University of Southern Denmark

Prospective Environmental Performance Assessment of Africa's Food Demand

Mariana Cipriano Jordão

T220014101

MSc Thesis Project

June 2020

Department of Chemical Engineering, Biotechnology and Environmental Technology

Faculty of Engineering

University of Southern Denmark

Title	**Prospective Environmental Performance Assessment of Africa’s Food Demand**
Danish Title	Prospektiv Vurdering af Miljøpræstationer af Afrikas Fødevarebehov
Project Type	Master’s Thesis
Course Code	T220014101
Field of Study	Environmental Engineering
Credits	40 ECTS
Language	English
Project period	September 2019 – June 2020
Written by	**Mariana Cipriano Jordão**
University	TEK Faculty of Engineering University of Southern Denmark Campusvej 55 5230 Odense M, Denmark
Supervisor	Morten Birkved Professor SDU Life Cycle Engineering

Preface

This Master's thesis of 40 ECTs was written by Mariana Cipriano Jordão in the Autumn and Spring semester of 2019/2020 at the Department of Chemical Engineering, Biotechnology and Environmental Technology (KBM) of the University of Southern Denmark. The project is the result of 8 months of research, modelling, and analysis, through data collection from the Food and Agriculture Organisation of the United Nations. The supervisor for the project was Professor Morten Birkved.

The thesis explores the environmental impacts of the current African agricultural system, as well as possible future pathways regarding population growth, farming techniques and diet, which could affect agriculture by 2050.

The project comprises a Life Cycle Assessment (LCA) of the main inputs and outputs of African agriculture, as well as potential elements affecting it in the future, to design prospective agricultural models for the continent.

02.06.2020 Mariana Cipriano Jordão

Abstract

Agriculture in Africa is essential to human welfare and economic growth, yet research has shown that its productivity is low, and the population continues to suffer from food insecurity and undernourishment. By 2050, the population is expected to double in the continent, creating uncertainty regarding the future of the agricultural sector. Agriculture plays a major role in environmental issues and between 2005 and 2017, it contributed to one-quarter of the global emissions. The purpose of this project was to address the existing agricultural system in 2013 and how it was supporting the African population, which changes to it could sustain population growth and which environmental impacts it would cause, by performing a ‘cradle-to-gate’ Life Cycle Assessment.

The African diet revealed that the continent was not providing enough food to feed its population, while the analysis of yields and pesticide and fertiliser use showed low agricultural productivity. In addition, to sustain its population growth by 2050, the environmental impacts of the current system would increase 2 to 3 times. The impact assessment of prospective models, based on potential farming technique transitions and nutritional changes by 2050, showed a better environmental performance concerning the vegetarianism model, whereas the environmental impact of the healthy diet model far exceeded that of the existing system. Furthermore, organic and intensive farming had similar overall impacts, yet intensive farming provided higher yields.

To improve food availability in Africa and reduce food insecurity and undernourishment while preventing significant impacts on the environment, the continent should focus on: (1) implementing an intensive farming system, (2) decreasing animal production through a vegetarian diet, and (3) reducing other factors affecting the food demand (fertility rates) or the agricultural system (losses due to lack of distribution, storage, and refrigeration infrastructures).

Abstract (Danish)

Landbrug i Afrika er vigtigt for menneskers velfærd og økonomisk vækst, men alligevel har forskning vist, at dens produktivitet er lav, og befolkningen lider fortsat under fødevaresikkerhed og underernæring. I 2050 forventes befolkningen at fordobles på kontinentet, hvilket skaber usikkerhed med hensyn til landbrugssektorens fremtid. Landbrug spiller en vigtig rolle i miljøspørgsmål, og mellem 2005 og 2017 bidrog det til en fjerdedel af de globale emissioner. Formålet med dette projekt var at tackle det eksisterende landbrugssystem i 2013, og hvordan det understøttede den afrikanske befolkning, hvilke ændringer til det kunne opretholde befolkningsvæksten og hvilke miljøpåvirkninger det ville forårsage ved at udføre et "vugge-til port" -livscyklusanalyse.

Den afrikanske diæt afslørede, at kontinentet ikke leverede nok mad til at fodre dens befolkning, mens Analysen af udbytte og brug af pesticider og gødning viste lav landbrugsproduktivitet. For at opretholde befolkningsvæksten i 2050 ville miljøpåvirkningerne af det nuværende system desuden stige 2 til 3 gange. Vurderingen af miljøpåvirkningen af fremtidige modeller baseret på potentielle overganger til landbrugsteknikker og ernæringsændringer i 2050 viste en bedre miljømæssig ydeevne for den vegetariskemodel, hvorimod miljøpåvirkningen af den sunde diætmodel langt oversteg den i det eksisterende system. Ydermere havde økologisk og intensivt landbrug samlet set samme virkninger, men intensivt landbrug gav dog højere udbytter.

For at forbedre fødevareadgang i Afrika og reducere fødevareusikkerhed og underernæring og samtidig forhindre betydelige påvirkninger på miljøet, bør kontinentet fokusere på: (1) implementering af et intensivt landbrugssystem, (2) reduktion af dyreproduktion gennem en vegetarisk diæt, og (3) reduktion af andre faktorer, der påvirker fødevarebehovet (fertilitetsrater) eller landbrugssystemet (tab på grund af manglende distribution, opbevaring og køleinfrastrukturer).

Acknowledgements

Firstly, I wish to express my sincere appreciation to my thesis supervisor, Morten Birkved, who was behind the idea for the study and guided me through each stage of the project, providing constructive recommendations when needed and allowing this project to be my own work.

I would like to thank the University of Southern Denmark for providing me with an education on a field I am passionate about and acquire skills on Environmental Engineering and pursue what should be a great career in this field.

Finally, I must thank my friends and family for their support throughout the last two years of study far away from home, and particularly, for the support during the last two semesters.

Table of Contents

List of Tables

CHAPTER 3 RESULTS

List of Figures

List of Acronyms

ACET	African Center for Economic Transformation
ADER	Adequate Dietary Energy Requirement
AU	Africa Union
BAU	Business-as-usual
DALY	Disability-adjusted life years
EA	Eastern Africa
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO's statistical database
GDP	Gross Domestic Product
GHG	Greenhouse gases
GWP	Global Warming Potential
IP	Impact Potential
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MA	Middle Africa
MDER	Minimum Dietary Energy Requirement
NA	Northern Africa
NEPAD	New Partnership for African Development
NGO	Non-governmental Organisation
SA	Southern Africa
UN	United Nations
WA	Western Africa
WHO	World Health Organization

1. Introduction

1.1. Background on the African continent

Africa has a population of about 1.3 billion people (United Nations, 2017) and it has the most rapidly expanding population of any region in the world, increasing at about 3 per cent per annum (Dickson et al., 2019). More than two-fifths of the population is younger than 15 years of age in almost every African country (Dickson et al., 2019). Regarding population distribution, the rural population is currently estimated at 60 per cent, with the urban population at 40 per cent. Although it is the fastest urbanising region worldwide, Africa remains the least urbanised continent in the world (Economic Commission for Africa, 2016).

The African continent is the second largest worldwide, covering around one-fifth of the total surface of the Earth (Dickson et al., 2019). The total land area of the continent amounts to about 30.4 million square km and most of it lies within the tropical region, diversifying its climate (Dickson et al., 2019). The continent is divided into eight climatic regions: hot desert, semi-arid, tropical, wet-and-dry, equatorial, Mediterranean, humid subtropical marine, warm temperate upland, and mountain regions (Dickson et al., 2019). The northern and southern regions are characterized by desert conditions, along with a Mediterranean climate, whereas the central regions are wetter, with tropical rainforests and semi-arid climates (Dickson et al., 2019).

1.2. African Diet and State of Food Insecurity

Food is critical to human survival, representing one of the basic human needs, by providing the required nutritional support to the organism. A healthy and balanced diet must be diverse and contain all food groups, including cereals, roots and tubers, vegetables, fruits, meat and animal products, fats and sugars (Schönfeldt et al., 2012).

Food habits are influenced by cultural background, determining what and when food is eaten, as well as how it changes across communities (Oniang et al., 2003). Diet is usually determined by availability, access, marketing, nutritional requirements, and economic, environmental, cultural, and social habits, amongst others.

The African diet differs between regions, due to different socio-cultural and economic environments, although it is similar throughout the continent (Oniang et al., 2003). In general, the African diet relies on locally available staples, including cereals and roots and tubers (maize, wheat, cassava, yam, sweet potato), which form the basis of a meal, along with legumes or food derived from animals (Oniang et al., 2003; Schönfeldt et al., 2012). However, meat and fish consumption – rich in proteins and fats/oil – is restricted, due to economic, cultural and religious reasons (Schönfeldt et al., 2012) and is generally a sign of wealth (Oniang et al., 2003). Low protein intake may have significant impacts on health, particularly stunting and wasting, which mainly affects African children (Schönfeldt et al., 2012). Animal-based food contains higher amounts of protein per portion and increasing its consumption in the African continent would considerably improve the nutritional condition of the population (Schönfeldt et al., 2012).

The different African diets maximize the use of local food, due to the existing scarce resources, inaccessibility to supermarkets or grocery stores, and unaffordable goods to the majority of the population (Oniang et al., 2003; Schönfeldt et al., 2012). Therefore, the African population mostly consumes cereal- and starch-based products, supplemented by plant-based products, leading to an inadequate diet and dietary deficiencies (Schönfeldt et al., 2012). Although the right to food is a human right and the world produces enough food to feed its entire population, 1 in 9 people go hungry every day (WHO, 2018).

Of the 2 billion people affected globally by moderate and severe levels of food insecurity – without regular access to safe, sufficient and nutritious food –, 34 per cent are in Africa, which is much higher than in any other part of the world, affecting more than half of its population, particularly women (FAO et al., 2019).

Beyond food insecurity, Africa is the continent with the highest prevalence of undernourishment, affecting nearly one-fifth of the population in 2018 according to FAO et al., (2019), particularly in rural areas where there is low access to resources (land, manure, tools) and income to purchase food (NEPAD, 2013). Undernourishment is steadily increasing in almost all African subregions, with more than 90 per cent living in sub-Saharan Africa, which is consistent with the extent of poverty in the region, considering sub-Saharan Africa accounted for 56 per cent of the world's extreme poor in 2015 (FAO et al., 2019). These issues result in less productive individuals, more vulnerable to diseases and, consequently, unable to have prosperous lives.

Thus, feeding the African population is fundamental to prevent hunger and food insecurity on the continent. To feed the population, Africa must rely on agriculture.

1.3. Agriculture in Africa

Agriculture is fundamental for both human welfare and economic growth in Africa, particularly in rural areas, by providing food and raw materials, and contributing towards the eradication of poverty and hunger, promoting investments and trade within the continent, and creating jobs and human prosperity (NEPAD, 2013).

Until the 1960s, when the colonial period ended for most African nations, agriculture was the primary sector in the continent’s economy, the result of an agricultural-exporting economy (Oxford Business Group, 2019). During this period, farmers produced cash crops, such as cocoa, coffee, tea and sugarcane, which were exported to European countries (Oxford Business Group, 2019). However, the post-colonial era was defined as a period of underinvestment in the agricultural sector, resulting in a poor performance throughout the 1970s and 1980s (Oxford Business Group, 2019).

Nevertheless, since the 2000s several policies have set the agricultural sector as a central key of Africa’s development by increasing its annual growth, resulting in a significant improvement since the 1990s (Oxford Business Group, 2019). The new strategy launched by the African Union (AU) aims at reducing hunger and poverty, by compelling each African country to allocate 10 per cent of the annual budget to the agricultural sector (Oxford Business Group, 2019). However, most countries do not comply and allocate much less of their budget to agriculture, causing the continent’s agricultural productivity to fall short of its potential (Oxford Business Group, 2019). Thus, despite Africa being self-sufficient in the 1960s, it has become a net importer of cereals, and overall imports account for 1.7 times the value of exports (NEPAD, 2013).

The agricultural sector in Africa currently employs 60-70 per cent of the labour force, but only accounts for 25-30 per cent of gross domestic product (GDP) (FAO, 2008; Garrity et al., 2010; Chauvin et al., 2012; Kassam, 2017; AGRA, 2018; FAO et al., 2019). According to NEPAD (2013), African women account for 70 per cent of the workforce in agriculture and a total of 48 per cent of the population relies on it.

African farming mainly depends on smallholder farmers, as 80 per cent of all farms occupy less than two hectares (Garrity et al., 2010; NEPAD, 2013). Only around 20 per cent of food production is for self-consumption and the remaining 80 per cent concern purchases by urban and rural consumers, which are marketed and mainly handled through private operators (AGRA, 2019). Urban areas are progressively more dependent on food imports, due to poor transport infrastructure interfering with intraregional trade and the belief that domestically produced foods are inferior to competing imports (ACET, 2017). Within the agricultural sector, livestock alone is responsible for 40 per cent of the global value of agricultural output (FAO, 2019a) and provides 18 per cent of calories worldwide, 34 per cent of protein consumption globally and vital micro-nutrients – vitamins, iron and calcium (FAO, 2018).

Although its highly diverse climate allows the growth of a wide range of products, including food crops, cash crops and livestock, water availability in most African regions is poor and drought events are common, leading to lack of water to support crop growth (Dinar et al., 2008). African agriculture is particularly vulnerable to climate change and extreme weather events, considering it is mostly rain-fed. Dinar et al. (2008) studied the vulnerability of African agriculture to climate change, determining the damages in absolute terms and as a fraction of agricultural GDP, whereas Waha et al. (2018) examined how agricultural diversification and transition of farming activities may support adaptation to a changing climate and achievement of food security.

Although Africa possesses more than 60 per cent of the world's arable land, its share in global agricultural production is low, due to vast uncultivated areas and the lowest productivity in the world (Oxford Business Group, 2019). The agricultural productivity in Africa has around half the average growth of other developing countries and mainly results from underinvestment (Oxford Business Group, 2019).

The low productivity is mainly caused by lack of access to modern farming technologies, mechanisation, high-yielding seeds, fertilisers and other inputs (ACET, 2017; Oxford Business Group, 2019). For instance, the use of fertilisers in Africa is extremely low when compared to other developing countries, accounting for 3 per cent of global consumption (Oxford Business Group, 2019). However, other factors also have an impact on the productivity, such as poor agricultural and distribution infrastructures; increasingly depleting soils; presence of pests and diseases (Toenniessen et al., 2008); inaccessibility to farming areas due to conflicts or poor transportation infrastructure; declining average age of African farmers – estimated at 60 years – and youth's unwillingness to work in the sector (ACET, 2017).

Water scarcity is one of the main reasons for low productivity, considering less than 6 per cent of agricultural land in Africa is irrigated and there is a short access to irrigation systems (ACET, 2017; Oxford Business Group, 2019), causing farmers to depend solely on scarce rainfall. Finally, agricultural manufacturing and processing industries are undermined by policy, regulatory and infrastructure constraints, preventing the use of agriculture to launch industrialization (ACET, 2017).

The African population has been growing throughout the decades and is expected to double by 2050 (United Nations, 2017), increasing the food demand by 97 per cent (Bruinsma, 2009). Urbanisation and economic growth can also increase food demand in the future, leading to shortages of food.

Africa has been dealing with this growth by significantly expanding the agricultural area and reducing the fallow period, contributing to deforestation and land degradation. For example, cereal production in sub-Saharan Africa increased from 31 million to 77 million tonnes between 1961 and 2001, yet more than 90 per cent of this increase was due to expansion of the cultivated area (Toenniessen et al., 2008). According to Grassini et al. (2013), cropland has been globally expanding by nearly ten million hectares per year since the 2000s. For example, Côte d’Ivoire has lost around 80 per cent of its rainforests since the 1970s, mainly due to cocoa production (Oxford Business Group, 2019). Tilman et al. (2001) explored how agricultural expansion will progress by 2050 and which will be the environmental impacts, considering one billion hectares of land will need to be converted into agriculture in developing countries.

However, African countries still need to raise their food production to prevent hunger and food insecurity amongst its population. Hence, feeding the African population while preserving the natural resources and the environment is one of the most urgent development challenges of the century, particularly considering continued global population growth, dietary transitions and climate change (Pretty et al., 2011; Waha et al., 2018).

By improving agricultural productivity in Africa, food availability will increase, resulting in healthier and more productive individuals, increasing the opportunities for employment and entrepreneurship (Toenniessen et al., 2008) and stimulating economic growth and poverty reduction. Thus, to satisfy food demand, agricultural productivity must rise rather than increasing the area of production.

According to Fuglie et al. (2014), investments in agricultural research, wider adoption of new technologies and policy reforms are key to improving productivity in sub-Saharan Africa. ACET (2017) defends access to education and information on farm management to African farmers as a way to improve agricultural productivity.

Wheat, rice and maize yields in Asia and South America have increased dramatically throughout the 1960s and 1970s due to the implementation of “Green Revolution” technologies (ACET, 2017). These technologies included improved seeds, fertilisers, irrigation, mechanisation and improved farming management techniques (ACET, 2017). The African countries where the “Green Revolution” technologies have been adequately available to farmers, the yields have exhibited improvement (ACET, 2017). For instance, in a region of Ghana, the use of irrigation, genetically improved seeds, fertilisers, tillage, and extension services generate average dry paddy rice yields comparable to the ones in Asia (ACET, 2017). According to Toenniessen et al. (2008) and ACET (2017), by making these technologies accessible to African farmers and adapted to local conditions, productivity will improve significantly.

More recently, other studies focused on more sustainable solutions to improve agricultural productivity. Thierfelder et al. (2013), Corbeels et al. (2014) and Brown et al. (2017) studied how Conservation Agriculture (CA) – an alternative sustainable production system to conventional agriculture, based on minimum or no mechanical soil disturbance, organic soil cover with crop residues and diversified crop rotations (Giller et al., 2009) – might be implemented to improve agricultural productivity and preserve natural resources in several African regions and its limitations. On the other hand, Vanlauwe et al. (2014) discussed how CA along with the adequate use of fertilisers in sub-Saharan Africa might increase crop productivity and production of crop residues used as soil cover.

Dile et al. (2013) examined how water harvesting practices may reduce risks and improve yields while benefiting other ecosystems. Pretty et al. (2015) investigated how Integrated Pest Management, which consists of the deployment of methods of pest control designed to complement, reduce or replace the application of synthetic pesticides; can be used to increase crop yields in Africa while reducing the environmental impacts.

By increasing productivity, farmers and their households can become self-sufficient and even sell surpluses and acquire capital to diversify their diets and satisfy other needs (ACET, 2017), or invest in their farming systems.

The African continent has a great potential for agriculture, due to its share of arable land; a young and growing labour force, estimated to be the largest in the world by 2050; tropical and subtropical climates favourable to long and multiple growing seasons; and a growing middle class capable of expanding national and intraregional markets for agricultural products (ACET, 2017).

1.4. Environmental Impacts of Agriculture

Agriculture plays a major role in environmental issues, such as climate change, deforestation, land degradation, water pollution and biodiversity loss. As the population and economies grow and urbanisation increases, global demand for food rises, causing the expansion of farming practices and increasing the environmental impacts.

The agricultural sector employed 37 per cent of the global surface area in 2017 and used around 70 per cent of the total freshwater for irrigation, becoming the largest water user worldwide (FAO, 2019c). Livestock alone is responsible for 78 per cent of the total use of agricultural land and 33 per cent of the cropland (FAO, 2019c). According to FAO (2018), 86 per cent of livestock feed is not suitable for human consumption, which means that feed wastes and residues result in environmental impacts.

Around 5 billion metric tonnes of CO_2 equivalent have been released to the atmosphere by agricultural activities each year between 2005 and 2017 and, along with land use, it contributed to one-quarter of the world emissions during this period (FAO, 2019c).

Conventional and intensive farming use considerable high inputs of synthetic fertilisers and pesticides, irrigation, and mechanisation, to obtain higher yields. These farming techniques cause great impacts on ecosystems, animals, and humans. As a result, organic farming, which has been on the rise for the past two decades (De Ponti et al., 2012), is proposed as a solution (Seufert et al., 2012). It is based on the use of organic fertilisers – manure, green manure, compost – and biological pesticides, yet using biological inputs results in higher costs for producers and, consequently, for consumers. According to Seufert et al. (2012), the difference in yields between farming systems depend on the context (different agricultural conditions), but when the systems are most comparable, organic farming, in general, has lower yields than conventional farming. So, although organic farming does not require the use of synthetic chemicals and reduces the impacts on the environment, using this farming technique to feed the world population may force farmers to expand the production area, leading to losses of biodiversity (De Ponti et al., 2012).

Of all the farming practices, livestock production has the highest impact on the environment, causing increasingly direct and indirect impacts, yet it is growing faster than the rest of agriculture in almost every country (FAO, 2006).

According to FAO (2006), the livestock sector accounts for 18 per cent of GHG emissions measured in CO_2 equivalent, emitting 9 per cent of anthropogenic CO_2 emissions, 37 per cent of anthropogenic methane (mainly released by ruminants), 65 per cent of anthropogenic nitrous oxide (from manure) and around 64 per cent of anthropogenic ammonia emissions, which contribute to acid rain and ecosystem acidification. The livestock sector accounts for over 8 per cent of the water use globally and has a great impact on water resources, contributing to its pollution, due to the wastes generated by livestock and use of fertilisers and pesticides for feed production (FAO, 2006).

In the future, agricultural outputs in Africa will have to increase significantly to satisfy the food demand. Considering agriculture and livestock play a major role in emissions to the environment, it is essential to determine the possible environmental impacts caused by it in the future and how to reduce these impacts.

1.5. Project Goals and Scope

Agriculture is essential for the well-being and development of any society. The African continent is the most limited at various levels, including food production and management, therefore it is particularly relevant to study the agricultural sector in this region. This study will explore the current African food production and projections of it by 2050, considering potential changes to social, cultural, and economic factors in the region.

The main aim of this thesis is to study the current agricultural system and future scenarios, developing prospective agricultural models based on these scenarios. Firstly, the study aims to analyse the current food demand, as well as agricultural productivity. Secondly, create scenarios for the future (by 2050), considering changes to population growth, farming techniques (organic and intensive) and diets (vegetarianism, meat increase and healthy diet). As an environmental project, the main goal of this study is to elaborate prospective agricultural models for Africa based on the current situation and the scenarios created, assess the environmental impact associated to each model and compare them, by applying the Life Cycle Assessment (LCA) framework. The LCA approach is chosen due to its advantages regarding model development and environmental impact assessment:

- LCA accounts for inputs (resources, materials, energy) required in the agricultural system, as well as outputs (products, wastes, emissions).
- LCA allows the use of parameters, which facilitates model development of the chosen scenarios.
- LCA provides results on the environmental impacts of using certain inputs in the model and releasing certain outputs.
- LCA is a methodological approach, which follows standards defined in the International Organisation for Standardisation (ISO, 2006), generating reliable results.

This project will try to answer the questions: Is the African continent providing enough food to feed its population? Is it viable for the continent to provide enough food to sustain its population growth, without causing significant environmental burdens? What are the potential nutritional shifts or system changes? What are their environmental consequences?

1.6. Existing Knowledge

Life Cycle Assessments are a relatively new approach to environmental impact assessment and were mainly developed to evaluate the impacts of industrial products and processes (de Backer et al., 2009).

Agricultural systems are different from industrial systems, thus its LCAs must also be distinct, which has been a subject of several publications (Haas et al., 2000: Meeusen et al., 2000; Audsley et al., 2003; Schmidt, 2008; Caffrey et al., 2013; Hauschild et al., 2017).

Globally, agricultural studies using the LCA approach mostly focus on the production of specific products: Milà i Canals et al. (2006) evaluated the environmental impacts of apple production in New Zealand; Pryor et al. (2017) studied the environmental impacts of sugarcane production in South Africa; Mattsson et al. (2000) explored the impacts on land use caused by the production of three vegetable oil crops; and Brentrup et al. (2001) studied the production of sugar beet using three different fertilisers.

Other LCA approaches focused on the production of a single product while comparing the agricultural method applied, such as the environmental impacts caused by organic and conventional production of wheat (Meisterling et al., 2009); lettuce (Foteinis et al., 2016); leek (de Backer et al., 2009); and milk (Cederberg et al., 1999; De Boer, 2003; Thomassen et al., 2008).

Hence, most LCAs focus on the production of a single product, without considering the whole agricultural system and, particularly, changes to it in the future regarding social, cultural, and economic factors. Moreover, most studies tend to emphasize smaller-scale analysis, such as country or region-specific, without considering a whole continent, such as Africa; and present-term analysis, rather than focusing on long-term, such as until 2050.

Thus, African agriculture is a challenging and critically important topic given its complexity regarding its scale and its variability across economic, social, cultural, political, and environmental factors.

1.7. Life Cycle Assessment Framework

Life Cycle Assessment, or LCA, is a methodology applied to assess the environmental impacts associated with the life cycle stages of a product, process, or service. Depending on the assessor's goal, LCAs may comprise all life cycle stages of a product, process, or service ('cradle-to-grave') or only certain stages of it (e.g. 'cradle-to-gate'). The 'cradle-to-grave' approach is the most common, covering all life cycle stages, i.e., extraction of materials, production, distribution, use and disposal.

The purpose of an LCA is to better inform decision-makers, including government officials, multinational corporations, non-governmental organisations (NGOs), by quantitatively comparing the human health and environmental impacts of different products, processes or services (Curran, 2008). It can also be used to identify the life cycle stages that contribute the most to impacts on the environment, evaluate potential changes in product or service designs and develop policies that contemplate the environment (Hauschild et al., 2017).

LCA methodology has a fixed structure and follows the ISO framework, specifically the ISO 14040 and 14044 (ISO, 2006). It consists of four phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation (Figure 1.1).

