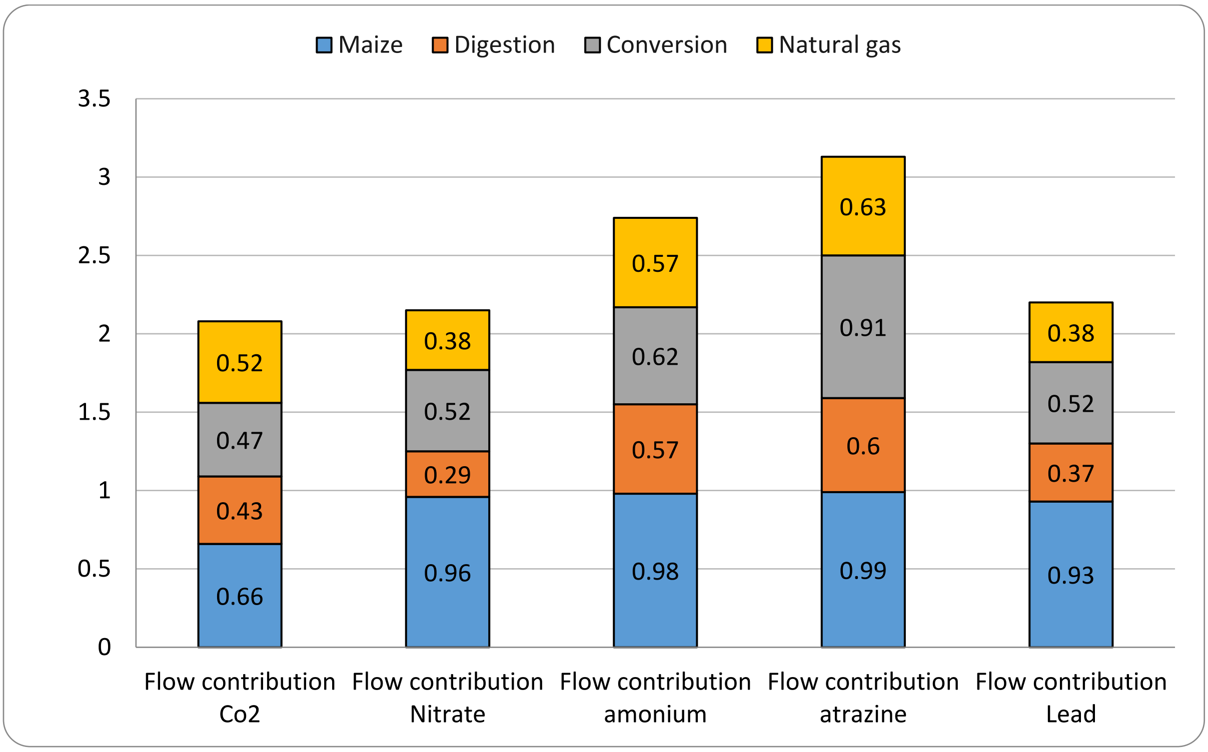
Appendix f

More inventory result analysis for the flows sensitivity analysis on maize production

For the emitted flow category elements, the focus are initially on nitrates, Co_2, atrazine, ammonia and lead in some cases being the most significant among other emissions in these processes before lead was excluded from the analysis due to insufficient data. Above mentioned comparison covers for the maize silage production, the digestion & conversion processes compared with natural gas figure. The results were converted to ratio in the graph, while the model percentage values are in table.

In addition, the life cycle stages were simulated and compared to see which stage contributes

For the emitted elements, focus are on nitrates, lead, Co_2, atrazine, ammonia being the most significant among others.



The chart shows that atrazine is the highest impact from maize cultivation and digestion process has the lowest impact from atrazine too

The highest here is Atrazine from maize cultivation to air is as low as 32.9%, while to the water surface and ground at 95 and 99 or 0.99% compared to (Co2, nitrate, ammonium and lead). However, the lowest is the nitrate emission from digestion process.