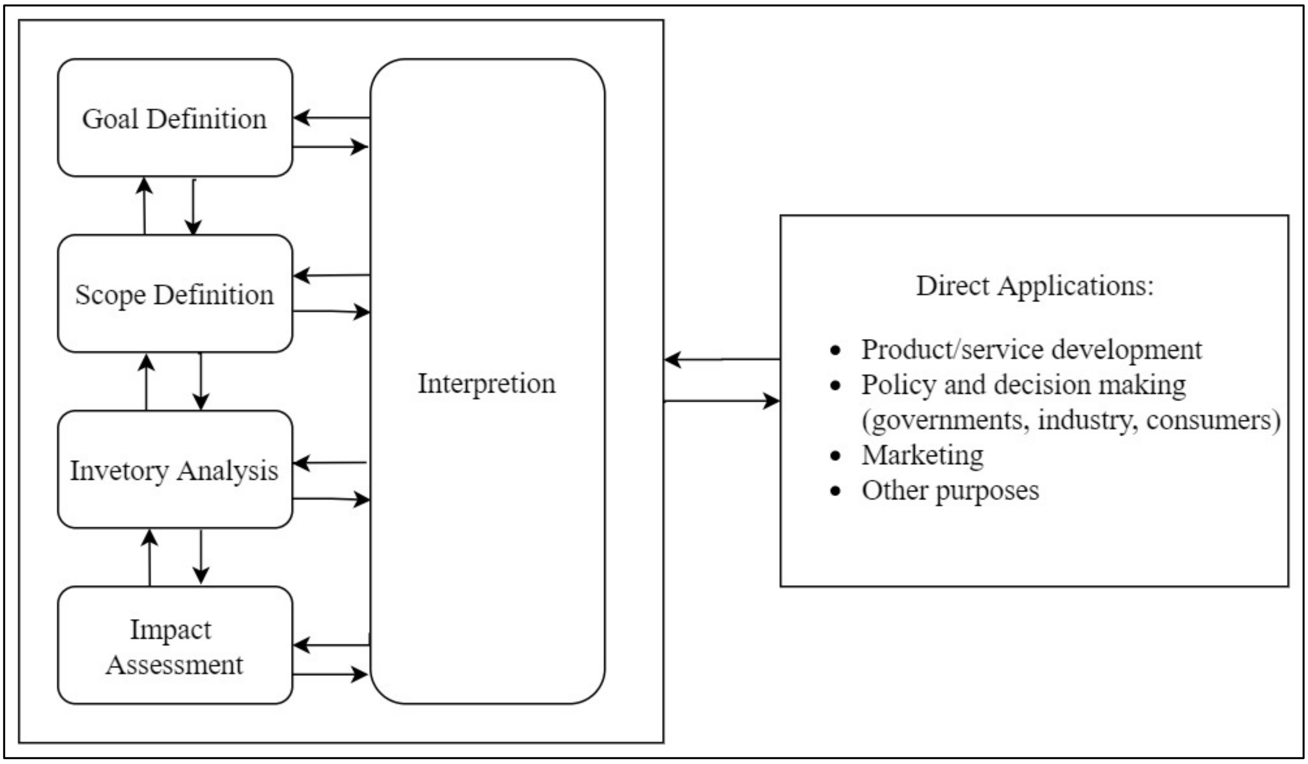

Figure 1.1. The LCA framework (based on Hauschild et al. (2017)).

- **Goal and Scope Definition:** define the purpose of the study, set the context of the LCA study, define functional unit, select the assessment parameters, and set boundaries to the system.
- **Inventory Analysis (LCI):** collect information on physical flows (inputs of resources, materials, energy, semi-products, and products; and outputs of emissions, waste, and products).
- **Impact Assessment (LCIA):** select impact categories and convert physical flows into impacts on the environment, through models from environmental science. Every impact category may be assessed by optional normalisation and weighting.
- **Interpretation:** results are evaluated according to goal and scope definition using critical review, sensitivity analysis and uncertainty analysis to assess the robustness of the conclusions and possible focus points for further work.

However, LCA is an iterative methodology, involving feedback loops between different phases, by updating information in each phase according to the goal, scope and data requirements set beforehand (Hauschild et al., 2017).

There are two LCI modelling frameworks: attributional and consequential modelling. The attributional LCI modelling accounts for immediate physical flows present throughout the life cycle of a product (Earles et al., 2011) and the impacts which may be attributed to the primary service (Wenzel et al., 2009), without considering secondary services arising from the system, as well as the technosphere or economy (Hauschild et al., 2017). The consequential LCI modelling describes changes to the economy caused by the introduction of the studied system (Hauschild et al., 2017), i.e. how an increase or decrease in demand or supply of the product system changes its physical flows (Earles et al., 2011).

LCI Methodology

The LCI is the outcome of the inventory analysis, which consists of collecting data for raw materials, energy, wastes and emissions present throughout the life cycle of the studied system, resulting in a list of quantified physical flows present in the system, which must be scaled according to the functional unit defined during Goal and Scope definition (Hauschild et al., 2017). The functional unit is a quantitative description of the function or service that must be fulfilled and for which the assessment is performed (Hauschild et al., 2017).

The level of accuracy and detail of the data collected will greatly influence the results of the LCA (Curran, 2008). However, the level of detail required also depends on the size of the system and the purpose of the study, but data constraints should also be considered when defining the system, to prevent gaps in data (Curran, 2008).

LCIA Methodology

During the impact assessment phase, the physical flows collected during the inventory analysis are converted into potential impacts on the environment (Curran, 2008; Hauschild et al., 2017). The purpose of this phase is to determine the connection between a product, process or service and its potential environmental impacts.

The LCIA consist of five steps, of which the last two are optional according to the ISO standards: selection of impact categories; classification of elementary flows according to their ability to contribute by impacting a chosen indicator; characterisation, to quantify the ability of the elementary flows to impact the indicator of the category; normalisation to express the impact categories relative to a common set of reference impacts; and weighting using factors to quantitively express how severe the impact is when compared to other impact categories (Hauschild et al., 2017).

The models applied in impact assessment are not indicators of absolute risk or actual damage to the environment but are used for relative comparisons of the potential environmental impacts between products, processes or services (Curran, 2008).

To calculate the impact assessment, the method ReCiPe is available. ReCiPe methodology includes two sets of impact categories – midpoint and endpoint categories – which are based on midpoint and endpoint indicators, respectively (Goedkoop, 2008). There are eighteen midpoint impact categories clustered into groups that contribute to the same environmental effect (Hauschild et al., 2017). ReCiPe 2016 has three different cultural perspectives, based on distinct assumptions and choices: individualist, hierarchist and egalitarian. The individualist perspective (I) is based on a short-term analysis, undisputed impacts and optimism regarding human adaptation (Huijbregts et al., 2016), through technological and economic development (Goedkoop et al., 2009). The hierarchist perspective (H) uses a scientific consensus regarding the time frame and probability of impact mechanisms (default model) (Huijbregts et al., 2016) while considering that the impacts can be avoided with proper management and mean level of adaptation (Goedkoop et al., 2009). Finally, the egalitarian perspective (E) has the most precautionary approach, considering the longest time-horizon, impact types that are not yet fully established (Huijbregts et al., 2016), and the worst-case scenario (Goedkoop et al., 2009).

Impact Categories

Acidification

Acidification consists in the reduction of the pH caused by the emission of anthropogenic compounds, such as ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x), increasing the acidity of water and soil (Acero et al., 2014), affecting the growth of plants and roots, and increasing the risk of issues for animals and humans. Agriculture is responsible for emitting ammonia from manure and fertilisers, contributing to acid rain and terrestrial acidification. On ReCiPe, terrestrial acidification potential is expressed as kg SO_2 equivalent.

Climate Change

Climate change is defined as a change in the state of the climate that persists for an extended period, caused by an increase in anthropogenic GHG emissions (carbon dioxide, methane, nitrous oxide), contributing to the phenomenon of rising surface temperature across the globe averaged over long periods – global warming (Hauschild et al., 2017). Climate change is currently one of the most pressing environmental issues, causing a rise of atmospheric and ocean temperature, wildfires, melting of glaciers and ice caps, rise of sea levels, and more frequent and intense extreme weather events, such as floods, droughts, cyclones, tornados and heatwaves (Hauschild et al., 2017). Livestock is a major GHG emitter, releasing high amounts of methane and nitrous oxides. Climate change is assessed through the Global Warming Potential and its reference unit is kg CO_2 equivalent on ReCiPe.

Ecotoxicity

Ecotoxicity is based on the emission of substances which may have toxic impacts, depending on its quantity, mobility, persistence, exposure patterns and bioavailability (Hauschild et al., 2017). For a substance to have a potential ecotoxic impact, it must reach a potential target organism (Hauschild et al., 2017). Ecotoxicity is divided into three impact categories, depending on which ecosystems are affected by toxic chemicals (terrestrial or aquatic), leading to biodiversity loss. Agriculture is a major user of fertilisers and pesticides, which can result in potential toxicity impacts. The three impact categories (terrestrial, marine, and freshwater ecotoxicity) are expressed as kg 1,4-DCB.

Eutrophication

Eutrophication is caused by high emissions of nutrients (nitrogen, phosphorous) to aquatic ecosystems, increasing biomass production of algae, resulting in degradation of water quality and hypoxia, leading to biodiversity loss (Hauschild et al., 2017). Agriculture emits nitrogen and phosphorous, due to the use of fertilisers and manure. On the ReCiPe method, freshwater eutrophication and marine eutrophication are expressed as kg P equivalent and kg N equivalent, respectively.

Human Toxicity

Human toxicity is dependent on the same factors as ecotoxicity: emitted quantity, mobility, persistence, exposure patterns and toxicity, yet during the exposure patterns, several other indicators are considered, such as human behaviour (dietary habits, e.g.) (Hauschild et al., 2017). Agriculture can contribute to human toxicity by emitting chemicals present in fertilisers and pesticides. Toxic chemicals contribute to health problems, by inhalation, ingestion or contact, and may cause respiratory diseases and increase cancer risk (Acero et al., 2014). This impact category is expressed as 1,4-DCB and accounts for carcinogenic and non-carcinogenic human toxicity.

Land Use

Land use is associated with anthropogenic activities in soil area. Soil is a finite resource and its increasing occupation as croplands, pastures and urban areas contributes to environmental impacts, leading to loss and modification of habitats, and decreasing biodiversity (Hauschild et al., 2017). Agriculture is a significant land user, converting land into cropland and pastures to satisfy food demand. Land use is measured in $m^2 \cdot yr$ crop equivalent on ReCiPe.

Photochemical Oxidant Formation

Photochemical oxidant formation consists on the generation of ozone in the troposphere, caused by the oxidation of anthropogenic emissions of volatile organic compounds and nitrogen oxides in the presence of light (Acero et al., 2014). This oxidation causes smog episodes, leading to impacts on human health and ecosystems (Hauschild et al., 2017). This impact is caused by carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NO) and ammonium. The use of nitrogen fertilisers leads to emissions of nitrogen oxides, which can contribute to this impact. On ReCiPe, the impacts on human health and terrestrial ecosystems are expressed as kg NO_x equivalent.

Particulate Matter Formation

Particulate matter consists of small particles emitted from anthropogenic activities or formed through reactions of precursor substances, such as nitrogen oxides, sulphur oxides and ammonia (Hauschild et al., 2017). These particles can be inhaled and cause respiratory and cardiovascular issues, cancer and mortality (Hauschild et al., 2017). Agriculture operations and processes (tillage, planting, fertiliser, and pesticide application, and harvesting) involve the emission of particles that spread in the air (Arslan et al., 2012). ReCiPe method studies fine particulate matter formation, which is measured in kg $PM_{2.5}$ equivalent, including particles with a size of 2.5 μM.

Resource Depletion

In general, depletion of resources refers to the consumption of natural resources, such as water, minerals and fossil fuels, contributing to its decrease in availability when extracted at high rates (Acero et al., 2014). Although water is a renewable resource, its availability is compromised when used unsustainably (Acero et al., 2014). The agricultural sector is the main consumer of water and also depends on fossil and mineral resources. The ReCiPe method studies water consumption, expressed as m^3; mineral resource scarcity, expressed as kg Cu equivalent; and fossil fuel scarcity, expressed as kg oil equivalent.

Stratospheric Ozone Depletion

Ozone is a highly reactive molecule and, by reacting with other molecules (CFCs and HCFCs, e.g.), reduces its stratospheric concentration, increasing UV radiation intensity at surface level (Hauschild et al., 2017). Ozone depletion can cause human health issues, including skin cancer, skin cell ageing and immune system diseases, as well as damage to animals and plants (Hauschild et al., 2017). Within agriculture, pesticides and fertilisers contribute to ozone depletion, due to the cooling agents used during its synthesis. This impact category is represented as kg CFC-11 equivalent on ReCiPe.

The endpoint impact categories (Table 1.1) result from the aggregation of the midpoint impact categories into three larger groups: damage to human health, damage to ecosystems and damage to resources (Goedkoop, 2008).

Table 1.1. Endpoint impact categories provided by the ReCiPe method.

Impact Category	**Indicator Name**	**Unit**
Damage to human health	Disability-adjusted loss of life years	DALY
Damage to ecosystem diversity	Loss of species during a year	species·yr
Damage to resource availability	Increased cost	US$ (2013)

Limitations

Conducting an LCA can be quite resource- and time-consuming, depending on how meticulous the assessor requires it to be (Curran, 2008). Collecting data can be particularly difficult and data unavailability will have a large impact on the results and will increase the uncertainty (Hauschild et al., 2017). LCA studies have different methodological approaches, such as distinct functional units, boundaries, and assumptions, which hinders the comparison of LCA studies. Thus, throughout the LCA, all assumptions and limitations must be reported, as the results might be taken out of context or be misinterpreted if these are omitted (Curran, 2008).

The results of an LCA only quantify the environmental impacts of a certain product or service and cannot account for its social, cultural, political and economic impacts (Curran, 2008). Another limitation of an LCA is that it only compares product systems or services and reveals which one is better for the environment, but it does not indicate if that specific product system or service is the best option for the environment (Hauschild et al., 2017). Moreover, it does not provide the solution for the existing environmental impacts of the product or service in question. Finally, although the impacts are quantified and categorised, the choice of which impact is worse is highly subjective and relies solely on the decision-maker (Curran, 2008).

2. Methods

This study intents to explore the agricultural system in Africa, by combining a set of methodologies: system analysis, scenario development, system modelling, and impact assessment.

In order to study the whole African continent thoroughly, the continent was divided into five subregions (Figure 2.1) (Eastern Africa – EA, Middle Africa – MA, Northern Africa – NA, Southern Africa – SA and Western Africa – WA), according to the division from the United Nations (UN). The year 2013 was selected, when available, to study the current African agricultural system.

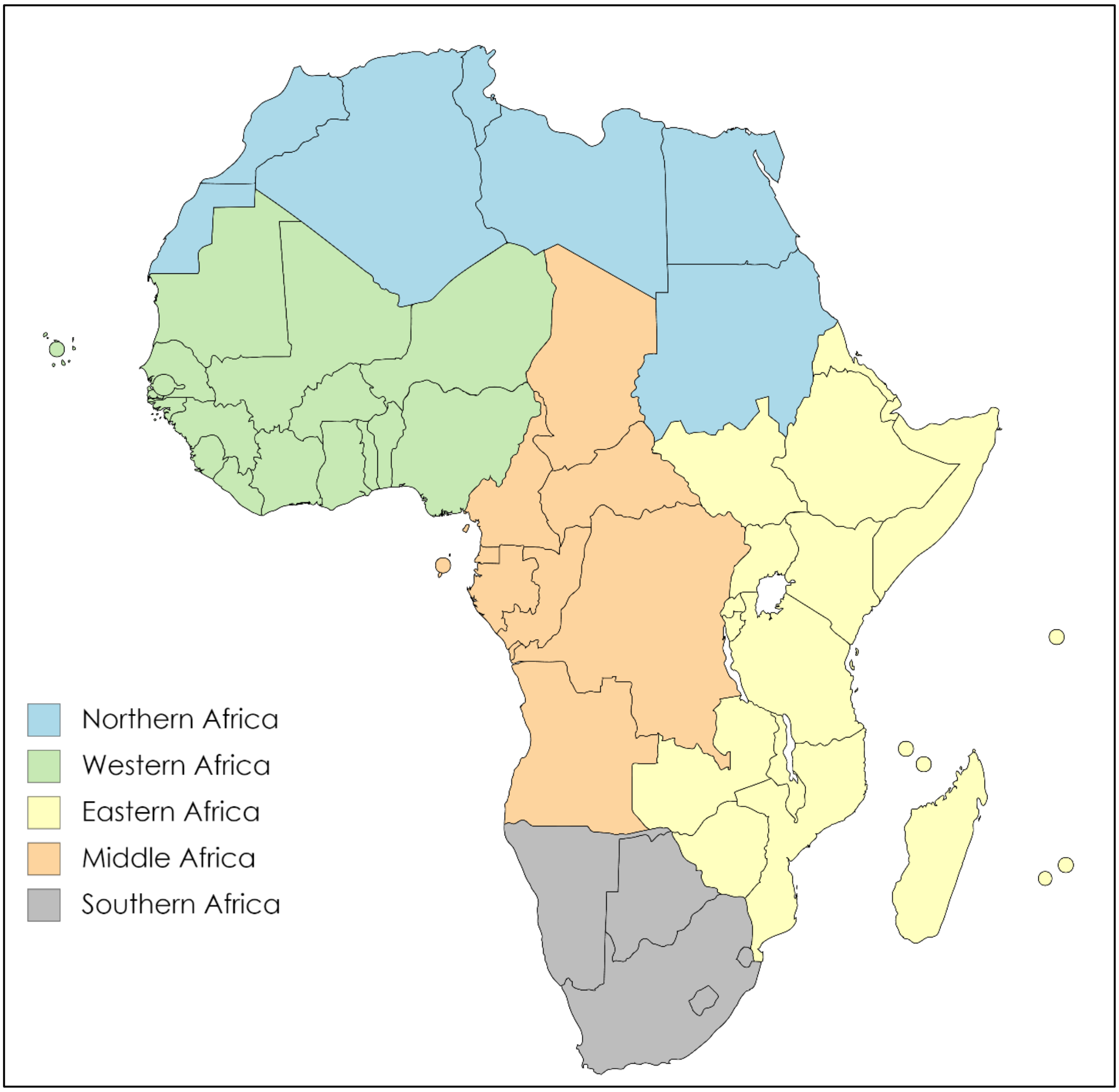

Figure 2.1. Geoscheme of the African continent according to the division of the United Nations. The study of the agricultural system in Africa focuses on the regional division of the UN, by collecting data referent to each region.

In system analysis, the current agricultural system in Africa is explored, focusing on food demand and consumption and agricultural productivity. During scenario development, potential scenarios were created based on social, cultural, economic, and environmental hypotheses. Both the current agricultural system and the scenarios were modelled, and the impact assessment was performed for all models developed.

2.1. System Analysis

Diet

Food habits vary significantly throughout the world and the African continent is no exception. Understanding food consumption, food demand and if the demand is being satisfied, as well as diet composition, is crucial to comprehending the African agricultural system.

To better understand the food demand, the dietary energy requirements and consumption were studied. According to FAO et al. (2001), human energy requirements consist of estimates of dietary energy required to satisfy energy expenditure to maintain optimal health, physiological function, and well-being. Data for adequate (ADER) and minimum dietary energy requirements (MDER) was collected from Our World in Data (Roser et al., 2019), along with the food deficit (Roser et al., 2020), in kcal/capita/day. This database provided data by country, which was collected, grouped by region and used to determine the actual food intake (kcal/capita/day). The data gathered referred to the years 2011-2013.

Although FAO's database does not provide data for food consumption in Africa, its Food Balance Sheets (FBS) offer food availability data (FAOSTAT, 2017), which presents a country's or region's food supply. Data for food availability (kcal/capita/day) in 2013 was collected from the FBS.

The African diet varies by region and mostly depends on locally available products. The food, protein, and fat supply in g/capita/day by commodity and region was provided by FAO's FBS (FAOSTAT, 2017). Using this data, the diet composition of the entire continent was determined. A more detailed assessment of the food supply in each subregion is found in Appendix A.1 (Table A.1), granting a better understanding of the African diet, particularly which food commodities were mostly available, as well as its contribution to protein and fat supply. Although food supply does not exactly represent food consumption, food availability plays a great role in defining the diet composition. Thus, I assumed that the supply of commodities was proportional to diet composition.

Yields

Most authors defend African agricultural productivity is low, due to underinvestment in the sector. Thus, agricultural productivity in the continent is an important subject of study, providing a wider understanding of the state of agriculture in the region.

FAOSTAT provides crop (FAOSTAT, 2020a) and livestock (FAOSTAT, 2020c) yields by commodity and region. Data regarding yields in the five subregions in 2013 was collected and compared to average global yields and maximum yields registered worldwide in the same year. A summary of the yield efficiency was determined for crop and livestock production, yet a more detailed analysis of it is presented in Appendix A.2 (Table A.2), providing a deeper understanding of which commodities had the lowest yields in each subregion.

Pesticides and fertilisers

According to most authors, the low use of inputs, such as fertilisers and pesticides, contributes significantly to the low agricultural productivity registered in Africa.

Fertiliser (FAOSTAT, 2019a) and pesticide (FAOSTAT, 2019f) use in Africa and the world were provided in tonnes for 2013. Although the fertiliser use was given both as nutrient and product, I focused on nutrient use, specifically, nitrogen, phosphate, and potassium. Using the amounts of pesticide and fertiliser used in the world, Africa and its subregions, the percentage of global consumption of the whole continent and each region was determined.

2.2. Scenario Development

Conventional farming is usually resource- and energy-intensive, as it is based on the use of a considerable quantity of synthetic fertilisers, pesticides, genetically modified organisms (GMOs), irrigation and mechanisation. In this study, I assumed that conventional agriculture was the practised system in Africa in 2013, although the continent employed fewer fertilisers, pesticides, irrigation, and mechanisation than developed countries. Henceforth, the conventional farming system in use in the continent will be referred to as the business-as-usual (BAU) system.

It is expected that in the next years there will be changes to social, cultural, economic, and environmental factors across the globe and, particularly, in Africa. Two farming systems and three diet changes scenarios were developed and their influence on the agricultural system in the continent was tested.

In total, 24 scenarios (Table 2.1) were studied for each subregion, and prospective models by 2050 were created based on these scenarios. The BAU system and all scenarios were modelled with the reference population (in 2013) and three projections for population growth by 2050 (low, medium and high).

Table 2.1. Scenarios to be studied in the project, regarding the current agricultural system (BAU system), farming techniques (organic and intensive farming) and diet changes (vegetarianism, meat increase and healthy diet), with reference population (in 2013), and low, medium and high population growth projections by 2050.

	Reference population	**Low projection**	**Medium projection**	**High projection**
BAU system	×	×	×	×
Organic farming	×	×	×	×
Intensive farming	×	×	×	×
Vegetarianism	×	×	×	×
Meat increase	×	×	×	×
Healthy diet	×	×	×	×

2.2.1. Population Growth

The African population is expected to double by 2050, doubling the future food demand. The Population Division of the UN, through the World Population Prospects 2019, offers low, medium, and high population growth projections from 2020 until 2100 for the five subregions (United Nations, 2019). The years 2013 until 2050 were selected, and the low, medium, and high population growth projections by 2050 were investigated.

For the BAU system and the scenarios studied, the food demand would increase proportionally with population growth. The rate at which the population would grow from 2013 until 2050 in each projection (low, medium, and high) was determined for each region and used to increase food production and satisfy future food demand (Table 2.2).

Table 2.2. Factors by which the agricultural system (inputs and outputs) must increase by 2050, in a BAU system, i.e., with population growth (low, medium, and high projections), food demand increases, increasing the food production to satisfy the demand in each subregion.

Region	**Low**	**Medium**	**High**
EA	2.11	2.31	2.51
MA	2.44	2.64	2.85
NA	1.58	1.73	1.88
SA	1.29	1.43	1.58
WA	2.21	2.39	2.58

All inputs (area, seed, fertilisers, manure, pesticides, water, energy, imports, and area, water and feed for livestock) and all outputs (production quantities and losses for crops and livestock, feed, and exports) increased according to the factors determined.

2.2.2. Farming system

Organic Farming

As previously stated, organic farming only relies on fertilisers and pesticides of organic origin, yet the yields generated are generally lower than those of conventional farming.

Several studies explored the difference between organic and conventional yields, and according to Seufert et al. (2012), in general, organic farming in developing countries is 43% less productive than conventional farming, but the yields vary across commodity groups and regions. De Ponti et al. (2012) determined the average yield gaps between organic and conventional farming: cereals have a 79% yield, roots and tubers and oil crops a 74% yield, pulses an 88% yield, vegetables an 80% yield, fruits a 72% yield and other food crops a 92% yield. However, this study mainly included data from developed countries and few data from North Africa, which does not represent the exact situation in the continent. Nevertheless, I assumed that the average yields determined may be applied in this study.

The lower productivity in organic farming force the expansion of the production area and increase of certain inputs, which must increase proportionally according to the yields, to produce the same amount of outputs. In this study, area, irrigation water, seed, and energy for irrigation of cereals increased by 21%, roots and tubers and oil crops 26%, pulses 12%, vegetables 20%, fruits 28%, and sugar crops and treenuts 8%.

In an organic farming system, manure can be used to substitute synthetic fertiliser. FAOSTAT offers data for manure applied to soils (as N content) (FAOSTAT, 2019d) and fertiliser use as nutrient (nitrogen, phosphate and potassium) (FAOSTAT, 2019b). I assumed that in this scenario, only the nitrogen synthetic fertiliser was substituted by manure, and phosphate and potassium fertilisers were not accounted for. Pesticides were excluded, as there are no biological substitutes for it accessible in Africa. Although nutrient sources for organic and conventional farming differ, I assumed that nutrient requirements per hectare harvested of commodity were the same for both systems.

Manure inputs, besides increasing proportionally according to the yields of each commodity, also increased to substitute the synthetic nitrogen fertilisers being used in the BAU system. The growth factors for each region and commodity were determined, according to the use of nitrogen fertiliser

(FAOSTAT, 2019b) and manure (FAOSTAT, 2019d) per area of cropland in 2013. The average manure increase factors per region were determined and used during model development (Table 2.3).

Table 2.3. Factors by which manure applied to soils increased in each subregion in an organic farming scenario to cover area expansion and nitrogen fertiliser use.

	EA	MA	NA	SA	WA
Manure	2.42	1.68	8.65	4.20	2.87

Intensive Farming

Intensive farming relies on high levels of inputs and technologies, which result in high yields. Intensive farming aims to increase the outputs, by better controlling the production environment of crops and preventing its destruction, through nutrient intake, pesticide use and irrigation. In this study, intensive farming considered only crop production and disregarded livestock production – where livestock is mass-produced, fed antibiotics and growth hormones, and left in confined housing.

Intensive farming relies on good irrigation systems, capable of providing adequate water to all crops. According to the water requirement ratio (irrigation efficiency) determined by FAO (2012), each African region was providing more than the adequate amount of water for irrigation. Hence, this input did not require an increase in this scenario. Although the irrigation water requirements were being met, irrigation systems are still scarce in the continent and its use could result in better distribution of water and, consequently, higher yields. However, to facilitate model development, irrigation systems were not considered, as well as genetically improved seeds and mechanisation.

Western Europe is characterised by high yields (FAOSTAT, 2020a; FAOSTAT, 2020c), due to high inputs of fertilisers, pesticides, and irrigation, as well as high use of farming technologies. Yields in this region were around 2 to 5 times superior to the ones in the African continent in 2013 (Table 2.4). For this scenario, I assumed that Western Europe represents an intensive farming system and the inputs for this scenario (area, fertilisers, pesticides) were based on the inputs used in this region.

By increasing the African yields similarly to Western Europe, the production area could be reduced quite significantly, leaving more land available for wildlife or crop production. The area and irrigation water were reduced based on the factors listed below for each commodity and region (Table 2.4). However, some commodities had higher yields in Africa than in Western Europe (fruit and sugar crops in NA; and fruit, treenuts and sugar crops in SA), so their production operated as in a BAU system.

Table 2.4. Factors by which the area used for each commodity decreased in each region in an intensive farming scenario, based on yields in Western Europe.

Commodity	EA	MA	NA	SA	WA
Cereals	4.16	7.46	3.56	1.98	6.45
Fruit	1.60	1.34	-	-	1.68
Oil crops	4.27	5.23	7.23	2.18	6.35
Pulses	3.84	5.67	3.48	4.20	5.01
Roots and Tubers	5.28	4.54	1.69	2.16	5.49
Treenuts	3.31	2.51	3.18	-	3.79
Vegetables	4.48	6.69	1.47	1.90	6.38
Sugar crops	1.12	3.30	-	-	1.46

The inputs of fertilisers and pesticides were likewise based on the ones in Western Europe. FAO provides data for fertiliser (FAOSTAT, 2019b) and pesticide use (FAOSTAT, 2019e) per hectare for the African subregions and Western Europe. Based on the data, the factors by which fertilisers and pesticides increased to resemble the ones in Western Europe were determined and are presented in Table 2.5.

Table 2.5. Factors by which fertilisers and pesticides increased in each region an intensive farming scenario, based on the fertiliser and pesticide inputs in Western Europe.

Input	Item	EA	MA	NA	SA	WA
Fertiliser	Nitrogen N	12.91	54.38	3.36	3.77	21.66
	Phosphate P_2O_5	5.57	32.44	1.75	1.78	11.99
	Potassium K_2O	22.15	25.53	9.75	3.34	19.95
Pesticide	Unspecified	18.80	94.00	4.64	1.94	94.00

2.2.3. Diet Changes

The African diet mainly includes cereals and roots and tubers, along with vegetables and fruit. Meat and fish consumption is low, but there is considerable consumption of dairy products. Cultural, ethical, environmental and economic factors might affect diet and change it by 2050.

Due to cultural, ethical, economic and environmental reasons, in the future the African population adopts a vegetarian diet, reducing meat consumption – vegetarianism. Economically, as the population becomes wealthier, two scenarios can be studied: meat consumption increases by 50%; or the population gets a healthy diet, increasing and diversifying food production.

Vegetarianism

Vegetarianism consists of abstinence of meat consumption and could also include animal by-products (eggs, milk). According to Nijdam et al. (2012), vegetal meat substitutes – derived from grains or vegetables – have a lower carbon footprint than meat (beef, pork, poultry), with lower GHG emissions and land use.

According to FAOSTAT (2017), in 2013 meat accounted for between 2 and 11% of the daily food supply and provided between 7 and 28% of daily protein supply (Table A.1), which suggests that meat consumption in the continent was low. Although the African population had a low meat consumption in 2013, a decrease in it must be followed by an increase in consumption of meat substitutes rich in protein, to ensure the population gets the adequate protein intake to maintain a healthy condition. In Africa, processed meat substitutes and alternatives, such as tofu, tempeh and algae are not common and most of the population cannot afford it.

To find which commodities were better suited to substitute meat, I determined the protein content of each commodity. Through the food and protein supply (g/capita/day) provided by the FBS (FAOSTAT, 2017), the protein content of 1 g of all commodities was studied. Meat had a protein content of at least 10% in all regions. Pulses had the highest protein content of all commodities addressed in this study, with around a 21% protein content, followed by oil crops, with 16% and eggs with around 10%. Thus, in this scenario, pulses, oil crops and eggs were the chosen substitutes for meat. Considering all the three commodities had a higher or similar protein content to meat, I assumed that the meat production quantity could be simply replaced by the production of pulses, oil crops and eggs, according to their contribution to protein intake.

Hence, pulse production covered around 45% of meat production, oil crops 34% and eggs 21%. The factors by which the production of these commodities increased to substitute meat were determined and are presented in Table 2.6. Pulses and oil crop factors affected all inputs (area, seed, water, manure, fertilisers, pesticides, energy, irrigation water, imports) and outputs (losses, production quantity, exports). Egg production factors affected its production quantity, imports, and exports.

Table 2.6. Factors by which pulse, oil crop and egg production increased in each subregion in a vegetarianism scenario, to substitute meat production.

Commodity	EA	MA	NA	SA	WA
Pulses	1.37	2.88	4.01	20.63	3.31
Oil crops	1.32	1.04	2.22	1.70	1.12
Eggs	2.65	4.38	1.83	2.32	1.56

It is important to note that the vegetarianism scenario cannot be completely 100% vegetarian and mainly semi-vegetarian. Considering there was still production and consumption of milk and eggs, livestock (poultry, cattle, and sheep and goat) was still being raised to produce these commodities, yet it would eventually be consumed, as the African population cannot afford to waste food, particularly meat. This diet can be regarded as a circular diet, where nothing goes wasted.

In this scenario, milk was produced by cattle and sheep and goats, as in a BAU system. The number of animals required to produce milk was determined, using the yields provided by FAOSTAT (2020c). Based on the cattle and sheep and goat required to produce milk, the factors by which cattle and sheep and goat (animal and meat) production would change were determined (Table 2.7). Although meat production decreased in most regions, in certain regions the opposite occurred: for example, the demand for milk production in EA increased the production of cattle meat. Nevertheless, I assumed that the cattle used to produce milk for one year was slaughtered in the same period, which is not necessarily true, as cattle could be used several years for that purpose, before being slaughtered.

Table 2.7. Factors by which cattle and sheep and goat (animal and meat) production changed in each region in a vegetarianism scenario, where cattle and sheep and goat were used to cover milk production.

Region	Cattle		Sheep + Goat	
	Animal production	**Meat production**	**Animal production**	**Meat production**
EA	0.26	2.54	0.19	0.36
MA	0.04	0.34	0.04	0.09
NA	0.32	1.51	0.40	0.34
SA	0.09	0.50	0.004	0.02
WA	0.16	1.37	0.16	0.33

While the animal production factors affected the area, feed and water, the meat production factors affected the livestock being slaughtered, the losses related to it and imports and exports.

The amount of poultry required to satisfy the egg demand under a vegetarian diet was determined based on poultry yields provided by FAOSTAT (2020c). The poultry required, along with its existing stock in each region in 2013 allowed for the calculation of the factors by which its production increased or decreased in each region. The meat generated by the poultry was determined, as well as the factors associated with it.

The factors (Table 2.8) concerning egg production affected its production quantity, imports and exports, whereas the poultry (animal) production affected area, feed, water and poultry amount.

Finally, the poultry meat production factors affected the amount of poultry being slaughtered, its losses and imports and exports.

It is important to note that this scenario depended solely on poultry capable of producing eggs, such as hens. I assumed that all existing poultry could produce eggs.

Table 2.8. Factors by which egg and poultry (animal and meat) production changed in each region in a vegetarianism scenario, where egg substitutes meat production and poultry was solely used for egg production.

Region	Egg production	Poultry (animal) production	Poultry (meat) production
EA	2.65	0.68	0.45
MA	4.38	0.43	0.30
NA	1.83	0.38	0.14
SA	2.32	1.02	0.18
WA	1.56	0.75	0.62

Meat Consumption Increase

As the African population becomes wealthier, the meat demand increases. Meat provides great amounts of protein and vital nutrients. In this scenario, I assumed that meat consumption increased by 50%, yet the remaining crop commodities were consumed as usual, without variations. Thus, meat production and all the factors affecting it (area, feed and water for livestock, and imports and exports) increased by 50%.

Healthy and Balanced Diet

A healthy and balanced diet is essential to prevent diseases and ensure the organism gets the nutrients required to function properly. An adequate nutrition is based on the consumption of food from each commodity group, particularly fruit, vegetables, grain foods and water. According to the NHS (2019), starchy roots, and vegetables and fruit contain a high amount of fibre, vitamins, and minerals and should contribute at least one-third of the daily diet, although fruit is rich in sugar (NHS, 2019). Pulses, fish, eggs, meat and dairy are great sources of protein and offer vitamins and minerals (iron, zinc and B vitamins), yet pulses have a low fat content (NHS, 2019). Finally, nuts are also high in fibre but contain high levels of fat and its consumption should be cautious (NHS, 2019).

For this scenario, I assumed, based on the nutrients provided and importance of each group commodity, that a healthy diet required the consumption of around 30% grains (15% cereals and 15% pulses), 25% vegetables (12.5% roots and tubers, and 12.5% vegetables), 20% fruit, 15% meat and dairy (7.5% meat, 5% dairy and 2.5% eggs), and 10% oils and sugar (3.3% oil crops, sugar crops, and treenuts).

The current pattern of food consumption in Africa was determined in section 2.1: System Analysis. According to Table A.1, cereals were the only commodity produced above the benchmarks set in all regions. The remaining commodities' production was below the percentages set, meaning their production had to increase. Using the total food supply by region provided by FAOSTAT (2017), it was possible to determine how much each commodity should increase to reach the benchmarks set and the factors by which it had to increase were calculated and are presented in Table 2.9, except for roots and tubers, sugar crops, vegetables, meat, and milk in some regions.

Table 2.9. Factors by which the production of each commodity increased in each region in a healthy and balanced diet scenario, where the population had an adequate availability of every commodity.

Commodity	EA	MA	NA	SA	WA
Fruits	1.71	1.51	1.54	2.73	2.04
Oil crops	2.96	2.20	4.61	8.03	2.79
Pulses	4.40	7.26	15.17	29.44	7.86
Roots and tubers	-	-	2.20	1.84	-
Sugar crops	1.46	1.58	-	-	1.87
Treenuts	26.55	28.25	16.23	47.75	6.16
Vegetables	1.99	1.19	-	1.69	1.42
Meat	3.25	1.88	1.95	-	3.62
Milk	-	2.94	-	-	2.44
Eggs	11.41	23.35	3.67	2.16	6.17

The factors determined above were used to increase all inputs affecting the production of each commodity: area, seed, feed, water, manure, fertilisers, pesticides, energy, production quantity, losses, imports, and exports. Regarding meat increase, considering three animal species were being raised, I assumed that the meat production factors were divided equally by the three animal categories.

Although the food supply quantity depended on other factors (imports, exports, stock variation) besides food production, I assumed that, in order to have a healthy diet and reach the targets set for each commodity, the food production had to increase according to the factors determined to ensure its availability at the percentages set.

2.3. Model Development

In this project, the current agricultural system was modelled, and prospective agricultural models were created, based on the scenarios developed in section 2.2. The models were developed considering all inputs and outputs of the systems.

LCA Methodological Approach

The standard LCA methodological approach, as described by the ILCD Handbook (European Commission et al., 2010), was followed as much as possible and deviations to it are presented throughout the methodology if required.

The modelling was developed using the openLCA software version 1.10, a free Life Cycle Assessment software, which was created in 2006 by GreenDelta to model and calculate the environmental impacts of product systems (Hildenbrand et al., 2006). The openLCA software was used along with the ecoinvent 3.3 database, which was released in 2016 and provides the Life Cycle Inventory (LCI) data on various sectors, particularly the agricultural sector (ecoinvent, n.d.). The ReCiPe method 2016 was used for the LCIA of each model, by generating the midpoint and endpoint H impacts, although the midpoint I and E impacts were also studied during the BAU system impact assessment.

2.3.1. Goal and Scope Definition

The purpose of this project was to explore the current agricultural system and develop prospective agricultural models for five African regions, considering changes to social, cultural, economic and environmental factors by 2050, such as population growth, farming systems and dietary shifts; and determine their environmental impacts, using data collected from databases and literature. Considering the increasing food demand and the environmental impacts of agriculture, it is essential to study how these impacts will be aggravated in the future and compare which factors contribute the most to it.

This study was purely research-based and may serve as decision support for policy-makers and grassroots organisations, whose purpose is to promote change in communities and may influence food production and nutritional habits in Africa.

Functional Unit

The primary service required from an agricultural system is providing goods to feed the population. The functional unit of this study was *an agricultural system capable of feeding the entire African population by 2050*, by providing crops and livestock to sustain the population growth.

The secondary services provided by the African agricultural system are displayed through the GDP and employment rates in the continent.

System Boundaries

The spatial scope comprised five subregions of the African continent: Eastern, Middle, Northern, Southern and Western Africa. The temporal scope of the study comprised the years 2013 (when available) and 2050, for which there are projections for population growth. The technological scope comprised a low use and advancement of technology, as it is characteristic in Africa.

The agricultural system considered a 'cradle-to-gate' approach, including crop and livestock production, harvesting and processing throughout one year. Storage, distribution, sale, consumption, and disposal of the goods were excluded from this study, due to time constraints (Figure 2.2).

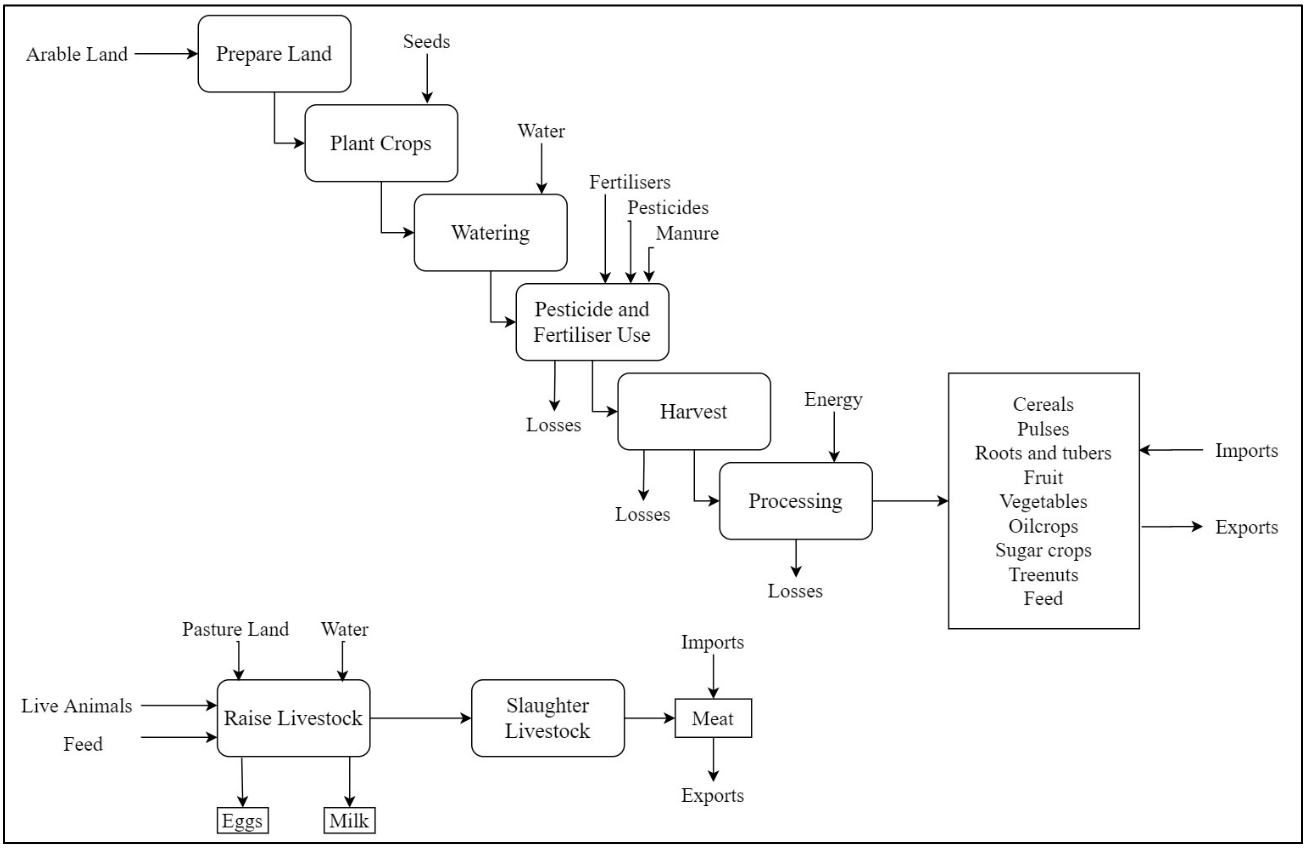

Figure 2.2. Process flow diagram of the African agricultural system, including all major processes of crop and livestock production, with its respective inputs and outputs.

Not all food commodities were included, which facilitated model development. The models considered the production of certain crops (cereals, roots and tubers, pulses, treenuts, oil crops, vegetables, fruits, and sugar crops) and livestock and products (cattle, poultry, sheep and goat, milk, and eggs). Fish and seafood, stimulants, and spices were excluded from the study, as each contributed to around 1% or less of the domestic supply quantity. Although alcoholic beverages had a higher contribution to the domestic supply quantity (between 4 and 8%), its production did not contribute to feeding the African population.

Although FAOSTAT provides data for Food Aid Shipments during emergency responses to hunger crisis, these shipments represented a significantly small amount (less than 0.5%) of the total domestic supply quantity and were disregarded during model development.

During the LCA, the consequential approach was applied, as changes in the agricultural system had an impact on several industries and sectors, affecting the African population.

Assumptions

Considering not much data could be found on machinery in African countries, I assumed that all farming labour was manual or dependent on animal labour and no machinery was used.

I assumed that the African population willingly implemented the diet changes scenarios (subsection 2.2.3), becoming semi-vegetarians, increasing meat consumption by 50 % or having a healthy diet.

Fertilisers, pesticides, irrigation water and feed are essential for crop and livestock production. I assumed that these inputs were available to all African farmers, regardless of their wealth. Thus, all crops were equally provided fertilisers, pesticides and irrigation water and all livestock had water and feed equally available for consumption. These assumptions facilitated model development on openLCA.

Data Quality Requirements

The study mainly relied on FAO's database (FAOSTAT), which compiles statistical data from 1961 until the most recent year available for 245 countries and territories; AQUASTAT, which provides data for water consumption in agriculture; reports from FAO – "Livestock's long shadow", "Global food losses and food waste – Extent, causes and prevention" and peer-reviewed articles. Although data provided by FAOSTAT is based on annual national statistics and estimates, data quality varies significantly between countries, depending on data collection methodologies (FAOSTAT, 2020c) and some countries provide little to no data or incomplete data (FAOSTAT, 2020c), it is assumed that the data used in this analysis was representative of the agricultural system in all five African regions in 2013.

Allocation Methods

Although most data collected in this project referred to the specific commodities being studied, data regarding certain inputs (irrigation water, energy, and feed and water for livestock) were provided in total consumption. To include these inputs in the model and to facilitate model development, the inputs were allocated to the commodities and livestock in question, through mass allocation.

Impact Categories

In this study, all default midpoint impact categories generated by the ReCiPe 2016 method were selected, except for Ionising Radiation (Table 2.10). This impact category was excluded due to its link to nuclear power. All the remaining impact categories were analysed in the study to get a more holistic understanding of the environmental burdens of the African agricultural system. All three ReCiPe perspectives (I, H, E) were considered for the midpoint impact assessment of the BAU system.

Table 2.10. Midpoint and endpoint categories included in the study and respective units.

Midpoint Categories			
Fine particulate matter formation	kg $PM_{2.5}$ eq	Marine ecotoxicity	kg 1,4-DCB
Fossil fuel scarcity	kg oil eq	Marine eutrophication	kg N eq
Freshwater ecotoxicity	kg 1,4-DCB	Mineral resource scarcity	kg Cu eq
Freshwater eutrophication	kg P eq	Ozone formation	kg NO_x eq
Global warming	kg CO_2 eq	Stratospheric ozone depletion	kg CFC11 eq
Human toxicity (carcinogenic)	kg 1,4-DCB	Terrestrial acidification	kg SO_2 eq
Human toxicity (non-carcinogenic)	kg 1,4-DCB	Terrestrial ecotoxicity	kg 1,4-DCB
Land use	m^2a crop eq	Water consumption	m^3

Endpoint Categories	
Damage to human health	DALY
Damage to ecosystem diversity	species·yr
Damage to resource availability	US$2013

The midpoint impacts were converted into endpoint impacts according to the ReCiPe methodology and all three endpoint impact categories were included in this study. The results of the endpoint impact assessment were both normalised and weighted to generate a single score impact, using normalisation and weighting factors provided by the ReCiPe method. Although weighting is subjective, its use is fundamental to have a general understanding of which of the systems studied has a better environmental performance.

2.3.2. Inventory Analysis

The prospective models were built based on the current inputs and outputs of the African agricultural system, which are presented below in Table 2.11.

Table 2.11. Data collected for model development and the respective unit, year, and source for both crop and livestock production in the African continent. Most data was collected according to region (EA, MA, NA, SA and WA).

	Data	Unit	Year	Source
Crop Production	Production quantity	Tonnes	2013	FAOSTAT (2017)
	Area harvested	Hectares	2013	FAOSTAT (2020a)
	Irrigation water	m^3	1999-2017	FAO (2016)
	Seed	Tonnes	2013	FAOSTAT (2017)
	Manure applied to soils	Tonnes	2013	FAOSTAT (2019d)
	Fertilisers use	kg/ha	2013	FAOSTAT (2019b)
	Pesticides use	kg/ha	2013	FAOSTAT (2019e)
	Energy use	Terajoule	2012	FAOSTAT (2016)
	Feed	Tonnes	2013	FAOSTAT (2017)
	Import quantity	Tonnes	2013	FAOSTAT (2017)
	Export Quantity	Tonnes	2013	FAOSTAT (2017)
	Losses	%	2011	FAO (2011)
Livestock Production	Livestock	Head	2013	FAOSTAT (2020b)
	Area for pasture	LSU/ha	2013	FAOSTAT (2019c)
	Water for livestock	L	1985-2003	FAO (2006)
	Feed	Tonnes	2013	FAOSTAT (2017)
	Animal weight	kg	2006; 2009	FAO (2006); FAO (2009) and assumptions
	Feed conversion ratio	kg DM feed/kg EW	2016	Alexander et al. (2016),
	Production quantity	Tonnes	2013	FAOSTAT (2020c)
	Import quantity	Tonnes	2013	FAOSTAT (2017)
	Export Quantity	Tonnes	2013	FAOSTAT (2017)
	Losses	%	2011	FAO (2011)

Crop Production

Data concerning crop production was mainly collected from FAOSTAT and its FBS, AQUASTAT and FAO's "Global food losses and food waste – Extent, causes and prevention".

The FBS from FAOSTAT (2017) provided data for production quantity, feed, seed, import quantity and export quantity for each subregion. The models developed represented the production of food commodities (e.g. cereals, vegetables, fruit), yet each food group was represented by the three most produced food items in that group, when available (e.g. maize, wheat and sorghum represented the cereal production in EA). The FBS consider tomatoes as vegetables (FAO, 2001), thus in this study tomatoes, likewise, represented the vegetable group.

Regarding seed data, the FBS provided the amounts of seed of the commodity in question set aside for sowing or planting and, in this project, I assumed that all seeds were used for that purpose in 2013, which may not have been the case. However, the FBS only had data available for some cereals, roots and tubers, pulses, and oil crops. Vegetables, fruits, treenuts and sugar crops lacked seed data, which were disregarded in this study.

Other agricultural inputs required for the system were also provided by FAOSTAT for each region: area harvested (FAOSTAT, 2020a), fertilisers (FAOSTAT, 2019b) and pesticides (FAOSTAT, 2019e) use, manure applied to soils (FAOSTAT, 2019d) and energy use (FAOSTAT, 2016).

Finally, the irrigation water consumption was provided by AQUASTAT (FAO, 2016), which is FAO's global water information system for water use on agriculture. This database provides irrigation water consumption per country per year. The irrigation water withdrawal in the period 1999-2017 was selected, due to a shortage of data for the year 2013, and the African countries were selected individually and grouped by region. As not all African countries provided data for water consumption, the data for irrigation water was incomplete for this study.

Inputs for which there was only the total consumption amount (irrigation water, energy use, manure applied to soils) were allocated by commodity, based on the total area harvested and area harvested per crop (Appendix B.1-Appendix B.3). When the consumption per hectare was available (fertilisers, pesticides), the consumption per crop was also determined based on the area harvested per crop. Hence, it may not represent the actual amount of input used but functioned as an approximation. For instance, some crops may require more or less water or pesticides to grow than others, which was not considered in this LCA – I assumed that the amount of input consumption was dependent only on the area used.