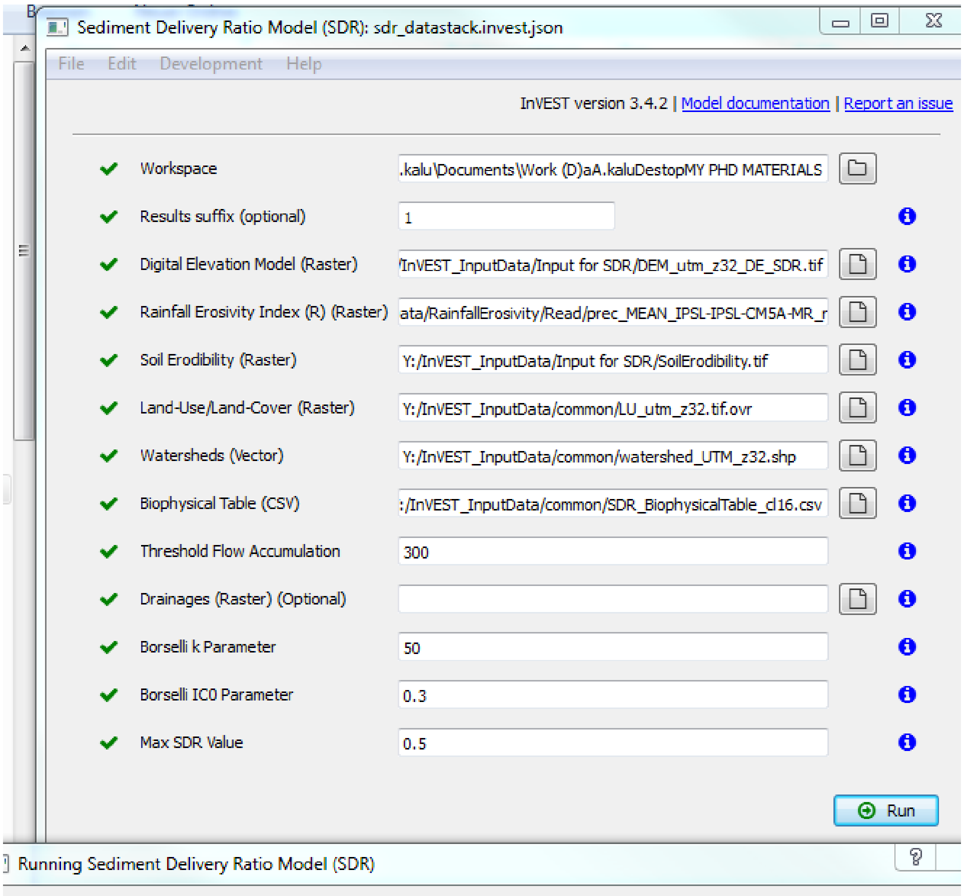
Initial assumptions: The mineral extraction under maize silage production process has the highest impact at 0.91% because of the aluminum, copper and other mineral mining that took place in the supply chain before the maize cultivation seemed like tripled compared to just digestion which a single entity with (e.g. sheds, agrochemicals, farm machines) . The smallest is fossil fuel use from natural gas production with 0.01% impact which we assumed reasonable coming from just the fossil fuel component that went into the equipment’s used to extract natural gas alone. (E.g. seismic equipment’s).