Energy sources vary throughout the African continent. Regarding energy use, six different energy sources were accounted for in this study: diesel, fuel oil, coal, electricity, natural gas, and energy for power irrigation, although not all regions used these six sources.

Although most African farmers own small-scale farms mainly for self-consumption and have little access to mechanisation, the existing large-scale farmers are highly mechanised, and a lot of energy is consumed by the agricultural system. Moreover, food processing was also within the scope of this study and it also contributes to energy use. Thus, energy was included in the models, although on openLCA it was represented in the last process of the system (processing of crops and slaughtering of livestock).

As all existing systems, losses occur throughout the agricultural system, which were considered to obtain more reliable results. The loss percentages in each stage of crop production were taken from FAO’s “Global food losses and food waste – Extent, causes and prevention” (FAO, 2011). In this study, only losses during agricultural production, postharvest handling and processing were accounted for, concerning cereals, roots and tubers, oil crops, pulses, fruits, and vegetables.

Livestock Production

Data regarding livestock production was collected from FAOSTAT, FAO’s “Livestock’s long shadow” and “Global food losses and food waste – Extent, causes and prevention” and “The state of food and agriculture 2009”, and the peer-review article “Human appropriation of land for food: The role of diet” by Alexander et al. (2016).

FAOSTAT (2020b) offered data regarding the live animal stock in 2013, which comprehends the number of animals of each species present in the country at the time of enumeration. It included animals raised for meat, eggs and dairy production, draft purposes or breeding. However, according to FAO, in certain countries, data for chickens, ducks and turkeys did not seem to represent the total number of these birds (FAOSTAT, 2020b). FAOSTAT (2020c) also provided data concerning the meat quantity generated by each species but it did not include data for bushmeat, which is an important food supply in Africa, particularly in rural areas.

The area used by livestock was determined, based on the area required per livestock units for each species (cattle, poultry, and sheep and goats), collected from FAOSTAT (2019c) for every region in 2013.

The total feed available for livestock by commodities and regions was given in tonnes (FAOSTAT, 2017). Although the values provided concern total available feed in 2013, I assumed that all the feed available was consumed in the same year, which may not represent the actual situation. The three animal categories studied have different feed requirements. According to Alexander et al. (2016), cattle require 25kg of feed to produce 1kg of meat, while sheep and goats require 15kg, and poultry requires 3.3kg. To allocate the feed according to feed requirements and number of animals of each species (Appendix B.4), the average weight of each animal was needed: based on FAO’s “Livestock’s long shadow" (FAO, 2006), cattle have an average weight of 250kg and sheep and goat have an average weight of 32kg, while according to FAO's "The state of food and agriculture" (FAO, 2009), poultry has an average weight of 2.5kg.

FAO's "Livestock's long shadow" (FAO, 2006), provided a collection of data from peer-reviewed articles (1985-2003) of water requirements (litres/animal/day) for different species with average weights (kg) under different temperature conditions (15ºC, 25ºC and 35ºC) – 25 ºC was chosen. From these values, the total water requirements (L) for cattle, poultry and sheep and goat were determined per year (Appendix B.5).

Finally, the losses occurring during livestock production were also accounted for and were taken from FAO's "Global food losses and food waste – Extent, causes and prevention" (FAO, 2011), considering percentage losses during agricultural production, postharvest handling and processing for meat, milk and eggs.

The current African agricultural system was modelled on openLCA, dividing the continent into 5 subregions, and studying crops and livestock individually. The modelling of crop production is represented in Figure 2.3, exemplifying cereal production, with the main processes and input providers.

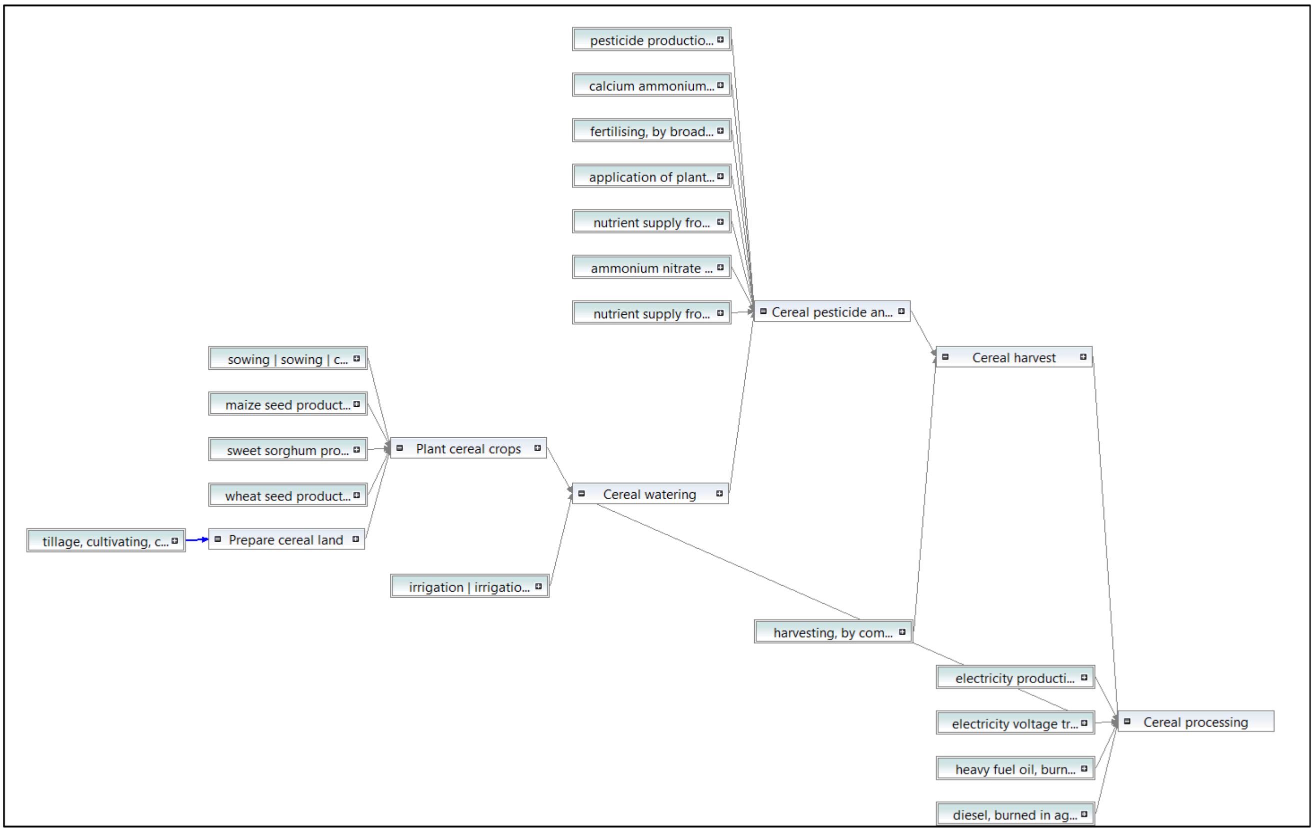

Figure 2.3. Example of representation of the modelling of cereal production on openLCA: main processes and input providers considered for crop production.

The example model representation of livestock production can be found in Appendix A.3 (Figure A.1), illustrating poultry production.

Using the current agricultural model developed on openLCA, the scenarios were set, using global parameters for each commodity and region individually. The values of the parameters were based on the factors determined in section 2.2, during scenario development. The impact assessment of the chosen scenarios was performed by changing the values of the parameters in question.

Model Limitations

Although FAO provides detailed data regarding inputs and outputs of the African agricultural system, a part of it was unavailable (seed for fruits, vegetables, amongst others) or had poor data quality (stock of live poultry animals, irrigation water, e.g.), due to lack of access to national statistics and estimates or incomplete data.

Furthermore, although the FBS provide quite complete data for food production in Africa, some of it should be more specific, to allow more thorough models and impact assessment results. For instance, the FBS offered vague data regarding pulse production: it only provided data for beans and peas and did not specify what kind of beans and peas were being produced. This data is important when developing models on openLCA, as ecoinvent provides flows and processes regarding specific products (fava beans. e.g.).

Both model development and environmental impact assessment were performed on openLCA using the ecoinvent database. However, this database lacked flows and processes related to specific products.

Ecoinvent database lacked flows for certain cereals, pulses, oil crops, fruits, roots and tubers, and milk. Regarding cereals, the database did not include flows for millet, a staple in the African diet, which ended up being disregarded in the model. The database also lacked flows and processes for beans in general and the only flows available concerned fava bean production, which was used to represent the whole bean production. Regarding oil crops, sesame seed was not represented on the database and was substituted by linseed. To represent citrus fruit, lemons were chosen. Roots and tubers were underrepresented on ecoinvent, particularly cassava, sweet potato, and yam. Cassava and sweet potato, being a crucial part of the African diet, had to be represented in the model, therefore potato flows and processes were chosen as substitutes to these two commodities, while yam was not included in the model. Finally, there were no flows for sheep and goat milk production, which was substituted by cow milk.

Sensitivity Analysis

LCAs are susceptible to uncertainty, mainly due to methodological choices, assumptions, allocation rules, system boundaries and data quality (Cellura et al., 2011). Secondary input data, which derives from referenced literature, originates considerable uncertainty (Cellura et al., 2011).

Uncertainty regarding the input parameters will result in uncertainty in the outcome (LCIA) of an LCA (Wei et al., 2015; Groen et al., 2017). To validate the models developed on openLCA, a sensitivity analysis was performed. A sensitivity analysis explores the influence of an input parameter on the value of another, testing its influence on the impact assessment results and providing a better understanding of the robustness of the results (Groen et al., 2017). To do so, local sensitivity analysis can be performed: it determines the effects of a small variation in one of the input parameters at a time in the results (Wei et al., 2015; Groen et al., 2017). In this study, local sensitivity analysis was applied, selecting 10 parameters, and variating them one at a time by 10%, to study their influence on the impact assessment results. For this analysis, I short-listed the parameters, considering the ones based on assumptions, allocation methods, secondary data, and data quality.

Regarding crop production, the parameters studied were irrigation water, energy, seed, manure applied to soils, fertilisers, pesticides, land, and production. The parameters for irrigation water, energy, manure applied to soils, fertilisers, and pesticides suffered from allocation. Concerning seed use, I assumed that all seed put aside for sowing or planting was used for that purpose in 2013, which may represent uncertainty in the results. Finally, all inputs stated were provided by FAOSTAT or AQUASTAT and could have poor data quality, as it is based on annual national statistics and estimates, which often lack data.

Regarding livestock production, the parameters studied were feed, water consumption, land use and production quantity. The feed used for livestock was allocated per animal, based on peer-reviewed articles and assumptions, which could have contributed to uncertainty. Water consumption by livestock was determined based on secondary data, whereas feed, land use and livestock production quantity were provided by the FBS and could lead to uncertainty.

3. Results

In this chapter, the results are divided into two sections: in section 3.1, the African agricultural system from 2013 is studied, starting from the diet composition and energy requirements of the African population. It also explores the productivity registered in the continent, as well as fertiliser and pesticide use. Finally, the impact assessment of the current system is studied, and the impacts of the food commodities are investigated.

Section 3.2 comprises the impact assessment of the prospective agricultural models developed on openLCA, based on the current system in practice and potential pathways regarding population growth, farming techniques and diet changes. The impacts of the scenarios are compared with the current situation.

3.1. African Agricultural System

Dietary Energy Requirements

Figure 3.1 represents and compares the adequate and minimum dietary energy requirements and consumption, with dietary availability in 2013. The results show that NA was the region with the highest food availability in 2013, with 3228 kcal/capita/day, followed by SA. EA registered the lowest food availability, with 2169 kcal/capita/day, after WA and MA. Figure 3.1 also shows that the ADER varied between African regions, ranging from 2218 to 2358 kcal/capita/day and all regions, except for EA, had a food supply superior to the ADER – NA had a food supply 37% higher than the ADER, while the food supply in EA was 2% inferior to the ADER.

However, in many African countries, there was a high prevalence of undernourishment and most of the population consumed only the MDER or less. According to the results, the MDER in the subregions ranged between 1888 and 2020 kcal/capita/day. The daily food deficit ranged between 5 and 421 kcal/capita/day in all African countries, with the highest average deficit in EA (208 kcal/capita/day), followed by SA and MA, and the lowest deficit in NA (20 kcal/capita/day), followed by WA. The difference between the MDER and the intake ranged between 1% for NA and 12% for EA.

The average dietary intake was lower than the MDER in all African subregions, indicating that there was an undernourishment issue across the continent in 2013, particularly in EA, suggesting the African population did not get a healthy diet.

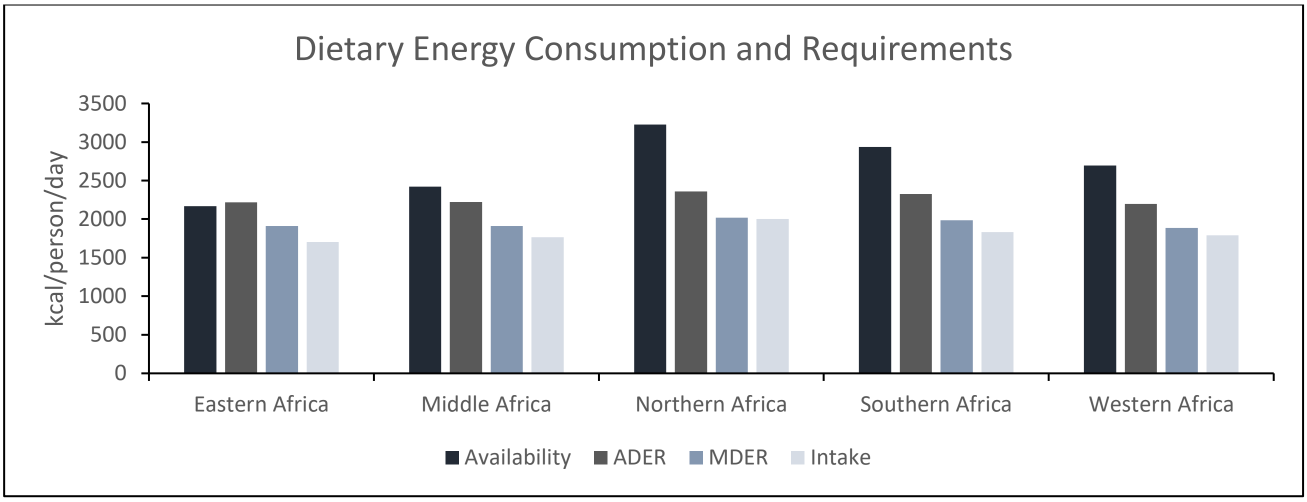

Figure 3.1. Daily dietary energy (in kcal/person/day) registered in each African subregion: caloric availability, and adequate, minimum, and actual caloric intake.

Diet Composition

The FBS provided data for the supply of all food commodities across the African continent (Table 3.1) and its subregions (Table A.1), to better understand how much of each commodity was available for consumption in 2013 and its respective protein and fat supply.

Table 3.1. Food, protein, and fat supply by commodity in the African continent in 2013, representing both crops and livestock.

Commodity	% Commodity in the food supply	% Protein supply	% Fat supply
Cereals	20.4	48.9	15.2
Fruits	8.9	1.8	1.0
Oil crops	0.8	4.2	9.2
Pulses	1.6	10.4	1.0
Roots and tubers	18.3	6.0	1.1
Sugar Crops	0.8	0.1	0.0
Treenuts	0.2	0.5	1.6
Vegetables	9.1	3.2	0.7
Eggs	0.4	1.1	1.2
Meat	2.6	10.4	12.0
Milk	5.9	5.8	7.5

The results in Table 3.1 show that, in 2013, the African continent was mainly supplied by cereals and roots and tubers, which contributed about 20 and 18% of the food supply, respectively, followed by vegetables and fruits, both contributing around 9% of the food supply. All these four commodities are staples of the African diet and the population relies on its availability daily, thus it is expected that these four commodities were highly produced in the continent in 2013. Most of the protein and fat supply was provided by cereals and meat. However, pulses also contributed considerably to protein supply and oil crops provided a high fat content. Moreover, pulses, meat, and animal products, rich in protein, composed only around 10% of the diet.

Table A.1 shows that the diet in 2013 was similar in all subregions, and EA, MA and WA mostly relied on cereals, roots and tubers and fruit. In EA and WA, the protein supply was mainly provided by cereals and pulses, yet cereals and meat contributed the most to fat supply in EA and cereals and oil crops offered more fat content in WA. In MA, cereals and meat were the major providers of protein, while oil crops and meat mostly supplied fat.

The greatest difference in diets concerns both NA and SA. The NA diet was mainly composed of cereals, vegetables, and fruit. Cereals and meat presented a higher protein content, while fat was supplied by cereals and milk. In SA, cereals, meat, and milk were the most supplied commodities, and the highest protein and fat supply came from cereals and meat. The data suggests that subregions with higher wealth levels (NA and SA) have higher quantities of meat and milk, which offer a great amount of protein and fat.

Yields

The yields of the African continent and its subregions were compared to average global yields and maximum yields registered in 2013, which are presented in Table 3.2. A more detailed overview of yield comparison is represented in Appendix A.2 in Table A.2.

Table A.2 reveals that the overall efficiency of crop and livestock production in the continent compared to global yields was around 75%, yet when compared to maximum yields, the efficiency dropped to 19% for crops and 30% for livestock.

Table 3.2. Summary of African's and its subregions' yields efficiency compared to global and maximum yields registered worldwide in 2013.

Yields	Commodity	Africa (%)	EA (%)	MA (%)	NA (%)	SA (%)	WA (%)
GLOBAL	Crops	75	58	46	97	129	44
	Livestock	74	57	52	77	135	47
MAXIMUM	Crops	19	15	11	26	30	11
	Livestock	30	25	22	34	47	21

With regards to subregions, the efficiency of crop and livestock production registered in EA, MA and WA in 2013 were low when compared to the global average (below 60% efficiency in all three regions) and maximum yields (below or equal to 25% efficiency), with WA representing the lowest yields in the continent. NA and SA had satisfactory yields for crop and livestock production compared to the global average – NA had an efficiency of at least 77%, whereas SA had an efficiency of at least 130% –, yet these regions fell short when compared to maximum yields, representing efficiencies of less than 50% for both crop and livestock production.

Table A.2 shows that oil crop production had the lowest efficiency in EA, NA, SA, and WA compared to global yields, whereas cereals had the lowest yields in MA. Regarding livestock production, the lowest yields in EA, MA, NA and WA were registered for milk, while in SA it was for egg production. However, when comparing the maximum yields in 2013 with the African yields, treenuts had the lowest efficiency in EA, MA, NA, and WA, whereas on SA, the lowest yield concerned pulses. Regarding livestock production, milk had the lowest yield in all regions. Considering the results registered in all African subregions, it is reliable to say that the yields of all commodities can be improved.

Pesticide and Fertiliser Use

Pesticide and fertiliser use in African and its subregions in 2013 is presented in Table 3.3. The results show that the overall use of pesticide and fertiliser in Africa as a percentage to worldwide use was significantly low. In 2013, the continent consumed 2.2% of pesticide use and between 1.7% and 3.4% of fertiliser use, depending on the nutrient.

Table 3.3. Pesticide and fertilisers (nitrogen, phosphate, and potassium) use in the African continent and its subregions compared to world consumption in 2013.

Input	Africa	EA	MA	NA	SA	WA
Pesticide (%)	2.2	0.4	0.0	1.0	0.7	0.1
Fertiliser N (%)	3.4	0.7	0.1	1.7	0.4	0.5
Fertiliser P_2O_5 (%)	3.2	0.7	0.0	1.5	0.4	0.5
Fertiliser K_2O (%)	1.7	0.3	0.1	0.5	0.4	0.5

A more detailed analysis by region shows that NA used the highest amount of pesticide and fertilisers in the continent, accounting for 1% of the pesticide worldwide, and between 0.5 and 1.7% of fertiliser use globally, depending on the nutrient in question. In contrast, MA had the lowest consumption of pesticide and fertilisers, representing around 0.1% of fertilisers consumption worldwide. SA was the second highest user of pesticide (0.7%), despite consuming slightly less fertiliser (0.4% for all fertilisers) than EA (between 0.3% and 0.7% of fertiliser use) and WA (0.5% for all fertilisers). However, EA consumed 0.4% of the pesticide, whereas WA used solely 0.1% of it.

Overall, it is fair to assume that the low yields found in the African continent can be related to the extremely low use of fertilisers and pesticides, which help crops grow and prevent pests and diseases. The diets, dietary energy requirements and consumption, yields, and fertiliser and pesticide use offer an understanding of the current agricultural sector and how it can be improved in the future.

Environmental Impact

Agriculture worldwide has a major impact on the environment and African agriculture is no exception, rendering it an important subject of study. The impact assessment for all commodities and regions relative to the BAU system in Africa (for 2013) was performed on openLCA. The results of the subregions were grouped and the results regarding crops and livestock for the whole continent were studied and compared and are presented below. The outcomes are based on the functional unit defined as a system capable of feeding the African population and the predicted impacts resulting from impact assessment on openLCA will henceforth be referred to as Impact Potentials (IPs).

In Figure 3.2, the relative contribution of each food commodity to global warming, land use, water consumption and terrestrial acidification is presented. Figure A.2, in Appendix A.4, presents the results for the remaining impact categories.

According to Figure 3.2, global warming was mainly affected by livestock (70%), with cattle contributing to 62% to this impact. Cereal production was responsible for 16% of the total 30% impact of crop production on global warming. The remaining commodities contributed little to global warming in comparison to the stated commodities. Regarding land use, livestock was the biggest contributor, causing 88% of land use impacts – cattle 43%, poultry 32%, and sheep and goat 12%. Crop production did not affect land use significantly, with a contribution of 5% by oil crops and 4% by cereals. Water consumption was mainly affected by crop production (81%), with cereals contributing with 45%, followed by oil crops with 16%. Water consumption by livestock was lower, yet cattle was the biggest contributor to it, with 12%. Regarding terrestrial acidification, livestock was again the greatest contributor (79%) – cattle had the highest impact, with 61%, followed by sheep and goat, with 13%. Terrestrial acidification was also affected by crop production, mostly cereals (11%) and oil crops (5%).

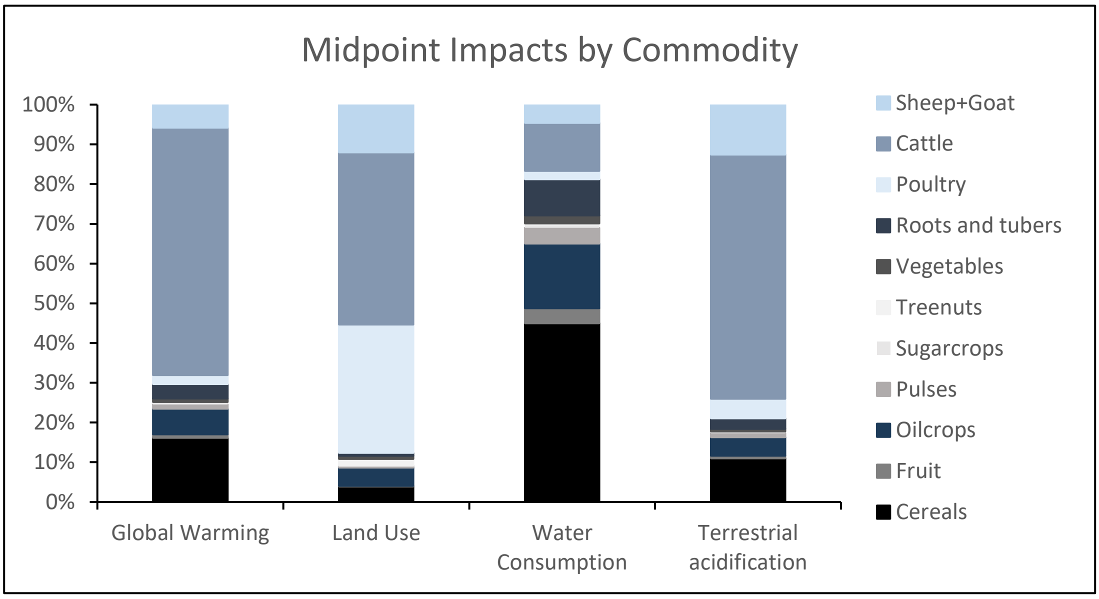

Figure 3.2. Relative contribution of food commodities (crops and livestock) in 2013 to the midpoint impacts being studied: global warming, land use, water consumption and terrestrial acidification.

Figure A.2 shows that livestock contributed the most to all impacts, except for ozone formation, which was mostly affected by crop production (54%). Livestock contribution for all impacts ranged between 46 and 85%, with cattle contributing the most to these impacts – between 43 and 83%. Cereal production was responsible for most of the crop IPs, contributing between 6 and 30%, depending on the impact category, as its production was much higher than that of the remaining crops.

Each African subregion contributes differently to impacts on the environment, which mostly depends on production capacity, as well as the quantity of inputs used (fertilisers, pesticides, energy, irrigation). Determining the IPs per capita for each subregion (Table A.3) allowed for a comparison of the actual impacts of the food production system by region. The IPs per capita for global warming, land use, water consumption and terrestrial acidification are shown in Figure 3.3, whereas the remaining impact categories are presented in Appendix A.4 (Figure A.3).

Figure 3.3 shows that SA had the highest IPs per capita on all four impact categories, followed by NA. On the other hand, MA had the lowest IPs per capita, followed by WA. Regarding the remaining impact categories, shown on Figure A.3, SA and NA once again had the highest IPs per capita on all categories, except for freshwater and marine eutrophication, whose IPs per capita were higher in EA. In contrast, MA had the lowest IPs per capita for the remaining categories, followed by WA.

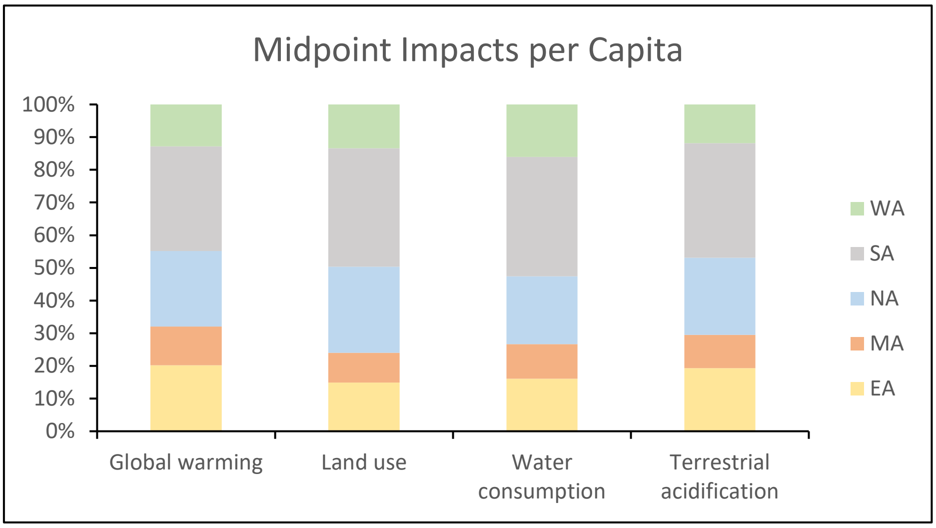

Figure 3.3. Relative contribution of each region to impacts per capita on global warming, land use, water consumption and terrestrial acidification in 2013.

It is interesting to study the IPs through different cultural perspectives (individualist, hierarchist and egalitarian), which are based on distinct time horizons and perspectives regarding human and nature adaptation to the impacts. For that reason, the midpoint IPs with I, H and E perspectives for global warming, land use, water consumption and terrestrial acidification are represented in Figure 3.4. The remaining midpoint IPs for I, H and E perspectives are presented in Appendix A.4, in Figure A.4.

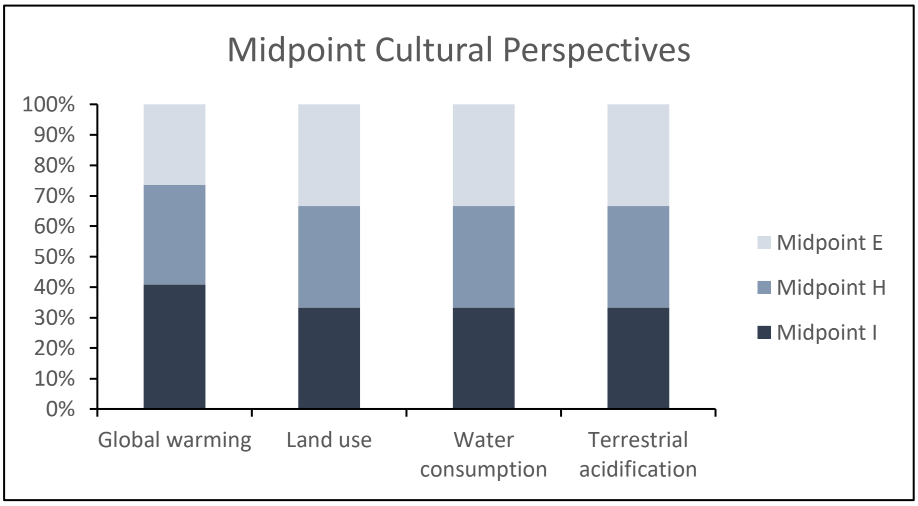

Figure 3.4. Relative contribution of the three cultural perspectives (I, H and E) to midpoint impacts on global warming, land use, water consumption and terrestrial acidification in 2013.

Figure 3.4 and Figure A.4 shows that land use, water consumption, terrestrial acidification, freshwater ecotoxicity, freshwater and marine eutrophication, fossil resource scarcity and ozone formation had the same trend in all cultural perspectives, which indicates that the IPs are equal, regardless of time horizon and perspective concerning adaptation. Global warming registered the highest IP on an individualist perspective, suggesting that the IPs are higher for a 20-year horizon and a more optimistic view, where mankind has a high adaptative capacity. Marine ecotoxicity, and human carcinogenic and non-carcinogenic toxicity registered significantly higher IPs in an egalitarian perspective, where a long-term approach and the worst-case scenario is applied. Terrestrial ecotoxicity, fine particulate matter formation, mineral resource scarcity, and stratospheric ozone depletion had similar IPs at hierarchist and egalitarian level, for a medium and long-term perspective, yet the impacts at individualist level were lower for a short-term and optimistic scenario.

To better understand the overall impacts of the BAU system, the relative endpoint IPs are presented in Figure 3.5. The endpoint impact assessment provided the impacts on human health, ecosystem biodiversity and resource availability by crop and livestock production. Figure 3.5 shows that livestock contributed up to 70% to damages on ecosystems, 65% to damages on human health and 54% to damages on resource availability. A deeper analysis of the contribution of each animal is presented in Figure A.5 and it shows that, within livestock, cattle had the highest contribution to all endpoint categories in 2013, particularly damages to resource availability.

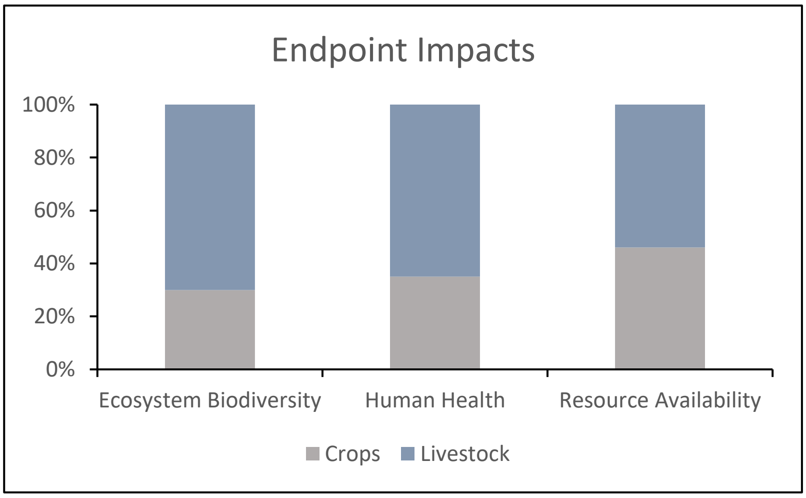

Figure 3.5. Relative contribution of crop and livestock production to endpoint impacts (damage to ecosystem biodiversity, human health, and resource availability) in 2013.

3.2. Prospective Scenarios

The future of agriculture in Africa is uncertain, mainly due to the already crippled food production system, poverty, continued population growth, urbanisation, dietary shifts, and environmental awareness. These elements render the future African agricultural system an important subject of study. Therefore, organic and intensive farming, vegetarianism, meat production increase and healthy diet scenarios were studied, along with population growth projections, and its impacts assessments were performed on openLCA.

According to the previous results, it is clear which regions had the highest IP per capita, which commodities contributed the most to impacts on the environment and overall damages. In this section, the results for the models developed on openLCA, based on the scenarios created, are presented for the reference population (of 2013) along with its population growth projections (low, medium, and high) by 2050. The midpoint H impacts provide a more detailed overview of the IPs of each scenario on different impact categories. Impact potentials on global warming, land use, water consumption and terrestrial acidification are shown to illustrate the impact of implementing each scenario, while the remaining impact categories are presented in Appendix A.5 (Figure A.6-Figure A.18).

3.2.1. Global Warming

Figure 3.6 shows that the scenarios listed in order of decreasing impacts on global warming potential (GWP) are healthy diet, meat increase, intensive farming, organic farming, BAU system and vegetarianism.

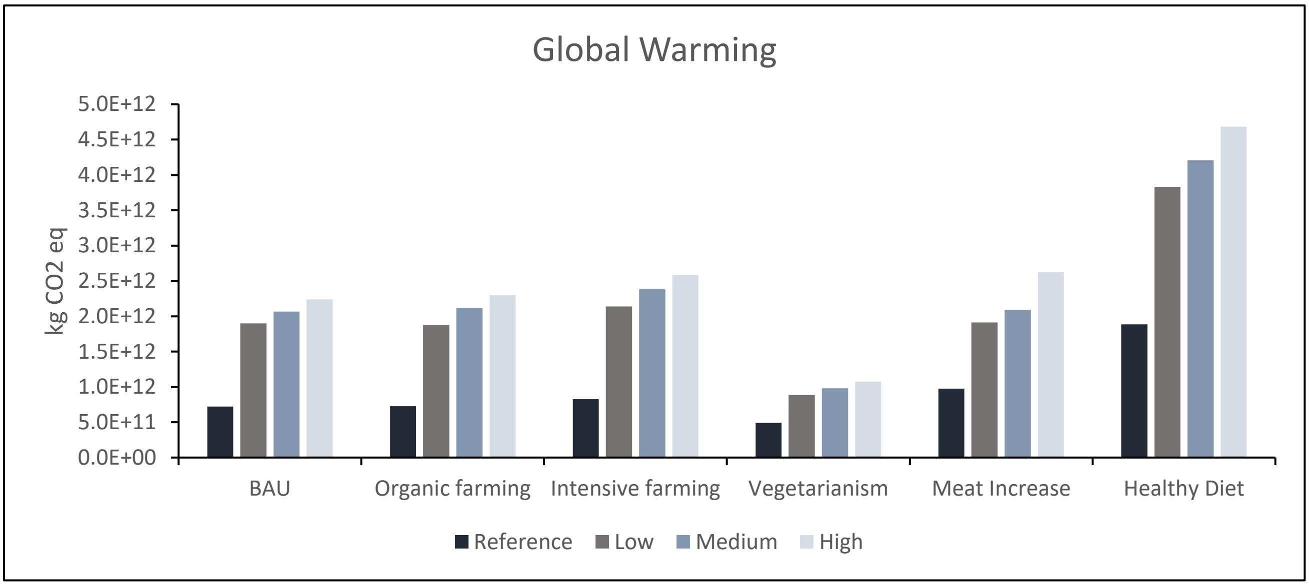

Figure 3.6. Midpoint GWP (in kg CO2 eq) for the scenarios studied (with reference population) and its population growth projections (low, medium, and high).

Regarding the farming techniques, intensive farming performed poorest on GWP, with a 15% higher impact than the BAU system. Organic farming, on the other hand, had a similar IP to the BAU system, being only 1% superior. Comparing the two farming techniques, intensive farming had a 14% higher IP than organic farming on global warming, due to the high input of fertilisers and pesticides.

Diet changes had a quite different impact on global warming. The IP of the healthy diet far exceeded that of the BAU system (more than doubled), whereas the meat increase had a higher impact (35% higher) than the current system. In contrast, vegetarianism was 32% less damaging than the BAU system. It is interesting to note that even in a high population growth projection, vegetarianism was 43% less harmful to GWP than the healthy diet scenario with the reference population. Comparing the diet changes scenarios, the healthy diet had a GWP 4 times superior to vegetarianism and almost 2 times superior to the meat increase. An option for reducing the impacts on global warming is to implement a vegetarian diet.

3.2.2. Land Use

Figure 3.7 displays that the scenario which contributed the most to land use was the healthy diet, followed by meat increase, organic farming, BAU, intensive farming and vegetarianism.

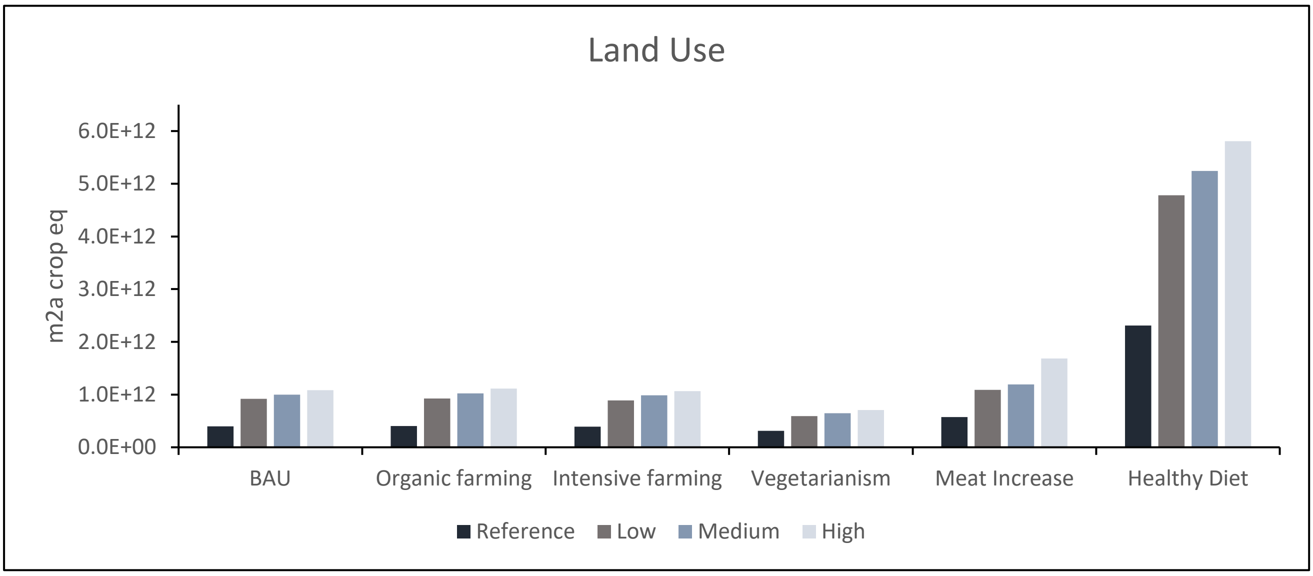

Figure 3.7. Midpoint land use impact (in m2a crop eq) for the scenarios studied (with reference population) and its population growth projections (low, medium, and high).

The differences in farming techniques lied on input and area expansion or reduction, although the impacts on land use are quite similar. Organic farming had a 2% higher contribution to land use than the BAU system, whereas intensive farming had a 3% inferior impact on land used when compared to the BAU system. Organic farming had a higher impact on land use than intensive farming (4% higher), as it was based on area expansion due to lower yields, whereas the use of fertilisers and pesticides in intensive farming enhanced the yields and allowed for area reduction.

Within diet changes, the healthy diet had a much higher impact on land use, almost 6 times superior to the BAU system, followed by meat increase (1.5 times superior). The healthy diet was based on increasing the production of almost all crops and animals, causing area expansion and higher impacts on land use, as it is seen. The meat increase scenario was also based on increasing animal production, which requires a significant land area. A vegetarian diet resulted in a 22% lower impact to the current agricultural system, since it was based on reducing animal production, although increasing pulse, oil crop and egg production. Comparing the diet changes scenarios, the healthy diet was almost 7.5 times more detrimental to land use than vegetarianism and 4 times more than meat increase.

3.2.3. Water Consumption

Figure 3.8 represents the impacts of each scenario and population growth on water consumption. The scenarios listed in order of decreasing impacts on water consumption are healthy diet, organic farming, meat increase, vegetarianism, BAU and intensive farming.

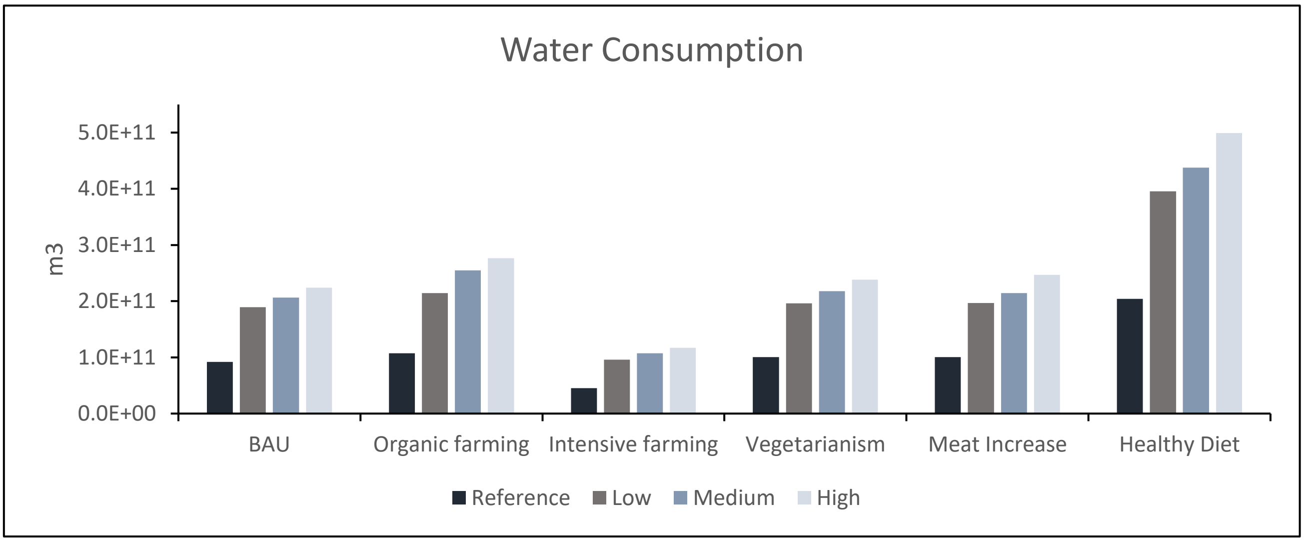

Figure 3.8. Midpoint water consumption impact (in m^3) for the scenarios studied (with reference population) and its population growth projections (low, medium, and high).

An evaluation of the impacts of farming techniques on water consumption shows that intensive farming had the lowest impact – around half the impact of the BAU system – as it was based on irrigation reduction. Organic farming, on the other hand, was based on area expansion, increasing the water used for irrigation by 17%, compared to the current system. Comparing both farming techniques, intensive farming used 58% less water than organic farming and is more beneficial from a water consumption perspective.

Water consumption was most affected by the healthy diet, doubling the impacts of the BAU system, followed by the meat increase and vegetarianism, which both had a 9% higher impact than the BAU system. The higher impacts of the healthy diet scenario were caused by a rise in overall food production, which increased the amounts of inputs used, in this case, water for irrigation and livestock. Comparing the diet scenarios, the healthy diet consumed 2 times more water than the meat increase and vegetarianism.

3.2.4. Terrestrial Acidification

Agriculture uses high inputs of fertilisers and manure to increase crop yields, and livestock produces high amounts of manure, which contribute to acidification. The impacts caused by agriculture on terrestrial acidification are shown below in Figure 3.9. The scenario which contributed the most to this impact is again healthy diet, followed by meat increase, intensive farming, organic farming and BAU, and vegetarianism.

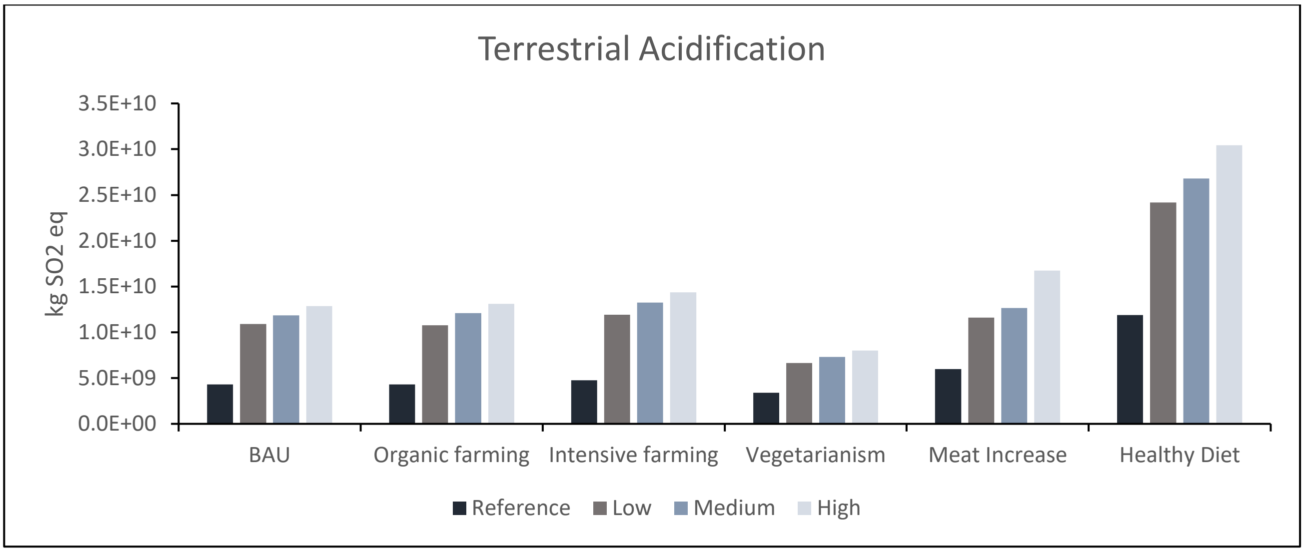

Figure 3.9. Midpoint terrestrial acidification impact (in kg SO_2 eq) for the scenarios studied (with reference population) and its population growth projections (low, medium, and high).

Within farming techniques, intensive farming had the poorest performance on terrestrial acidification, with an 11% higher IP than organic farming and the BAU system. As expected, intensive farming requires a high input of fertilisers which are important sources of nutrient-related emissions, contributing to acidification. Despite not requiring synthetic fertilisers, organic farming had the same impact than the current system, potentially due to the high manure inputs to substitute nitrogen fertilisers.

Regarding diet changes scenarios, the healthy diet relies on the large increase of food production of all scenarios, leading to the highest IP on terrestrial acidification, almost 3 times superior to the BAU system. Meat increase had the second poorest performance on terrestrial acidification, due to the higher production of livestock, which releases nitrogen emissions through manure. In contrast, vegetarianism was the most beneficial to terrestrial acidification, being 21% less harmful than the BAU system. Comparing the diet scenarios, the healthy diet was 3.5 and 1.5 times more damaging to this impact category than the meat increase and vegetarianism, respectively.

3.2.5. Remaining Impacts

The remaining impact categories studied (freshwater, marine and terrestrial ecotoxicity, freshwater and marine eutrophication, human carcinogenic and non-carcinogenic toxicity, fossil and mineral resource scarcity, stratospheric ozone depletion, and ozone formation in terrestrial ecosystems and human health) are presented in Appendix A.5 (Figure A.6 - Figure A.18).

Regarding freshwater, marine and terrestrial ecotoxicity (Figure A.6, Figure A.7 and Figure A.8, respectively), the highest impact is assigned to the healthy diet, followed by meat increase, intensive farming, organic farming, BAU and vegetarianism. Compared to the BAU system, the healthy diet had an impact almost 3 times superior for all three categories, whereas vegetarianism had around half the impact. It is interesting to note that organic and intensive farming had very similar impacts on ecotoxicity, particularly freshwater and marine. Although intensive farming used high inputs of fertilisers and pesticides and organic farming solely depended on manure to enrich the soil with nutrients. Nevertheless, organic farming required more land, which could be behind the similarity of ecotoxicity impacts.

Figure A.9 and Figure A.10 display the impacts of the scenarios studied on marine and freshwater eutrophication. The results show that marine eutrophication was highly affected by the healthy diet, followed by meat increase, intensive farming, organic farming, BAU and vegetarianism. Freshwater eutrophication was most affected by the healthy diet, followed by meat increase, organic farming, intensive farming, BAU and vegetarianism. Although intensive farming had a higher impact on marine eutrophication, organic farming was more harmful to freshwater eutrophication. However, intensive farming required a much higher input of fertilisers than organic farming of manure.

The results for human carcinogenic and non-carcinogenic toxicity (Figure A.11 and Figure A.12, respectively) show that the healthy diet had the biggest impact on both categories, followed by meat increase, organic farming, BAU, intensive farming and vegetarianism. While the healthy diet had an impact around 2.5 times higher than the BAU system, vegetarianism had around half the impact.

Regarding resource scarcity, both fossil and mineral resource scarcity impacts were studied (Figure A.13 and Figure A.14, respectively). For fossil resource scarcity, the healthy diet had the highest impact, followed by meat increase, intensive farming, organic farming, BAU and vegetarianism. Mineral resource scarcity was mainly affected by the healthy diet, meat increase, organic farming, BAU, intensive farming and vegetarianism. The healthy diet had an impact 2.5 times superior to the

BAU for both impacts, whereas vegetarianism was between 32% and 37% less harmful to both impacts than a BAU system.

Figure A.15 displays the impacts on fine particulate matter formation. The results show that the healthy diet had the highest impact, followed by meat increase, intensive farming, organic farming, BAU and vegetarianism. The impacts of the healthy diet are around 2.6 times higher than that of the BAU system, whereas vegetarianism had an impact 35% lower than the BAU.

Ozone formation has impacts on human health and terrestrial ecosystems, which are represented in Figure A.16 and Figure A.17, respectively. The scenarios listed in order of decreasing impacts on both categories of ozone formation are healthy diet, meat increase, organic farming, BAU, intensive farming and vegetarianism. The healthy diet contributed around 2.4 times more than the BAU system for both impacts and vegetarianism had an impact 18% lower than the BAU system for both categories.

Stratospheric ozone depletion is represented in Figure A.18. It shows that intensive farming had the highest impact on this category, followed by the healthy diet, meat increase, BAU, vegetarianism and organic farming. Intensive farming had an impact around 3.3 times higher than that of the BAU system, while organic farming had a 14% lower impact than this system. Furthermore, considering intensive farming had the highest impact on stratospheric ozone depletion, while organic farming had the lowest, this impact category was highly affected by fertiliser and pesticide use.

3.2.6. Population Growth

Looking at the population growth estimates, it is clear that the IPs for all scenarios would increase significantly, regardless of the projection (low, medium, and high).