Appendix g

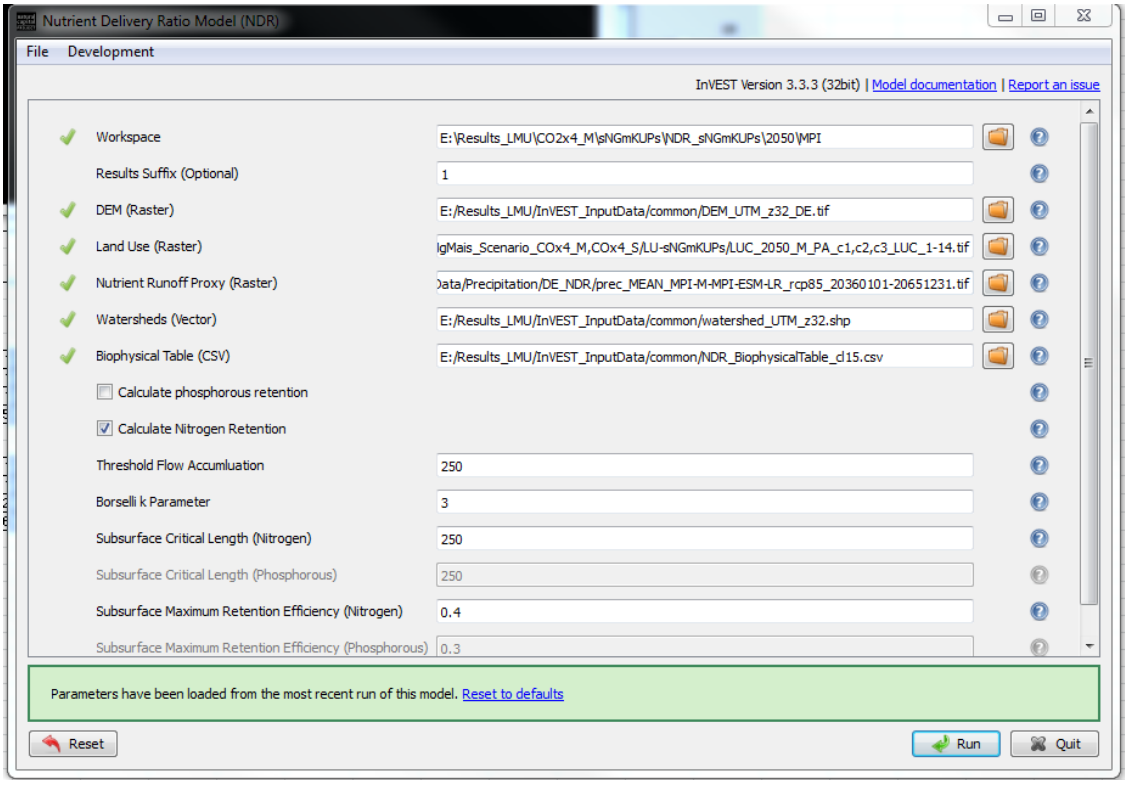
Digestion: The dataset represents the manufacturing of aluminium alloyed, metallic matrix composite, billets and ingots. It represents production of ceramic reinforced aluminium alloys. Primary aluminium slab is used as the main aluminium bearing input (75-80%). Scrap aluminium is used as aluminium input up to 20-15%. Aluminium scrap and cold primary slabs and other metal additive are pre-heated in a furnace to remove all trace of water. Powder alloying additives are dried by cycloning with hot air. Aluminium is melt in an induction furnace where aluminium based alloys, silicium carbide and bore carbide powders and pure metals are added to obtain desired alloy composition. Refractory material is used to prevent oxidation of molten aluminium alloy and as coating for mold. Final product is cast by direct chilled vertical casting or ingot mold and allowed to cool down slowly in an oven. This activity ends with the casting in ingot by direct chilled vertical casting and cooling. The dataset includes material and energy related to the alloy production and casting: scrap and primary metal input, preheating, induction melting, alloying, degassing, water use and ingot casting)

Appendix h

InVEST SDR model sample



InVEST NDR model sample



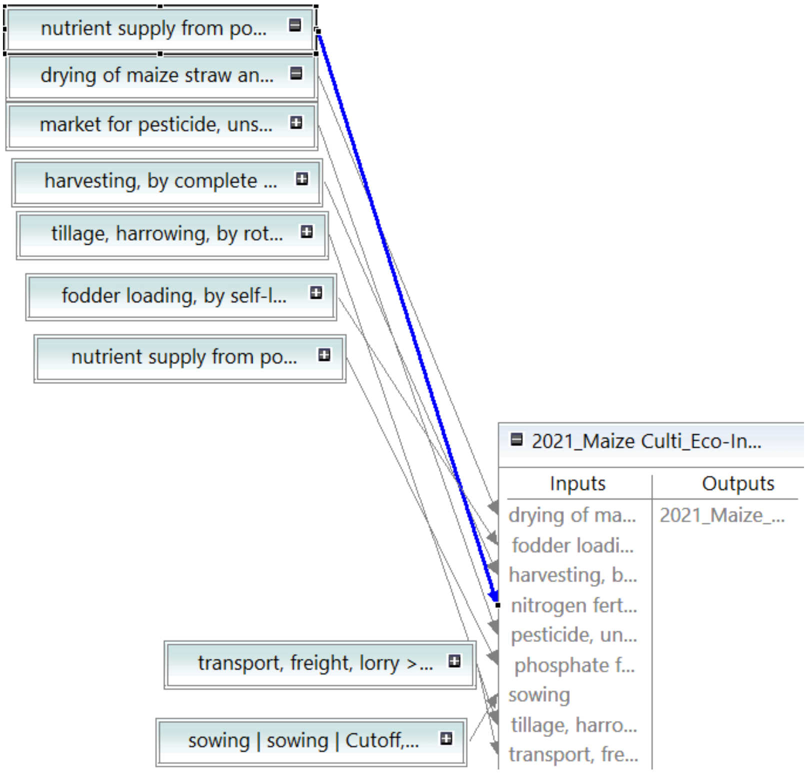
Appendix i

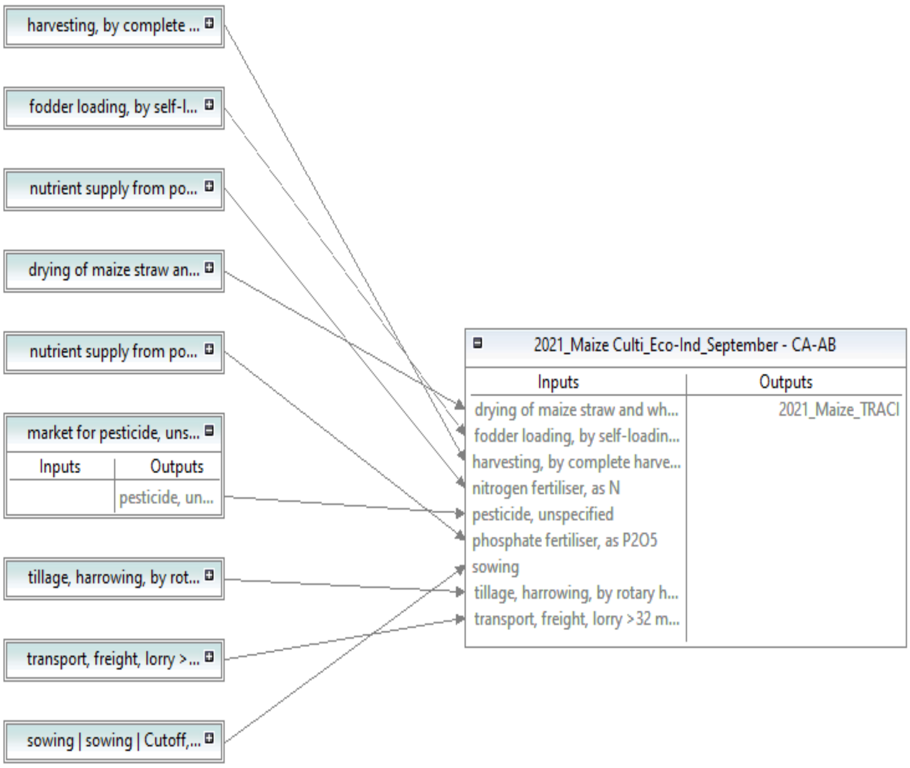
Scenarios creation

The sustainable and non-sustainable scenarios were determined based on the potential demand of biomass in tons per hectare and predetermined scenarios we got from the energy engeneering team (EVT). We got two major scenarios, a black and an unrealistic scenario such as BAU_M and a sustainable scenario CO2_*4 from the EVT team which we analyzed. The black scenario which would involve over exploitation of forest biomass for example, a clear cut of an important forest land was created for an illustration purpose only. The sustainable scenarios which was finally chosen as the best environmentally acceptable scenario involves the increasing of the CO2 tax price up to four times compared to the current state, (Kolb et al., 2019). Our final sustainable scenario saw a reduction of demanded biomass by 46 percent in other to create a balance between the technological demand and ecological sustainability. More scenarios were processed in the course of trying to find out the most suitable one. These scenarios were defined by the EVT team and post processed by GEO team to see their impact on the environment considering few selected RGP´s using the reference (2018) and future state (2030, 2040, 2050).