Regarding the BAU system, the IPs for all impact categories were between 2 times higher for a low projection to 3.4 times superior for a high forecast, compared to the reference population. Thus, even in a conservative outlook, the environmental impacts of the current agricultural system would double by 2050.

The IPs of farming techniques vary considerably depending on the impact category, yet the impacts for both techniques studied increased significantly with the population growth forecasts. The IPs were 2 times higher for a low estimate and 3.5 times superior for a high projection.

The IPs for diet changes varied considerably between scenarios and projections. The healthy diet had the highest IPs for all impact categories, which increased significantly with population growth: the IPs increased between 1.9 times on a low projection and 2.6 times on a high forecast. In contrast, although the IPs of vegetarianism would increase significantly considering population growth, its IPs on all categories and outlooks were much lower than the healthy diet and meat increase scenarios. The IPs of vegetarianism were between 1.6 for a low projection and 2.5 times higher for a high projection, compared to the reference population. Furthermore, vegetarianism IPs for a high population growth projection was 12 to 48% of the IP of the healthy diet scenario for the same projection, depending on the impact category. The meat increase scenario for a low forecast was 1.9 times higher to 2.9 times superior for a high projection, compared to the population in 2013.

The large increase of the impact potentials for all the scenarios studied is caused by the large population growth that is expected to occur by 2050: the population is expected to increase by a factor of 1.9, 2.1 and 2.3 for low, medium and high projections, respectively.

3.2.7. Overall Environmental Performance

One of the outcomes of an LCA is the endpoint impacts, which present a simplified view of the overall impacts of the scenarios studied. These results are practical for policy-makers and the public, as they provide a general understanding of the impacts, by aggregating them into three categories: damages to human health, ecosystem biodiversity and resource availability. The damages to human health, ecosystem biodiversity and resource availability for each scenario, without considering population growth projections, are presented below in Figure 3.10, Figure 3.11 and Figure 3.12, respectively.

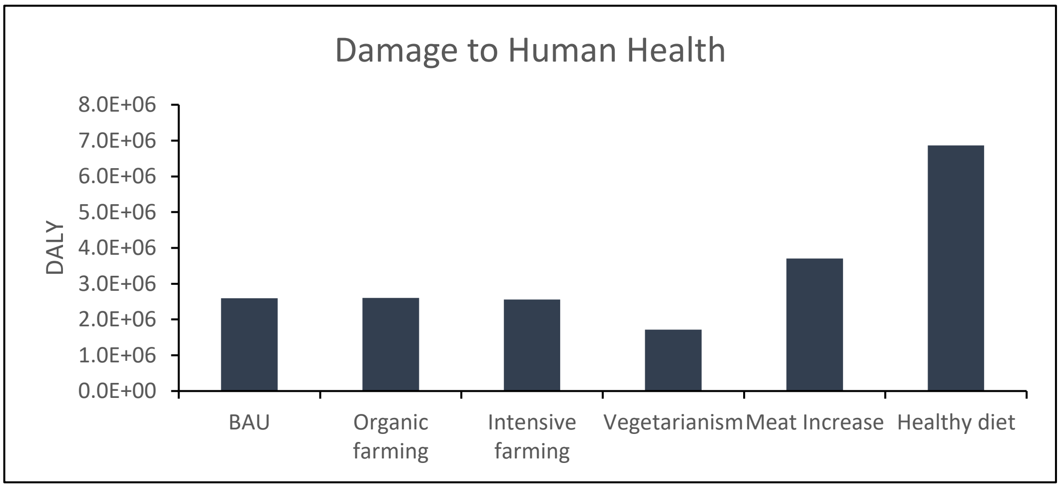

Figure 3.10. Endpoint impacts on damage to human health (in DALY) for each scenario studied – BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet.

Figure 3.10 shows that the healthy diet had the highest damage to human health, while vegetarianism caused the lowest damage. The meat increase scenario had the second highest impact on human health, followed by the BAU system, organic farming, and intensive farming, although the latter three had a quite similar impact. The healthy diet had a higher damage on human health than the remaining scenarios because it was based on an increase in food production, regarding all commodities. On the other hand, the vegetarianism scenario had a better performance, as it was based on a reduction of livestock production, which is a major contributor to overall emissions.

Figure 3.11 and Figure 3.12 display the damages to ecosystem biodiversity and resource availability, respectively. As can be observed, the ranking of the scenarios for damage to ecosystem biodiversity follows those found for damages to human health. On the other hand, damage to resource availability differs regarding the impacts of the BAU system and farming techniques, as intensive farming had the highest impact of the three, followed by the BAU system and organic farming.

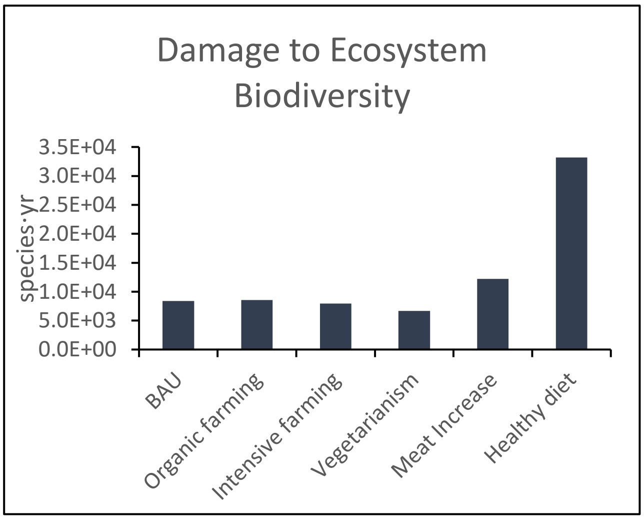

Figure 3.11. Endpoint impacts on damage to ecosystem biodiversity (species·yr) for each scenario studied.

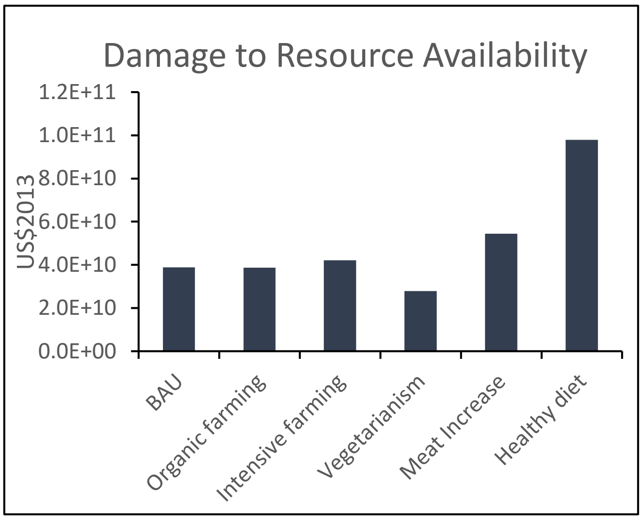

Figure 3.12. Endpoint impact on damage to resource availability (US$2013) for each scenario studied.

The endpoint results obtained were similar to the trend in the midpoint results as, for most impact categories, the healthy diet scenario had the highest impact, followed by meat increase, and with vegetarianism having the lowest impact on most categories. Although the endpoint impacts provide an understanding of the damages of each scenario on human health, ecosystems and resources, a more general overview was studied using the single score.

Figure 3.13 presents the single score results for the scenarios studied. The results unambiguously show that the healthy diet was the most harmful to the environment, followed by meat increase, organic farming, BAU system, intensive farming, and vegetarianism. The IP of the healthy diet was 2.8 times superior to the BAU system, whereas the meat increase had an IP 1.4 times higher than the BAU system. Vegetarianism was the most advantageous for the environment, being 1.5 times and 4.2 times less detrimental to the environment than the BAU system and the healthy diet, respectively. Organic farming had a quite similar impact to the BAU system, while intensive farming had a slightly lower IP than these, differing by 2%.

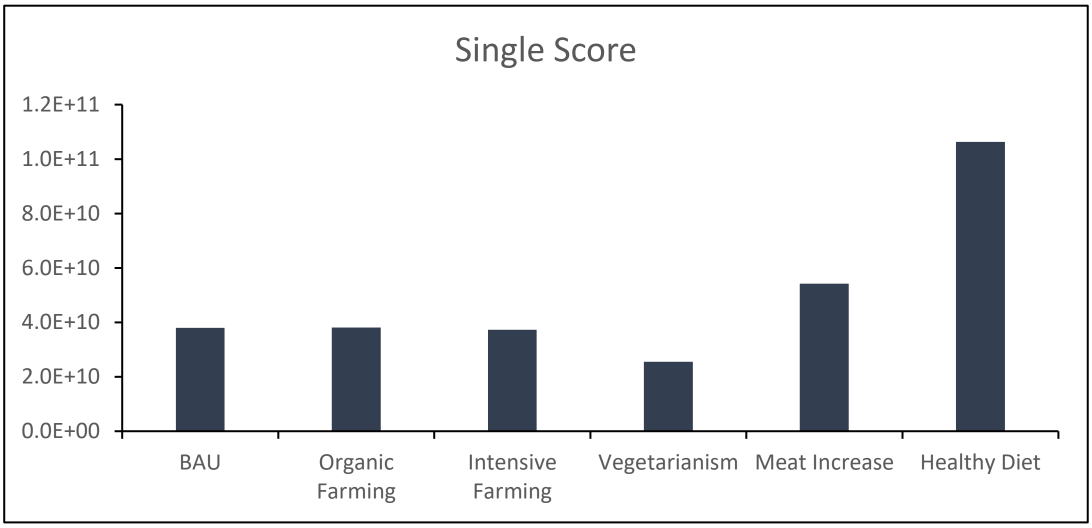

Figure 3.13. Single score impact of the scenarios studied, where the impacts of the scenarios can be studied and compared, based on a single score calculated through normalisation and weighting factors provided by ReCiPe method.

3.3. Model Validation

Model development was mainly based on data collection from databases and peer-reviewed articles. The data provided for the African continent, being composed of developing countries, could have poor quality, as it relies on annual statistics and estimates, which at times are unavailable or incomplete. This, along with assumptions and allocations performed during model development, could lead to higher uncertainty regarding the results obtained. Sensitivity analysis was performed in this study, to better understand the influence of certain parameters and evaluate the robustness of the results.

The influence of 10 parameters was studied, by changing their values by 10%, examining the outcomes and comparing them to the results from the BAU system impact assessment, to test the sensitivity of the model to these parameters. In this case, the outcomes of the sensitivity analysis were tested for the four main impact categories being studied: global warming, land use, water consumption and terrestrial acidification.

To exemplify the results obtained during sensitivity analysis, the results for variations in energy and feed are illustrated on Figure 3.14 and Figure 3.15, whereas the results for the remaining parameters are presented in Appendix A.6 (Figure A.19-Figure A.28). Figure 3.14 shows that a 10% variation on energy led to a change in the overall impacts of 0-13%, depending on the impact category: water consumption was more sensitive to changes in energy. The results in Figure 3.15 show that a 10%

variation on feed affected the impacts by 0-2%, which suggests that feed has little influence on the outcome.

Regarding the remaining parameters concerning crop production (fertiliser, manure, pesticide, seed, water, production, and land), the overall impact on the outcome varied between 1 and 8% for global warming, land use and terrestrial acidification, whereas the impact on water consumption varied around 2 to 23%. The variation of most livestock production parameters (feed, water for livestock and land for livestock) had little impact on the outcomes, between 0 and 4% for all impacts studied, whereas the production parameter had a higher influence on all impacts, ranging between 2 and 49%, which indicates the model is very sensitive to this parameter.

The parameters listed in order of decreasing influence on the outcomes of the impacts are livestock production, energy, crop land, crop production, crop water, pesticide, manure, fertiliser, seed, livestock land, livestock water and feed.

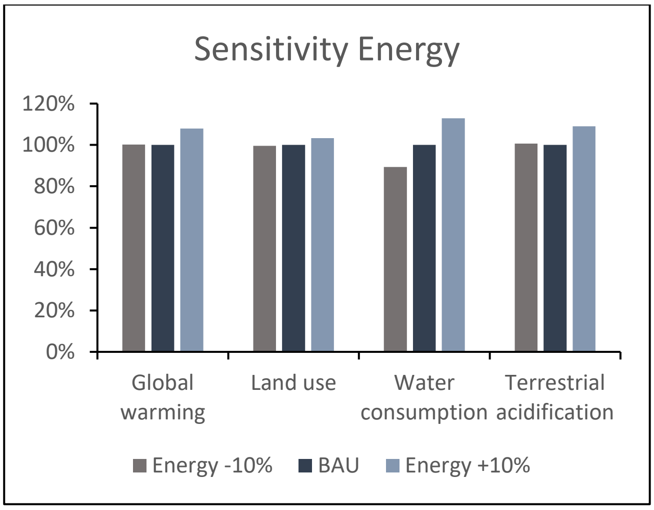

Figure 3.14. Sensitivity analysis of the use of energy in modelling: 10% increase and decrease of energy inputs and its influence on the outcome of global warming, land use, water consumption and terrestrial acidification.

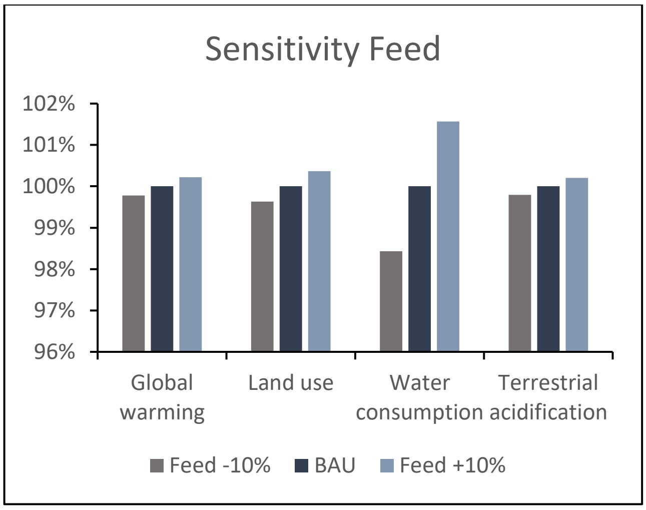

Figure 3.15. Sensitivity analysis of the use of feed in modelling: 10% increase and decrease of feed inputs and its influence on the outcome of global warming, land use, water consumption and terrestrial acidification.

4. Discussion

The discussion chapter is divided into four sections: the analysis of the current agricultural system in Africa, the prospective agricultural scenarios developed, data quality and gaps of the project.

Section 4.1 focuses on the state of food insecurity and undernourishment in Africa, agricultural productivity, and environmental impacts of the agricultural system in place. In section 4.2, the environmental impact of the prospective scenarios regarding nutritional changes, farming techniques and population growth projections are discussed. Additionally, the interpretation and application of the results are also discussed in this section. Finally, sections 4.3 and 4.4 refer to data quality, and gaps to be addressed and other perspectives, respectively.

4.1. Understanding the African Agricultural System

4.1.1. State of Undernourishment and Food Insecurity

Results from the dietary energy requirements and consumption (Figure 3.1) showed that, although food availability in most of the continent was sufficient to sustain an adequate diet in 2013, the population consumed less than the MDER per day, suffering from undernourishment. The population of EA was particularly affected by it, considering food supply in the region was lower than the ADER, meaning insufficient food was available to ensure an adequate diet. These results provide additional support to the claims by FAO et al. (2019), who reported that nearly half of the African population suffered from food insecurity in 2018 and one-fifth experienced undernourishment in the same period. Furthermore, EA, SA and MA had the highest food intake deficits, which could be related to the study by FAO et al., (2019), who reported that 90% of Africans suffering from undernourishment lived in sub-Saharan Africa, due to the proportion of poverty in the region. Despite being a wealthier region compared to its neighbours, SA had the second highest food deficit after EA, although its food supply was the second highest, suggesting there are deeper issues than availability in this region.

The results obtained concerning the African diet suggest the continent is not entirely providing enough food to feed its population. Although most regions had a food supply capable of sustaining the adequate daily dietary energy requirements per capita, on average, the population suffered from undernourishment in 2013. Thus, the results suggest that these issues were not so much a matter of lack of food availability (except for EA) but of food access in poorer regions, inadequate food distribution, and losses and waste occurring between production- and household-level (FAO, 2019b). Since most Africans cannot invest in refrigeration, distribution and storage infrastructures, losses will continue to occur throughout the food supply chain. A potential solution for the undernourishment issue affecting the continent is to increase the food supply in a BAU system by increasing food production – whether by area expansion or by improving agricultural productivity.

Regarding diet composition, the results (Table 3.1) showed that, although the diet varied between regions, the continent mainly relied on cereals, roots and tubers, vegetables, and fruits, which supports the claims by Schönfeldt et al. (2012) and Oniang et al. (2003), who reported that these commodities form the basis of the African diet. Furthermore, the results present an overall low availability of meat and animal products, which is consistent with the study by Schönfeldt et al. (2012), who stated that meat consumption in the continent is low, due to economic, cultural and religious reasons. The detailed analysis of food supply in each subregion (Table A.1) revealed a higher consumption of meat and animal products in NA and SA, the wealthiest regions in the continent, supporting the study by Oniang et al. (2003), who reported that the consumption of these products is associated to higher wealth levels.

Moreover, EA, MA and WA are poor regions and its population relied on affordable and locally available products, mainly cereals, roots and tubers and fruit, as shown by the results on Table A.1, which is consistent with the studies by Oniang et al. (2003) and Schönfeldt et al. (2012). These products had an overall low protein and fat content, often resulting in an inadequate diet, as discussed by Schönfeldt et al. (2012).

A healthy diet ensures the body gets the nutrients required to function optimally and prevent diseases. According to the NHS (2019), starchy roots and vegetables and fruit should contribute around one-third of the diet. Pulses, fish, eggs, meat and dairy are essential, due to high protein contents, vitamins and minerals (NHS, 2019). The diet composition suggests that the African population was not being provided with a healthy and balanced diet, as cereals and roots and tubers made up around 40% of the diet, rather than composing around 30% of it. Vegetables and fruits formed only 18% of the diet and should represent at least 30% of it. Lastly, pulses, meat, and animal products composed around 10% of the diet yet its contribution to it should be higher, due to its high protein content, providing the required protein intake daily.

4.1.2. Agricultural Productivity

The results regarding crops and livestock yields in Africa (Table 3.2) demonstrate that EA, MA, and WA registered low yields compared to global yields, whereas NA had good productivity and SA registered the best yields of the continent. However, when comparing the yields in each region to the maximum yields registered in 2013, all regions fell short of its potential, particularly EA, MA and WA. The results are in accordance with the study by the Oxford Business Group (2019), who stated that Africa has the lowest productivity in the world. Although SA and NA are not representative of this statement, the three remaining regions are.

Results concerning crop and livestock yields show that, in general, all regions have great potential for yield improvement, compared to global and maximum yields. Therefore, improving agricultural productivity must be contemplated in the future agricultural system, in order to increase the food supply on the continent.

According to ACET (2017) and the Oxford Business Group (2019), low productivity is caused by lack of access to farming technologies, mechanisation, high-yielding seeds, fertilisers and other inputs. Although farming technologies, mechanisation and high-yielding seeds were outside the scope of this study, the use of fertilisers, pesticides, and irrigation water was studied.

Albeit irrigation systems being uncommon in Africa and its absence causing low productivity, according to FAO (2012), each region was providing the adequate amount of water for irrigation in the agricultural system and, for this reason, irrigation systems were excluded from the study. However, according to ACET (2017) and the Oxford Business Group (2019), less than 6% of the agricultural land in Africa is irrigated and lacks irrigation systems, which may contribute to low productivity. By investing in these systems, the yields in the continent could increase considerably.

The results from fertiliser use (Table 3.3) show that the overall consumption of fertiliser in Africa ranged between 1.7% and 3.4%, depending on the nutrient in question. These results are consistent with the study by the Oxford Business Group (2019), who reported that fertiliser use in the continent accounts for 3% of global consumption. Furthermore, according to the results (Table 3.3), Africa was responsible for an average of 2.2% of the total global consumption of pesticides in 2013.

It is also important to note that the fertiliser and pesticide use varied amongst regions, with NA consuming the highest amount in the continent and MA the lowest. The results demonstrate a potential correlation between inputs and agricultural productivity, as regions where fertiliser and pesticide use were lower – such as MA – had poor productivity, while regions where input use was higher – NA– registered larger yields. The results are also consistent with the wealth of the regions: NA is a wealthier region and invests more on agriculture, whereas MA is one of the poorest regions and agriculture suffers from underinvestment. These results provide additional support to the claims by Fuglie et al.

(2014) and the Oxford Business Group (2019), who stated that investments in agriculture are crucial to improving productivity. Although SA consumed fewer fertilisers than NA, EA and WA, it registered the highest yields in the continent, suggesting that fertilisers and pesticides are not the only factors affecting productivity.

Furthermore, from the results of the impact assessment (Figure 3.3), the per capita IPs by region were determined. The results show that SA and NA had the overall highest IPs per capita in 2013, while MA registered the lowest, followed by WA. The data suggests that the richer the region is, the higher are the investments in agriculture – higher input of fertilisers, pesticides, irrigation, and farming technologies –, and the higher are its environmental impacts, due to said inputs.

4.1.3. Environmental Impacts of the BAU System

According to the results of midpoint impacts by commodity from Figure 3.2, livestock had the highest IPs on all impact categories studied, ranging between 57% to 88% of the IPs, depending on the impact category, except for water consumption (19%) and ozone formation (46%). The endpoint impact assessment (Figure 3.5) reinforces the previous results, showing that livestock had a considerably higher contribution to damages on human health (65%), ecosystem biodiversity (70%) and resource availability (54%) than crop production. The results are in accordance with FAO (2006), who claimed that the livestock sector has the largest environmental impact of all farming practices, and has a major role on CO_2, methane, nitrous oxides, and ammonia emissions, which are great contributors to most impact categories studied.

The agricultural sector is reported as the biggest water user globally, using 70% of the total freshwater to irrigation (FAO, 2019c), with livestock consuming only 8% of it (FAO, 2006). According to the results, crop production had a significantly bigger IP on water consumption (81%), than livestock (19%), which is in line with the literature. It is important to note that cereal production was responsible for most of the share of impacts caused by crops, due to its massive production throughout the continent.

Cultural perspectives were applied in the LCA to reflect the insights of hypothetical stakeholders or decision-makers, who display different moral beliefs, concerns or interests regarding society and nature (Van Asselt et al., 1996). Results from the midpoint cultural perspectives (Figure 3.4 and Figure A.4) show that certain impacts had similar trends, regardless of cultural perspective. Examples of it are land use, water consumption, terrestrial acidification, freshwater ecotoxicity, freshwater and marine eutrophication, fossil fuel scarcity, and ozone formation. Other categories had different IPs between cultural perspectives: global warming had a higher impact on an individualist perspective, meaning that from a more optimistic and short-term approach, global warming is more harmful to the environment. In contrast, the remaining impact categories (marine and terrestrial ecotoxicity, human carcinogenic and non-carcinogenic toxicity, fine particulate matter formation, mineral resource scarcity, and stratospheric ozone depletion) had higher IPs on an egalitarian perspective, which considers a long-term and fatalist approach. The results from the cultural perspectives indicate that the IPs vary between outlooks, due to the assumptions regarding time horizon and adaptation potential, amongst others. Although the cultural perspectives aim to represent distinct world views and management styles (Van Asselt et al., 1996), the hierarchist perspective is still the consensus and the one that should be regarded during decision making.

Concerning population growth, the results presented in section 3.2 show that the impacts of the BAU system by 2050 would at least double, regardless of projection. Hence, by 2050, it is not viable for the BAU system in practice in Africa to provide enough food to sustain its population growth without causing considerable impacts on the environment. The low use of inputs, genetically improved seeds, and mechanisation, as well as the general underinvestment in agriculture, result in low yields, which translate into low food supplies and caloric intake deficits. For the BAU system to satisfy the food demand by 2050, the agricultural system in place must at least double its food production. To do so by 2050, the system must be expanded – through area expansion and input increase –, which results in larger environmental impacts. Therefore, perhaps to sustain the future population growth in Africa, farming practices and nutritional changes must be regarded.

4.2. The Future of African Agriculture

To study the potential effects of changes to farming techniques and diets, five scenarios were analysed, along with the population growth projections, which are discussed below: organic and intensive farming, vegetarianism, meat increase, and healthy diet. Using the LCA methodology, the environmental impacts of the models created were compared to the BAU system in 2013. The LCA approach proved to be a great tool to develop prospective models and perform their impact assessment, due to the quantification of inputs and outputs and use of parameters.

4.2.1. Farming Techniques

The midpoint impact assessment results from section 3.2 showed that the impacts of intensive and organic farming varied between impact categories, but were overall similar, except for stratospheric ozone depletion and water consumption. Intensive farming had the highest impact of all scenarios on stratospheric ozone depletion, whereas organic farming had the lowest, suggesting that this impact is highly affected by fertiliser and pesticide use. Regarding water consumption, intensive farming was the most beneficial of all scenarios studied.

Organic farming had higher midpoint IPs on land use, water consumption, mineral resource scarcity, and human carcinogenic and non-carcinogenic toxicity. On the other hand, intensive farming had higher impacts on global warming, terrestrial acidification, fossil resource scarcity, fine particulate matter formation, ecotoxicity, stratospheric ozone depletion, and ozone formation. Results from the endpoint impact assessment (Figure 3.10-Figure 3.12) display higher IPs on resource availability for intensive farming and higher IPs on ecosystem biodiversity for organic farming. The results on ecosystem biodiversity provide additional support to the claims by De Ponti et al. (2012), who stated that organic farming may lead to losses of biodiversity, due to area expansion. Although Seufert et al. (2012) claimed that organic farming is a solution to the high impact of intensive farming on human health, the results for this study, under the conditions reported, show that organic farming had a slightly higher impact on human health than intensive farming. Finally, the single score results (Figure 3.13) reveal that both farming systems had a similar impact to the BAU system, yet organic farming had a slightly higher environmental burden. Differences in IPs between farming techniques mainly lie in differences in pesticide and fertiliser use, which cause distinct yields and force area expansion and water increase in organic farming and reduce it in intensive farming.