Appendix j

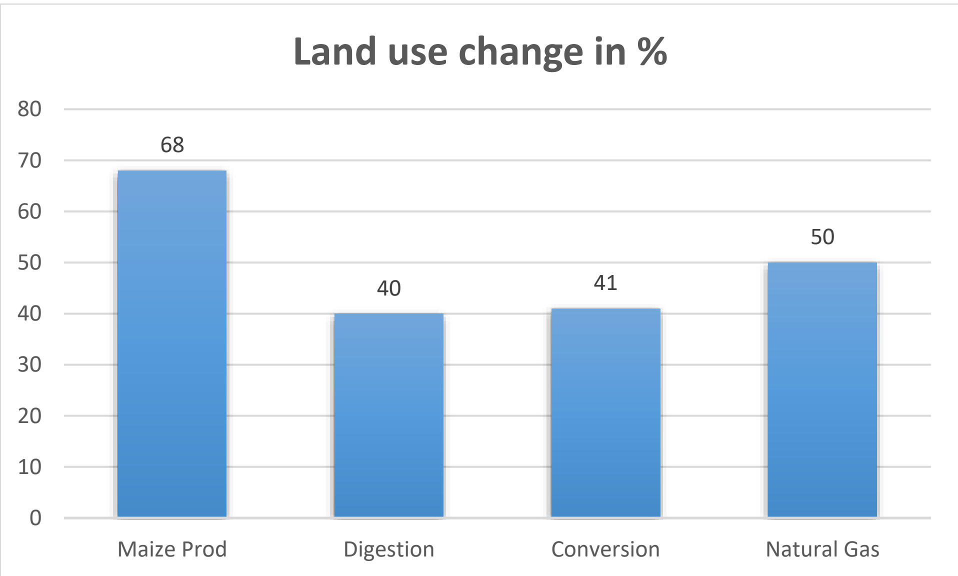
Model graph and impact analysis chart taken from the model directly showing the order of the flow category indicators and major contributing elements of (H.E.R)





Name	Category	Inventory result	Impact factor
total - total			
resources - total			
human health - ionising radiation			
ecosystem quality - land occupation			
human health - ozone layer depletion			
human health - respiratory effects			
ecosystem quality - acidification & eutrophication			
P drying of maize straw and whole-plant | drying of maize straw and w	016:Support activities to agriculture and p...		
P nutrient supply from poultry manure, fresh | nitrogen fertiliser, as N |	016:Support activities to agriculture and p...		
P market for pesticide, unspecified | pesticide, unspecified | Cutoff, S -	202:Manufacture of other chemical produ...		
F Nitrogen oxides	Emission to air / high population density	0.01295 kg	0.55682 points/kg
F Nitrogen oxides	Emission to air / low population density	0.00978 kg	0.55682 points/kg
F Sulfur dioxide	Emission to air / high population density	0.04873 kg	0.10146 points/kg
F Sulfur dioxide	Emission to air / low population density	0.01783 kg	0.10146 points/kg
F Nitrogen oxides	Emission to air / unspecified	0.00290 kg	0.55682 points/kg
F Ammonia	Emission to air / high population density	0.00095 kg	1.51750 points/kg
F Ammonia	Emission to air / low population density	0.00033 kg	1.51750 points/kg
F Ammonia	Emission to air / unspecified	0.00016 kg	1.51750 points/kg
P nutrient supply from poultry manure, fresh | phosphate fertiliser, as P	016:Support activities to agriculture and p...		
resources - fossil fuels			
ecosystem quality - total			
human health - climate change			
human health - carcinogenics			
ecosystem quality - ecotoxicity			
human health - total			
resources - mineral extraction			

Appendix k



Another model run initially carried out to be able to make a clear comparison between biogas pathways and the natural gas one when input data are manipulated.