Population growth by 2050 caused similar IPs on all three outlooks: by 2050, the impacts of the two farming techniques would be between 2 times higher for a low projection and 3.5 times superior for a high estimate compared to the reference population. The results imply that regardless of projection, to satisfy food demand in 2050, the impacts on the environment must increase considerably under these farming systems.

The results display that under an intensive farming system, if crop yields increased, more land and water would be available for wildlife or to potentially grow more crops, which could increase the food supply in the continent and better feed the African population. Although both organic and intensive farming, in general, had similar impacts, intensive farming had higher impacts on most midpoint impact categories, due to the high fertiliser and pesticide inputs. Organic farming, on the other hand, required more area and inputs (water, seed, manure) and, according to the endpoint results, was not more beneficial from a human health and ecosystem biodiversity perspective. Nevertheless, between farming techniques, intensive farming may be the best alternative to feed the African population by

2050, although the decision relies on which impact categories the decision-makers regard as most relevant.

4.2.2. Diet Changes

The impact assessment greatly depends on the chosen functional unit. Although the functional unit is the same for all systems studied (BAU and scenarios), the quantity of food produced to fulfil the functional unit for the diet changes scenarios differs from the BAU system: the healthy diet relies on an increase of crop and livestock production; the meat increase relies on higher animal production; and vegetarianism relies on an increase in pulse, oil crop and egg production and a decline of livestock. The functional unit for this study was defined as an agricultural system capable of feeding the African population and all these scenarios fit the functional unit.

Although a 50% vegetarianism scenario was initially within the scope of the study, data provided by FAO displayed inconsistencies, which led to unreliable results. For this reason, this scenario was excluded from the study but there is a higher probability of the population shifting to a 50% vegetarian diet, rather than becoming nearly 100% vegetarian.

Results from the midpoint (Figure 3.6-Figure 3.9 and Figure A.6-Figure A.18) and endpoint (Figure 3.10-Figure 3.11) impact assessment, and single score (Figure 3.13) showed that within the diet changes scenarios and BAU system, the healthy diet had the highest IPs, followed by the meat increase, whereas vegetarianism was the most beneficial of all, including the current BAU system.

Both the healthy diet and meat increase were based on an increase in livestock production. As previously stated, the livestock sector has a major impact on the environment, due to its emissions, and feed and land requirements. Therefore, a rise in livestock production led to higher IPs on all impact categories for both scenarios. Furthermore, the healthy diet was also based on a rise in crop production in all five subregions, further increasing the IPs on all categories.

In contrast, vegetarianism was based on the reduction of animal breeding to cover solely milk and egg production. Although this scenario relied on an increase in pulses, oil crop and egg production to substitute meat, a reduction in livestock resulted in a major cut in emissions caused by it, making this scenario the most beneficial to the environment, more so than the current BAU system.

The models with population growth projections for the BAU system and the three diet scenarios were based on food production increase, by area expansion and input increase. Population growth by 2050 caused food production to increase, leading to larger environmental burdens: the IPs increased by a factor of around 2 for a low projection, to a factor of around 3 for a high projection, compared to the reference population.

Although the population growth projections for the BAU system and the healthy diet rely on a production rise of all commodities, the healthy diet requires a larger increase, to reach the adequate levels of food supply and ensure high availability of all commodities to the population. On the other hand, the BAU system was based on the situation in Africa in 2013, where, although the food supply was sufficient to ensure the adequate energy requirements in most regions, the population still had a low caloric intake and suffered from undernourishment. Although the best scenario for the African population, from a health perspective, is to introduce an adequate diet in the continent, the environmental burdens are significant when considering population growth by 2050. Thus, in order to feed a healthy and balanced diet to the African population, perhaps there must be a trade-off between human health and the environment.

Regarding the meat increase scenario, despite protein being essential in a diet and, according to Schönfeldt et al. (2012), significantly improving the nutritional condition of the population, this scenario had the second highest impact for most categories. Increasing meat consumption would considerably intensify the impacts, particularly considering population growth. On the other hand, under this scenario, crop production did not undergo any increase, leaving crop supply to fall short of its requirements. Thus, it may not be the best choice to feed the African population.

Vegetarianism had the lowest IPs on the environment, and it was more beneficial than the current BAU system, even considering population growth projections. Although it required a higher production of pulses and oil crops, which increased land and water consumption, livestock production declined and was solely produced to satisfy egg and milk demand, which translated into a high cut of emissions compared to the BAU system. Furthermore, this scenario did not lead to waste, as the animals required to produce milk and eggs were consumed after serving their purpose, also contributing to higher protein intake.

4.2.3. Pathways for Agriculture in Africa

According to the results, vegetarianism is the most beneficial scenario from an environmental perspective, more easily satisfying future food demands. Although from a health point of view, the healthy diet scenario is ideal, providing adequate caloric intakes, it is not sustainable by 2050, and neither is the meat increase scenario. However, although the African population already has a low consumption of animal products and mostly relies on crop consumption, implementing a vegetarian diet in the future will become more difficult, as urbanisation and economies grow – Africa is the fastest urbanising region in the world (Economic Commission for Africa, 2016) –, and mass production becomes widely in effect, leading to more affordable animal products, and increasing emissions by livestock.

Furthermore, there are no significant environmental savings in employing organic or intensive farming techniques. Nevertheless, the future of agriculture in Africa may involve implementing intensive farming to satisfy food demand, as it provides higher yields while using high amounts of fertilisers and pesticides and reducing cropland and water consumption.

The scenarios studied are not exclusive and may be complemented with each other. For example, the production of certain commodities can increase to provide more adequate food supplies, as in a healthy diet, while using an intensive farming system, which yields higher agricultural outputs. Moreover, vegetarianism may be complemented with a healthy diet, i.e., maintain the animal breeding to cover milk and egg demand, but increase the crop production to adequate levels, while employing an intensive farming system, for example. The environmental burdens will only decline under a vegetarianism scenario and will otherwise increase regardless of the pathway chosen. Nevertheless, the health of the African population may improve if the right scenarios are implemented.

However, nutritional changes and farming techniques may not be the answer to feed the African population in the future. Perhaps the best method to achieve it is by stabilizing population growth, and consequent food demand. For instance, high fertility rates cause high population growth and by providing education to African girls, these rates can lower considerably. According to the Central Statistical Agency et al. (2012), a woman with no education will have 5.8 children, which falls to around 4.6 if she finishes primary school, to 1.9 if she finishes secondary school and to 1.3 if she has more than the secondary school. According to The World Bank (2020), primary school enrolment rates for African girls increased from 60% in 2000 to 78% in 2013 and is likely to increase in the next years. However, African governments may struggle to provide education for its population, due to the high investments it requires. Nevertheless, if such occurs, the population growth can be reduced significantly by 2050, reducing the food demand and the pressure on the agricultural system.

Information regarding the agricultural sector in Africa is essential, as the continent has the fastest growing population worldwide (Dickson et al., 2019), yet around half its population suffers from food insecurity (FAO et al., 2019). The results from this study suggest that the agricultural system is weak, and its low productivity, along with underinvestment and lack of distribution, storage, and refrigeration infrastructures, leads to higher prospects of food insecurity by 2050.

Although this study is purely research-based, it may serve as decision support for policy-makers and grassroots organisations, who can influence the implementation of these scenarios, by providing subsidies to farmers to invest in farming technologies (fertilisers, pesticides, improved seeds, irrigation systems, mechanisation); applying taxes for livestock production; investing on transport, refrigeration and storage infrastructures; facilitating intraregional trade; and providing financial incentives to farmers to attract youth.

4.2.4. Africa's Potential in Agriculture

Although the current agricultural system does not provide enough to feed the African population, it has significant potential. The African continent holds around 60% of the world's arable land (Oxford Business Group, 2019), it possesses a highly diverse climate (Dickson et al., 2019) which is propitious to long and multiple growing seasons, and a young and growing labour force (ACET, 2017), all of which can contribute to improving the agricultural system. Nonetheless, as several authors defend, the success of African agriculture is dependent on policy reforms and strong investments in research, farming technologies (Fuglie et al., 2014), education, and management (ACET, 2017). Although the AU attempted to compel African governments to allocate 10% of the annual budget to agriculture, most countries have not complied (Oxford Business Group, 2019), leading to underinvestment in this sector. However, if the appropriate measures are administered, all these factors will contribute to better farming practices and higher yields, which will affect the food supply system and provide the African population with a more adequate diet. Moreover, agriculture is fundamental to African livelihood, as almost half the population relies on it (NEPAD, 2013), it employs 60-70% of the labour force and accounts for 25-30% of the GDP (AGRA, 2018; FAO et al., 2019). Therefore, feeding correctly the African population will, in the future, contribute to its development at all levels.

Furthermore, the African continent is the second largest worldwide (Dickson et al., 2019), and it has great potential to grow a variety of crops due to its climate. In the future, planning the production of crops based on the climates of the continent could lead to higher yields and higher diversification of products. Albeit the intraregional trade in Africa being weak, due to poor policies and transport infrastructures (ACET, 2017), if African nations collaborate and invest on it, the products available in the continent will be more diverse and of higher quality, contributing to a more balanced diet.

However, the African agricultural system is highly sensitive to external elements, such as the current locust swarms and the coronavirus pandemic. Currently, East Africa is facing the worst desert locust crisis in over 25 years (FAO, 2020b). According to FAO (2020a), locust swarms have a high potential for crop destruction: a one square kilometre swarm can eat the same amount of food in one day as

35 000 people, which could have devastating impacts, considering new swarms are beginning to form, coinciding with the start of the harvesting season (FAO, 2020b). The emergence of this pest could cause large-scale crop damage, affecting food security in the region (FAO, 2020b).

The current Covid-19 pandemic is changing the way people live, affecting food production, imports, and exports. Africa is particularly being affected by this pandemic, as farmers are struggling to produce food, and lockdowns are hampering exports, imports, and intraregional trade, causing a rise in food insecurity. According to George (2020), stocks of seeds, fertilisers and other inputs are declining and farmers rely on it for crop production. As more countries impose lockdowns or even bans on exports and imports, African countries struggle to get the required food to feed its population, particularly rice, a staple in Africa (George, 2020). On the other hand, food scarcity is causing the prices of the main staples to rise (George, 2020), making it unaffordable for a big part of the population. Although there are no restrictions for truck drivers in Africa, fear of the pandemic or potential fines is leading to a declining truck fleet, causing food shortages and crop waste (George, 2020). Furthermore, agriculture plays a major role in the emergence of infectious diseases: according to the United Nations Environment Programme (UNEP, 2016), 75% of all emerging infectious diseases are transmitted by animals. Livestock is a great transmitter of pathogens to humans and increasing demand for animal products leads to higher livestock populations worldwide. The higher contact between animals and lower genetical diversity to resist pathogens raises the prospect of disease transmission (UNEP, 2016). Agricultural intensification causes environmental changes and ecological disturbances, leading to changes in hosts and, consequently, the emergence of zoonotic diseases and epidemic outbreaks (UNEP, 2016). The agricultural sector plays a major role on the emergence of infectious diseases, thus it is crucial to understand the potential consequences of its practise on human health and perceive how it can change in the future, without damaging ecosystems and generating new infectious diseases.

Although African agriculture is significantly vulnerable to the external elements, potential similar issues to locust swarms and the Covid-19 pandemic could affect the food system in Africa in the future, which must be considered and given priority in order to build resilience against food insecurity.

4.3. Data Quality

This study highlighted the importance of data availability and completeness for agricultural inputs in Africa, for a robust impact assessment.

The results of the sensitivity analysis on section 3.3 show that the models developed are very sensitive to the livestock production parameter, which had a high influence on the outcomes of impact assessment. Hence, uncertainties in this parameter will lead to high uncertainties in the model and its impact assessment. Considering the influence of this parameter on the impacts studied, it is essential to ensure the most accurate values are applied during model development. However, collecting data in the African continent is difficult, as annual statistics and estimates are at times unavailable or incomplete, resulting in inherent uncertainties associated with the model. The remaining parameters had a low influence on the outcomes (energy, fertiliser, manure, pesticide, seed, irrigation water, crop production, crop land, feed, livestock water, livestock land) and the model has little sensitivity to them. So, a higher uncertainty on these parameters will not cause a high uncertainty in the model and its results.

4.4. Gaps To Be Addressed

This project does not represent the whole agricultural system in Africa, as only the most relevant food commodities in the African diet were selected (cereals, fruits, oil crops, pulses, roots and tubers, sugar crops, treenuts, vegetables, meat, milk and eggs) and crop commodities are only represented by the three most produced food items (when available). To have a more holistic understanding of the agricultural system in Africa and all its products, this gap should be addressed in future research.

Furthermore, the study did not consider the impact assessment of each life cycle stage, hence it cannot reveal which stages contribute the most to environmental burdens. Future research should focus on identifying the life cycle stages which contribute the most to environmental impacts so that potential improvement in these stages can reduce them.

It is beyond the scope of this study to explore the social, economic, cultural, and political impacts. As it was stated previously, agriculture is essential for the African population, employing 60-70% of the labour force and accounting for 25-30% of the GDP of the continent. Therefore, the current agricultural system already has a great impact on peoples’ lives and changing it until 2050 by altering diets and farming systems will cause significant modification in African society, which are not discussed in this project.

From a social point a view, future research should focus on the role of women in agriculture and African society in general, as women account for 70% of the workforce, yet suffer the most from food insecurity. Furthermore, educating young girls and women could have a significant impact on population growth, potentially declining the food demand by 2050 and, consequently, the pressure on the agricultural system.

Future research should address factors not accounted for in this study and which will have a great impact on the African society and its agricultural sector in the future, such as urbanisation and climate change, and even the current locust swarms and Covid-19 pandemic and potential consequences of its resurgence.

As it was mentioned previously, although there was an adequate food supply in most of the continent to feed an adequate diet to the African population, the population suffered from undernourishment. These results suggest that there is an underlying issue with the food supply system in Africa, which could be caused by losses and wastes throughout the food supply chain, due to lack of refrigeration, distribution, and storage systems, yet this study cannot answer. Future research should focus on a deeper analysis of the economic and social aspects that cause this issue: corruption, underinvestment, and poor governance, management, and education, amongst others. These factors could significantly improve the losses and waste and increase the food supply on the continent.

Although this study focused on five separate prospective scenarios (farming systems and diet changes), it did not consider the potential implementation of more than one scenario and its implications to the environment: healthy diet under an intensive farming system, vegetarianism under an organic farming system, amongst other possibilities. Implementing more than one scenario could potentially improve the health condition of the African population while limiting the increase of environmental impacts by 2050.

5. Conclusion

This research aimed to explore the current African agricultural system, as well as develop prospective models based on farming technique transitions and diet changes while satisfying future food demand. Based on the analysis of the diet and agricultural inputs and productivity, it can be concluded that the agricultural system is failing and is not providing adequate caloric energy to its population. With regards to the impact assessment, the results indicate that the livestock sector is the major contributor to environmental burdens. The impact assessment of the prospective scenarios shows that to sustain population growth by 2050, the environmental impacts of all scenarios will at least double. Vegetarianism is the least harmful scenario for the environment, despite being difficult to implement in Africa in the future.

The conclusions of the project can be summarised as follows:

- The African continent is not providing adequate dietary energy requirements to its population, leading to undernourishment issues.
- Agricultural productivity is low, which is likely due to low use of fertilisers and pesticides, and low access to farming technologies.
- The healthy diet model has the highest environmental burden, followed by the meat increase model. Vegetarianism is the most beneficial from an environmental perspective.
- Organic and intensive farming have similar overall impacts, which suggests that intensive farming could be a potential solution to increasing food production in the continent.
- Population growth projections suggest that by 2050, the impacts of the BAU system and scenarios, in general, will double or triple.
- The best method to achieve food security and health for the population by 2050 could involve decreasing fertility rates, through female education.

However, the future of agriculture in Africa has become extremely uncertain due to the locust swarms and the Covid-19 pandemic, which are affecting and will continue to affect the agricultural sector unpredictably in the near future.

To better understand the implications of these results, future studies should address the social, economic, and cultural impacts of the prospective scenarios or other potential pathways regarding how agriculture and food habits will change in the future.

6. References

Acero, A. P., Rodríguez, C., & Ciroth, A. (2014). LCIA methods: Impact assessment methods in Life Cycle Assessment and their impact categories. *OpenLCA*, *February*, 1–23.

ACET. (2017). *Agriculture Powering Africa's Economic Transformation*. 1–191. www.acetforafrica.org.

AGRA. (2019). *Africa Agriculture Status Report: Driving Agricultural Transformation the Hidden Middle: A Quiet Revolution in the Private Sector Driving Agricultural Transformation (Issue 7)*. 1–220. https://agra.org/wp-content/uploads/2019/09/AASR2019-The-Hidden-Middleweb.pdf

Alexander, P., Brown, C., Arneth, A., Finnigan, J., & Rounsevell, M. D. A. (2016). Human appropriation of land for food: The role of diet. *Global Environmental Change*, *41*, 88–98. https://doi.org/10.1016/j.gloenvcha.2016.09.005

Arslan, S., & Aybek, A. (2012). Particulate Matter Exposure in Agriculture. *Air Pollution - A Comprehensive Perspective*, *10*. https://doi.org/10.5772/50084

Brentrup, F., Kü, J., Kuhlmann, H., & Lammel, J. (2001). Brentrup et. al. - 2001 - Application of the life cycle assessment methodology to agricultural production an example of {…}.pdf. *European Journal of Agronomy*, *14*, 221–233. www.elsevier.com/locate/eja

Brown, B., Nuberg, I., & Llewellyn, R. (2017). Stepwise frameworks for understanding the utilisation of conservation agriculture in Africa. *Agricultural Systems*, *153*, 11–22. https://doi.org/10.1016/j.agsy.2017.01.012

Bruinsma, J. (2009). The Resource Outlook to 2050. In *How to Feed the World in 2050* (Issue June). https://doi.org/10.1007/978-3-642-41714-6_180309

Cellura, M., Longo, S., & Mistretta, M. (2011). Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. *Renewable and Sustainable Energy Reviews*, *15*(9), 4697–4705. https://doi.org/10.1016/j.rser.2011.07.082

Central Statistical Agency, & ICF International. (2012). *Ethiopia Demographic and Health Survey 2011*. https://doi.org/10.4172/2376-127x.1000165

Corbeels, M., de Graaff, J., Ndah, T. H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, H. D., & Adolwa, I. S. (2014). Understanding the impact and adoption of conservation agriculture in Africa: A multi-scale analysis. *Agriculture, Ecosystems and Environment*, *187*, 155–170. https://doi.org/10.1016/j.agee.2013.10.011

Curran, M. A. (2008). Human Ecology: Life Cycle Assessment. *Encyclopedia of Ecology, Five-Volume Set*, 2168–2174.

de Backer, E., Aertsens, J., Vergucht, S., & Steurbaut, W. (2009). Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA): A case study of leek production. In *British Food Journal* (Vol. 111, Issue 10). https://doi.org/10.1108/00070700910992916

De Boer, I. J. M. (2003). Environmental impact assessment of conventional and organic milk production. *Livestock Production Science*, *80*(1–2), 69–77. https://doi.org/10.1016/S0301-6226(02)00322-6

De Ponti, T., Rijk, B., & Van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agricultural Systems*, *108*, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004

Dickson, K. B., McMaster, D. N., & Others. (2019). *Africa*. Encyclopædia Britannica, Inc. https://www.britannica.com/place/Africa

Dile, Y. T., Karlberg, L., Temesgen, M., & Rockström, J. (2013). The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agriculture, Ecosystems and Environment*, *181*(2013), 69–79. https://doi.org/10.1016/j.agee.2013.09.014

Dinar, A., Hassan, R., Mendelsohn, R., & Benhin, J. (2008). *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies*. Taylor & Francis.

Earles, J. M., & Halog, A. (2011). Consequential life cycle assessment: A review. *International Journal of Life Cycle Assessment*, *16*(5), 445–453. https://doi.org/10.1007/s11367-011-0275-9

ecoinvent. (n.d.). *No Title*. https://www.ecoinvent.org/

Economic Commission for Africa. (2016). *The Demographic Profile of African Countries*.

European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance. In *Constraints*. https://doi.org/10.2788/38479

FAO. (2001). *Food balance sheets: A Handbook.*

FAO. (2006). Livestock's long shadow. In *Frontiers in Ecology and the Environment*. FAO. https://doi.org/10.1890/1540-9295(2007)5[4:D]2.0.CO;2

FAO. (2008). Water for Agriculture and Energy in Africa: the Challenges of Climate Change. In *Resources and challenges*. https://doi.org/10.1007/978-1-4757-2043-3_39

FAO. (2009). *The State of Food and Agriculture*. https://doi.org/10.18356/6e4ebb75-en

FAO. (2011). *Global food losses and food waste - Extent, causes and prevention*.

FAO. (2012). Water requirement ratio and comparison with water resources by country (165 countries and 2 territories in this review). In *AQUASTAT*. https://firebasestorage.googleapis.com/v0/b/fao-aquastat.appspot.com/o/PDF%2FTABLES%2FTable4.pdf?alt=media&token=fdba62dc-ca8f-4b80-adcd-909baa2ddf87

FAO. (2016). *AQUASTAT*. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

FAO. (2018). *More Fuel for the Food/Feed Debate*. AGA News. http://www.fao.org/ag/againfo/home/en/news_archive/2017_More_Fuel_for_the_Food_Feed.ht ml

FAO. (2019a). *Animal Production*. http://www.fao.org/animal-production/en/

FAO. (2019b). *Food Balance Sheets and The Food Consumption Survey: A Comparison of Methodologies and Results*. http://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/food-balance-sheets-and-the-food-consumption-survey-a-comparison-of-methodologies-and-results/en/

FAO. (2019c). World Food and Agriculture - Statistical Pocketbook 2018. In *World Food and Agriculture - Statistical Pocketbook 2018*. https://doi.org/10.4060/ca1796en

FAO. (2020a). Alarm over Desert Locusts increases as new generation of the destructive pests starts breeding in Horn of Africa. *News*. http://www.fao.org/news/story/en/item/1258877/icode/

FAO. (2020b). *Desert locust crisis*. Crisis. http://www.fao.org/emergencies/crisis/desertlocust/intro/en/

FAO, WHO, IFAD, UNICEF, & WFP. (2019). *The state of food security and nutrition in the world. Safeguarding against economic slowdowns and downturns*. https://doi.org/10.1109/JSTARS.2014.2300145

FAO, WHO, & UNU. (2001). *Human energy requirements*.

FAOSTAT. (2016). *Energy Use*. Data: Emissions - Agriculture. http://www.fao.org/faostat/en/#data/GN

FAOSTAT. (2017). *Food Balances (old methodology and population)*. Data: Food Balance. http://www.fao.org/faostat/en/#data/FBSH

FAOSTAT. (2019a). *Fertilizers by Nutrient*. Data: Inputs. http://www.fao.org/faostat/en/#data/RFN

FAOSTAT. (2019b). *Fertilizers Indicators*. Data: Agri-Environmental Indicators. http://www.fao.org/faostat/en/#data/EF

FAOSTAT. (2019c). *Livestock Patterns*. Data: Agri-Environmental Indicators. http://www.fao.org/faostat/en/#data/EK

FAOSTAT. (2019d). *Manure applied to soils*. Data: Emissions - Agriculture. http://www.fao.org/faostat/en/#data/GU

FAOSTAT. (2019e). *Pesticides Indicators*. Data: Agri-Environmental Indicators. http://www.fao.org/faostat/en/#data/EP

FAOSTAT. (2019f). *Pesticides Use*. Data: Inputs. http://www.fao.org/faostat/en/#data/RP

FAOSTAT. (2020a). *Crops*. Data: Production. http://www.fao.org/faostat/en/#data/QC

FAOSTAT. (2020b). *Live Animals*. Data: Production. http://www.fao.org/faostat/en/#data/QA

FAOSTAT. (2020c). *Livestock Primary*. Data: Production. http://www.fao.org/faostat/en/#data/QC

Foteinis, S., & Chatzisymeon, E. (2016). Life cycle assessment of organic versus conventional agriculture. A case study of lettuce cultivation in Greece. *Journal of Cleaner Production*, *112*, 2462–2471. https://doi.org/10.1016/j.jclepro.2015.09.075

Fuglie, K. O., & Rada, N. E. (2014). Resources, policies, and agricultural productivity in Sub-Saharan Africa. *Global Agriculture: Developments, Issues, and Research*, *5*(145), 63–126. https://doi.org/10.2139/ssrn.2266459

Garrity, D. P., Akinnifesi, F. K., Ajayi, O. C., Weldesemayat, S. G., Mowo, J. G., Kalinganire, A., Larwanou, M., & Bayala, J. (2010). Evergreen Agriculture: A robust approach to sustainable food security in Africa. *Food Security*, *2*(3), 197–214. https://doi.org/10.1007/s12571-010-0070-7

George, L. (2020). How Africa risks reeling from a health crisis to a food crisis. *Reuters*. https://www.reuters.com/article/us-health-coronavirus-food-africa-insigh/how-africa-risks-reeling-from-a-health-crisis-to-a-food-crisis-idUSKCN2260M2

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics’ view. *Field Crops Research*, *114*(1), 23–34. https://doi.org/10.1016/j.fcr.2009.06.017

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2009). ReCiPe 2008. *Potentials*, 1–44. https://doi.org/10.029/2003JD004283

Goedkoop, M. J. (2008). *Category indicators at the midpoint and the endpoint level ReCiPe 2008*. *June 2016*. https://doi.org/10.2307/40184439

Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications*, *4*. https://doi.org/10.1038/ncomms3918

Groen, E. A., Bokkers, E. A. M., Heijungs, R., & de Boer, I. J. M. (2017). Methods for global sensitivity analysis in life cycle assessment. *International Journal of Life Cycle Assessment*, *22*(7), 1125–1137. https://doi.org/10.1007/s11367-016-1217-3

Haas, G., Wetterich, F., & Geier, U. (2000). Life cycle assessment framework in agriculture on the farm level. *International Journal of Life Cycle Assessment*, *5*(6), 345–348. https://doi.org/10.1007/BF02978669

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2017). Life Cycle Assessment: Theory and Practice. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3

Hildenbrand, J., Srocka, M., & Ciroth, A. (2006). *openLCA*. http://www.openlca.org/

Huijbregts, M., Steinmann, Z. J. N., Elshout, P. M. F. M., Stam, G., Verones, F., Vieira, M. D. M., Zijp, M., & van Zelm, R. (2016). ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. *National Institute for Public Health and the Environment*, 194. https://doi.org/10.1007/s11367-016-1246-y

ISO. (2006). *ISO 14040:2006 - Environmental management — Life cycle assessment — Principles* *and framework*. https://www.iso.org/standard/37456.html

Kassam, A. H. (2017). Conservation agriculture: growing more with less - the future of sustainable intensification. In A. H. Kassam, S. Mkomwa, & T. Friedrich (Eds.), *Conservation agriculture for Africa: building resilient farming systems in a changing climate*. https://doi.org/10.1079/9781780645681.0030

Mattsson, B., Cederberg, C., & Blix, L. (2000). Agricultural land use in life cycle assessment (LCA): Case studies of three vegetable oil crops. *Journal of Cleaner Production*, *8*(4), 283–292. https://doi.org/10.1016/S0959-6526(00)00027-5

Meisterling, K., Samaras, C., & Schweizer, V. (2009). Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production*, *17*(2), 222–230. https://doi.org/10.1016/j.jclepro.2008.04.009

Milà i Canals, L., Burnip, G. M., & Cowell, S. J. (2006). Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. *Agriculture, Ecosystems and Environment*, *114*(2–4), 226–238. https://doi.org/10.1016/j.agee.2005.10.023

NEPAD. (2013). *African Agriculture, Transformation and Outlook*. *July*, 1–4.