Appendix l

Inputs phase of openlca model used

Inputs/Outputs: JULY2021_Maize silage productionbiogas2

Inputs

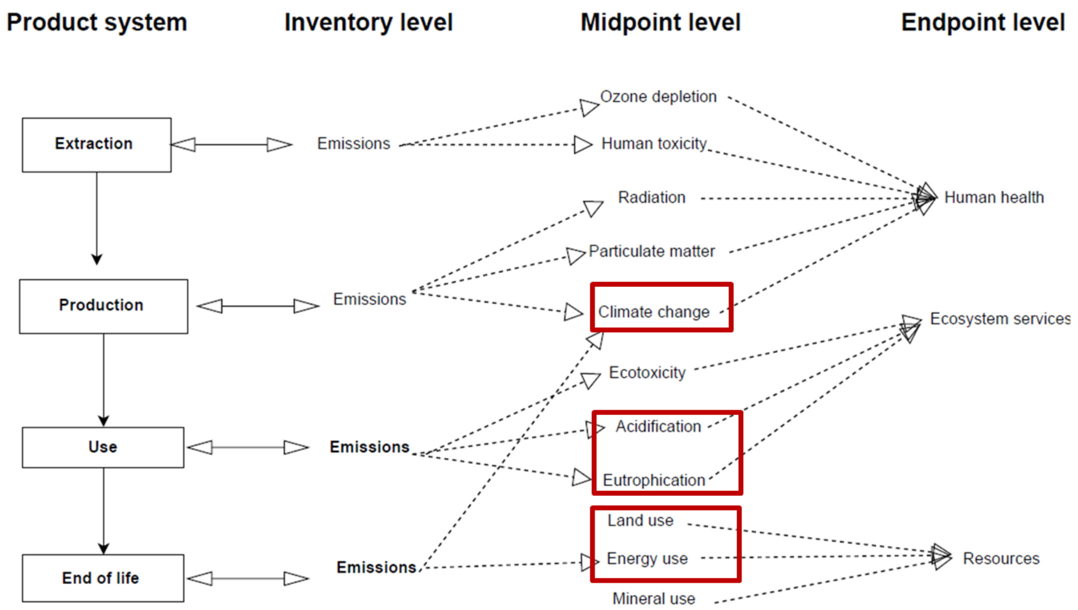
Flow	Category	Amount	Unit	C...	U..	A	Provider	Data quality
drying of maize straw and whole-plant	016:Support activities to agriculture and post-harvest crop activities/0...	1.00000	m3		n.		market for drying of maize straw and whole-plant | dry...	(2; 3; 2; 2; 1)
fertilising, by broadcaster	016:Support activities to agriculture and post-harvest crop activities/0...	1.00000	ha		n.		fertilising, by broadcaster | fertilising, by broadcaster | ...	
fodder loading, by self-loading trailer	016:Support activities to agriculture and post-harvest crop activities/0...	1.00000	m3		n.		fodder loading, by self-loading trailer | fodder loading,...	
harvesting, by complete harvester, groun...	016:Support activities to agriculture and post-harvest crop activities/0...	2.50000	m2		n.		harvesting, by complete harvester, ground crops | harv...	
Herbicides, unspecified	Emission to soil/agricultural	3.00000	kg		n.			
maize grain	011:Growing of non-perennial crops/0111:Growing of cereals (except rice...	1.00000	kg		n.		maize grain production | maize grain | Cutoff, U - CA-...	
nitrogen fertiliser, as N	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, ...	120.00000	kg		n.		market for nitrogen fertiliser, as N | nitrogen fertiliser, a...	
pesticide, unspecified	202:Manufacture of other chemical products/2021:Manufacture of pestici...	1.00000	kg		n.		market for pesticide, unspecified | pesticide, unspecifie...	
sowing	016:Support activities to agriculture and post-harvest crop activities/0...	1.00000	ha		n.		sowing | sowing | Cutoff, U - CA-QC	
tillage, rotary cultivator	016:Support activities to agriculture and post-harvest crop activities/0...	1.00000	m2		n.		tillage, rotary cultivator | tillage, rotary cultivator | Cuto...	
transport, freight, lorry >32 metric ton, E...	492:Other land transport/4923:Freight transport by road	40.00000	kg*...		n.		market for transport, freight, lorry >32 metric ton, EUR...	
anaerobic digestion plant, agriculture, wit...	429:Construction of other civil engineering projects/4290:Construction o...	1.00000	Ite...		n.		market for anaerobic digestion plant, agriculture, with ...	
heat and power cogeneration unit, 1MWe...	4220:Construction of utility projects/4220a: Construction of utility pro...	1.00000	Ite...		n.		market for heat and power cogeneration unit, 1MWel, ...	

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality en...	Description
2021_Maize silage	**A:Agriculture, forestry and fis...**	**1.00000**	**kg**		**none**				
biogas, from grass	19:Manufacture of coke and ref...	1.00000	m3		none	☐			Biogas from...

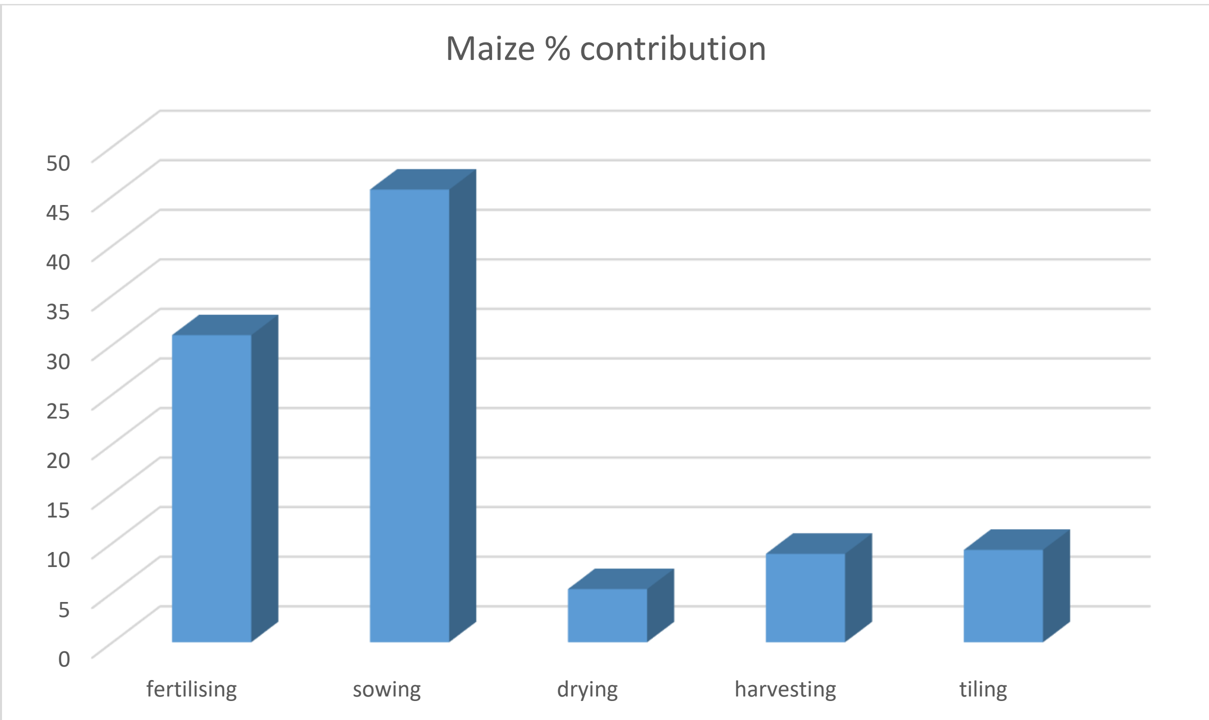
Appendix m

The indicators are in three stages namely, the initialpoint, midpoint and endpoint. This study focused more on the endpoint impacts also known as endpoint level indicators which can also be applied to protected areas in LCA analysis. Those areas are typically quantified as the natural environment, human healths and natural resources, (Hauschild and Huijbregts, 2015). Different names are sometimes used by different authors to explain the endpoint indicator. For instance, the disability- adjusted years (DALY) that quantifys the years of life lost due to premature deaths and disability, can be used for the impact assessment on human health at an endpoint level according to Huijbregts et al., 2017 as cited in Arrvidsson. R, 2021. However, the midpoint indicators chosen at an intermediate point between the product system and the endpoint level includes; climate change, stratosphere ozone layer depletion, acidification and eutrophication.



Schematic diagram showing the LCA indicators development in different levels as modified from Goedkoop et al., 2013.

Appendix n



Appendix n: Impact percentage contribution of different cultivation stages on land where sowing has more impacts on land, drying has the list direct land use change during the sensitivity analysis.