NHS. (2019). *Eat well*. Live Well. https://www.nhs.uk/live-well/eat-well/

Nijdam, D., Rood, T., & Westhoek, H. (2012). The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy*, *37*(6), 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002

Oniang, R. K., Mutuku, J. M., & Malaba, S. J. (2003). *Contemporary African food habits and their nutritional and health implications*. *12*(June), 231–236.

Oxford Business Group. (2019). *THE REPORT: Agriculture in Africa 2019*.

Pretty, J., & Bharucha, Z. P. (2015). Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*, *6*(1), 152–182. https://doi.org/10.3390/insects6010152

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, *9*(1), 5–24. https://doi.org/10.3763/ijas.2010.0583

Pryor, S. W., Smithers, J., Lyne, P., & van Antwerpen, R. (2017). Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. *Journal of Cleaner Production*, *141*, 137–145. https://doi.org/10.1016/j.jclepro.2016.09.069

Roser, M., & Ritchie, H. (2019). *Food Supply*. OurWorldInData.Org. https://ourworldindata.org/food-per-person

Roser, M., & Ritchie, H. (2020). *Hunger and Undernourishment*. OurWorldInData.Org. https://ourworldindata.org/hunger-and-undernourishment

Schönfeldt, H. C., & Hall, N. G. (2012). Dietary protein quality and malnutrition in Africa. *British Journal of Nutrition*, *108*(SUPPL. 2). https://doi.org/10.1017/S0007114512002553

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*(7397), 229–232. https://doi.org/10.1038/nature11069

The World Bank. (2020). *Adjusted net enrollment rate, primary, female (% of primary school age children)*. World Development Indicators. https://data.worldbank.org/indicator/SE.PRM.TENR.FE

Thierfelder, C., Cheesman, S., & Rusinamhodzi, L. (2013). Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. *International Journal of Agricultural Sustainability*, *11*(2), 108–124. https://doi.org/10.1080/14735903.2012.703894

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., & Swackhamer, D. (2001). Forecasting Agriculturally Driven Global Environmental Change. *Science*, *292*(5515), 281–284. https://science.sciencemag.org/content/292/5515/281

Toenniessen, G., Adesina, A., & DevRies, J. (2008). Building an alliance for a green revolution in Africa. *Annals of the New York Academy of Sciences*, *1136*, 233–242. https://doi.org/10.1196/annals.1425.028

UNEP. (2016). Zoonoses: Blurred Lines of Emergent Disease and Ecosystem Health. In *UNEP Frontiers 2016 Report*. https://wedocs.unep.org/bitstream/handle/20.500.11822/32060/zoonoses.pdf?sequence=1&isAllowed=y

United Nations. (2017). *World Population Prospects*. https://esa.un.org/unpd/wpp/publications/files/wpp2017_keyfindings.pdf

United Nations. (2019). *World Population Prospects 2019*. https://population.un.org/wpp/Download/Standard/Population/

Van Asselt, M. B. A., & Rotmans, J. (1996). Uncertainty in perspective. *Global Environmental Change*, *6*(2), 121–157. https://doi.org/10.1016/0959-3780(96)00015-5

Vanlauwe, B., Wendt, J., Giller, K. E., Corbeels, M., Gerard, B., & Nolte, C. (2014). A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crops Research*, *155*, 10–13. https://doi.org/10.1016/j.fcr.2013.10.002

Waha, K., van Wijk, M. T., Fritz, S., See, L., Thornton, P. K., Wichern, J., & Herrero, M. (2018). Agricultural diversification as an important strategy for achieving food security in Africa. *Global Change Biology*, *24*(8), 3390–3400. https://doi.org/10.1111/gcb.14158

Wenzel, B. H., Wesnæs, M., & Dall, O. (2009). *Consequential Life Cycle Assessment*. 1–19. https://doi.org/10.1021/ct300999w

WHO. (2018). *Global hunger continues to rise, new UN report says*.

7. Appendix

Appendix A: Agricultural System

APPENDIX A.1
Food Supply

Table A.1. Food, protein, and fat supply by commodity in each African region.

Region	Commodity	% Commodity in food supply	% Protein supply	% Fat supply
EA	Cereals	26.1	48.7	16.7
	Fruits	11.7	2.0	1.6
	Oil crops	1.1	4.1	10.7
	Pulses	3.4	17.1	2.0
	Roots and tubers	27.1	6.9	1.3
	Sugar Crops	1.3	0.1	0.1
	Treenuts	0.1	0.2	0.9
	Vegetables	6.3	1.9	0.4
	Eggs	0.2	0.5	0.6
	Meat	2.3	7.3	12.1
	Milk	8.6	6.1	9.3
MA	Cereals	18.4	38.5	11.8
	Fruits	13.2	2.7	1.1
	Oil crops	1.5	8.4	18.7
	Pulses	2.1	11.9	1.1
	Roots and tubers	30.8	8.3	1.2
	Sugar Crops	0.5	0.0	0.0
	Treenuts	0.1	0.3	0.1
	Vegetables	10.5	3.4	0.6
	Eggs	0.1	0.3	0.3
	Meat	4.0	14.3	15.5
	Milk	2.6	2.2	2.8
NA	Cereals	29.0	53.9	16.1
	Fruits	13.0	2.0	1.3
	Oil crops	0.7	1.5	4.9
	Pulses	1.0	5.1	0.5
	Roots and tubers	5.7	1.7	0.2
	Sugar Crops	2.3	0.1	0.1
	Treenuts	0.2	0.4	1.5
	Vegetables	21.5	5.1	1.1
	Eggs	0.7	1.6	1.8
	Meat	3.8	11.4	12.8
	Milk	12.8	9.7	13.3

Region	Commodity	% Commodity in food supply	% Protein supply	% Fat supply
SA	Cereals	31.4	48.4	13.0
	Fruits	7.3	0.6	0.3
	Oil crops	0.4	2.1	2.1
	Pulses	0.5	2.1	0.2
	Roots and tubers	6.8	1.9	0.2
	Sugar Crops	0.0	0.0	1.4
	Treenuts	0.1	0.1	0.3
	Vegetables	7.4	1.7	0.4
	Eggs	1.2	2.5	2.2
	Meat	10.7	28.2	28.6
	Milk	10.3	5.7	6.8
WA	Cereals	23.3	46.6	14.7
	Fruits	9.8	1.5	0.7
	Oil crops	1.2	6.2	11.5
	Pulses	1.9	10.9	1.0
	Roots and tubers	33.8	9.5	1.7
	Sugar Crops	0.0	0.5	3.5
	Treenuts	0.5	1.1	2.8
	Vegetables	8.8	3.1	0.7
	Eggs	0.4	1.1	1.0
	Meat	2.1	7.5	6.4
	Milk	3.1	2.8	3.1

APPENDIX A.2
Yields

Table A.2. African subregions’ yields compared to global and maximum yields registered worldwide.

	GLOBAL YIELDS (%)					MAXIMUM YIELDS (%)				
Commodity	**EA**	**MA**	**NA**	**SA**	**WA**	**EA**	**MA**	**NA**	**SA**	**WA**
Cereals	45	25	53	95	29	7	4	8	15	5
Fruit	54	65	102	175	52	18	22	34	59	17
Oil crops	35	29	21	68	24	18	15	11	36	12
Pulses	92	62	101	84	70	5	3	5	5	4
Roots and Tubers	59	69	184	144	57	17	20	53	42	16
Treenuts	47	62	49	260	41	2	2	2	9	1
Vegetables	39	26	119	92	27	5	4	17	13	4
Sugar crops	95	32	147	112	52	50	17	78	59	28
Cattle Meat	65	66	96	140	58	30	31	44	65	27
Poultry Meat	71	47	76	103	54	21	17	40	27	17
Sheep and Goat Meat	77	91	100	163	74	43	29	46	62	33
Milk	24	15	23	209	10	2	2	2	22	1
Eggs	48	38	89	62	38	29	34	37	61	28
Total	**52**	**46**	**79**	**125**	**42**	**14**	**12**	**20**	**28**	**11**

APPENDIX A.3
Model Representation

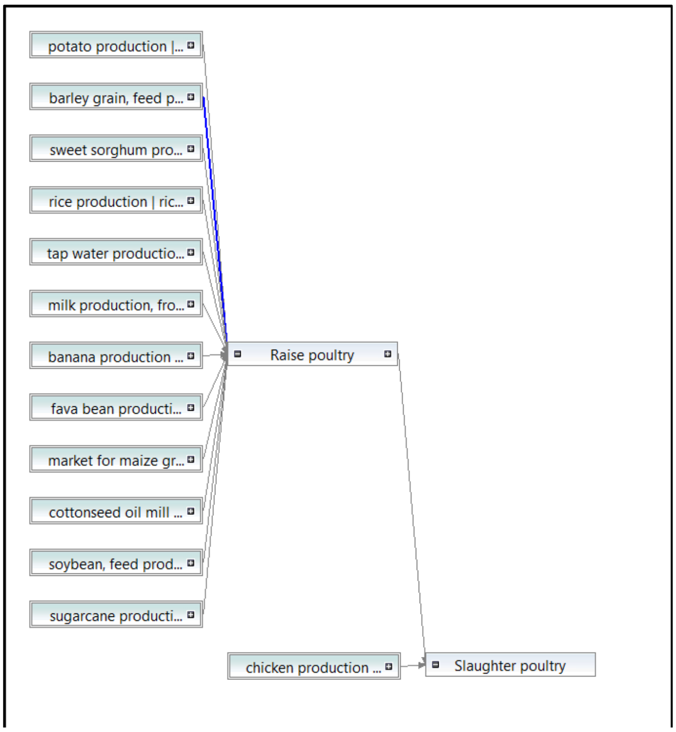

Figure A.1. Example of representation of livestock production on openLCA, illustrating poultry production.

APPENDIX A.4
Impacts of BAU System

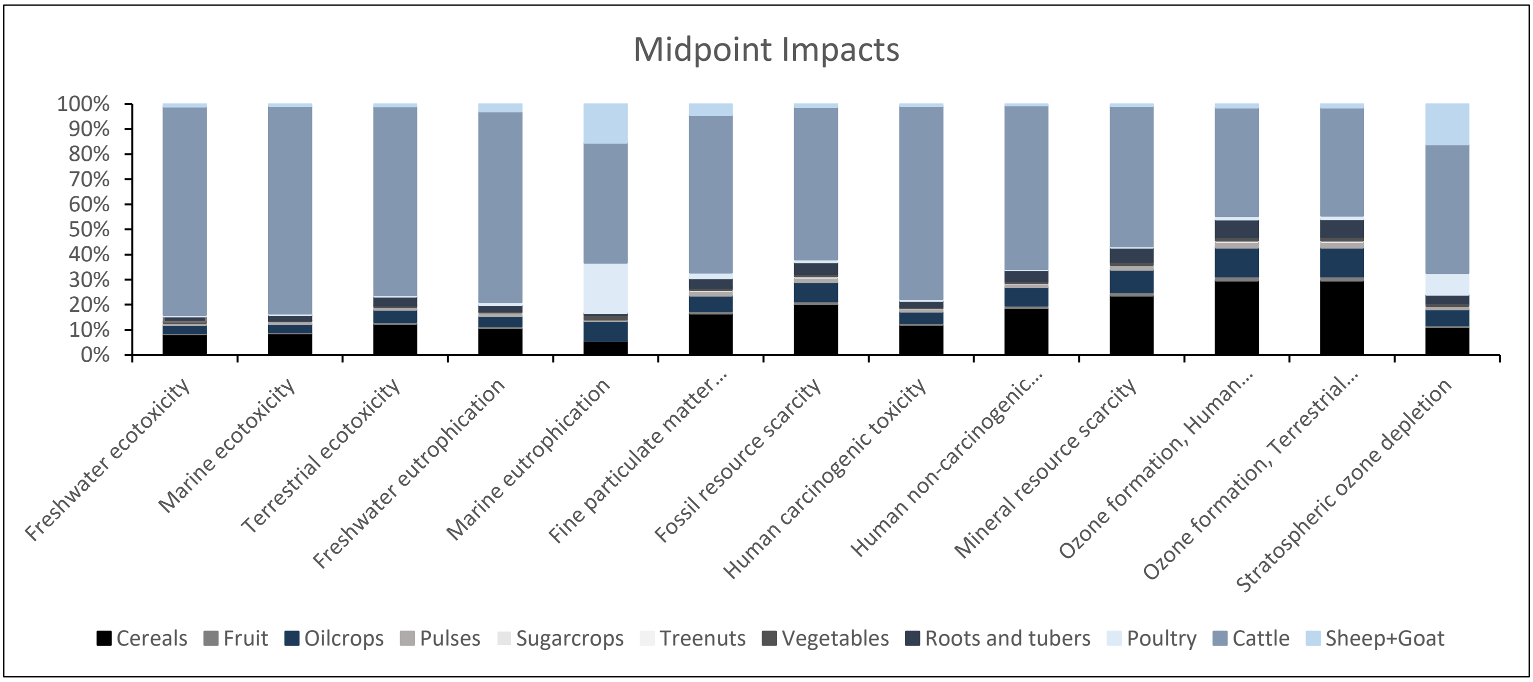

Figure A.2. Relative contribution of each commodity on the remaining impacts being studied in 2013 (freshwater, marine and terrestrial ecotoxicity, freshwater and marine eutrophication, fine particulate matter formation, fossil resource scarcity, human carcinogenic and non-carcinogenic toxicity, mineral resource scarcity, ozone formation – human health and terrestrial ecosystems – and stratospheric ozone depletion.

Table A.3. Environmental impacts per capita in each subregion.

Indicator	Unit	EA	MA	NA	SA	WA
Global warming	kg CO2 eq/cap	712.95	422.15	817.78	1132.40	454.46
Land use	m2a crop eq/cap	310.03	189.95	548.89	755.41	279.70
Water consumption	m3/cap	75.87	50.03	97.92	172.78	75.64
Terrestrial acidification	kg SO2 eq/cap	4.19	2.24	5.12	7.63	2.59
Freshwater ecotoxicity	kg 1.4-DCB/cap	45.82	28.67	32.05	43.90	24.85
Marine ecotoxicity	kg 1.4-DCB/cap	61.99	38.78	43.64	59.24	33.69
Terrestrial ecotoxicity	kg 1.4-DCB/cap	3490.87	2212.22	2925.22	3638.06	2097.22
Freshwater eutrophication	kg P eq/cap	0.46	0.28	0.37	0.52	0.26
Marine eutrophication	kg N eq/cap	0.17	0.10	0.30	0.52	0.13
Fine particulate matter formation	kg PM2.5 eq/cap	2.25	1.16	2.09	2.72	1.18
Fossil resource scarcity	kg oil eq/cap	150.46	90.78	166.48	191.61	95.27
Human carcinogenic toxicity	kg 1.4-DCB/cap	49.79	30.03	41.08	51.57	26.47
Human non-carcinogenic toxicity	kg 1.4-DCB/cap	1249.94	787.09	1447.04	1499.64	787.35
Mineral resource scarcity	kg Cu eq/cap	6.19	3.94	7.57	7.95	4.50
Ozone formation. Human health	kg NOx eq/cap	1.73	1.03	2.68	2.66	1.33
Ozone formation. Ter. ecosystems	kg NOx eq/cap	1.77	1.05	2.75	2.74	1.37
Stratospheric ozone depletion	kg CFC11 eq/cap	0.00	0.00	0.00	0.00	0.00

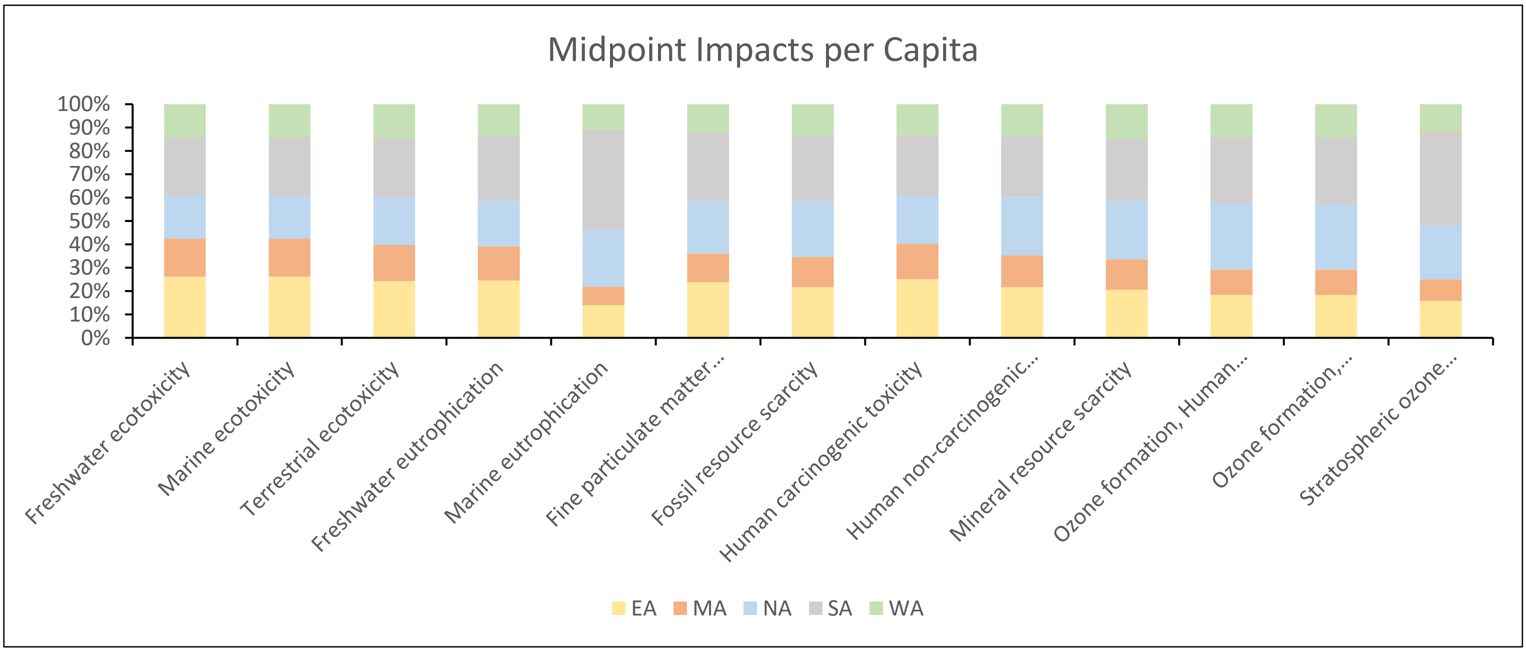

Figure A.3. Contribution of each region to the remaining impacts in 2013 (freshwater, marine and terrestrial ecotoxicity, freshwater and marine eutrophication, fine particulate matter formation, fossil resource scarcity, human carcinogenic and non-carcinogenic toxicity, mineral resource scarcity, ozone formation – human health and terrestrial ecosystems – and stratospheric ozone depletion).

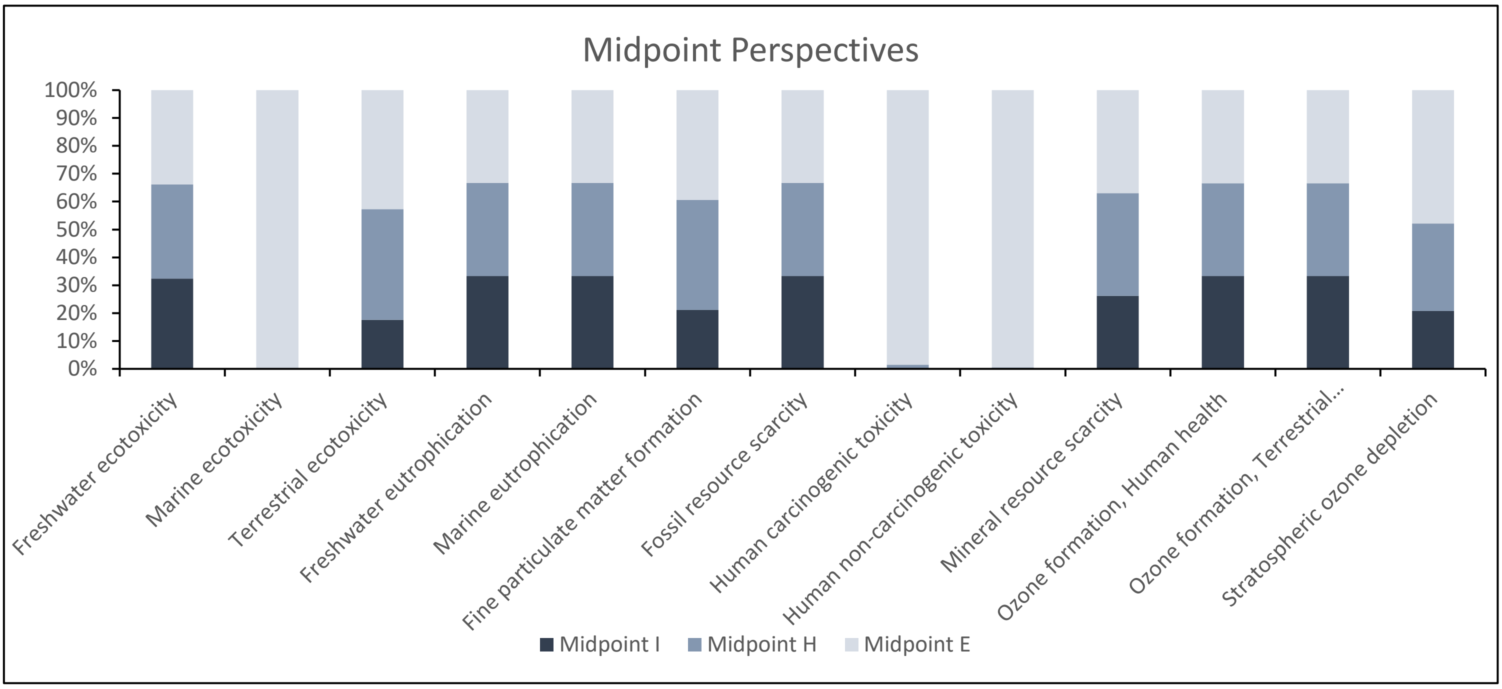

Figure A.4. Relative contribution of each commodity on midpoint I, H and E cultural perspectives for the remaining impacts being studied in 2013 (freshwater, marine and terrestrial ecotoxicity, freshwater and marine eutrophication, fine particulate matter formation, fossil resource scarcity, human carcinogenic and non-carcinogenic toxicity, mineral resource scarcity, ozone formation – human health and terrestrial ecosystems – and stratospheric ozone depletion.

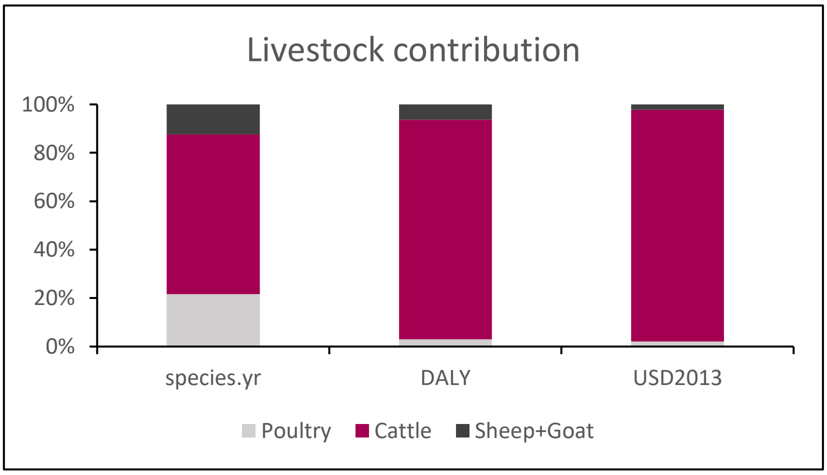

Figure A.5. Livestock (poultry, cattle, and sheep and goat) contribution to endpoint impacts.

APPENDIX A.5
Midpoint Impacts for Scenarios

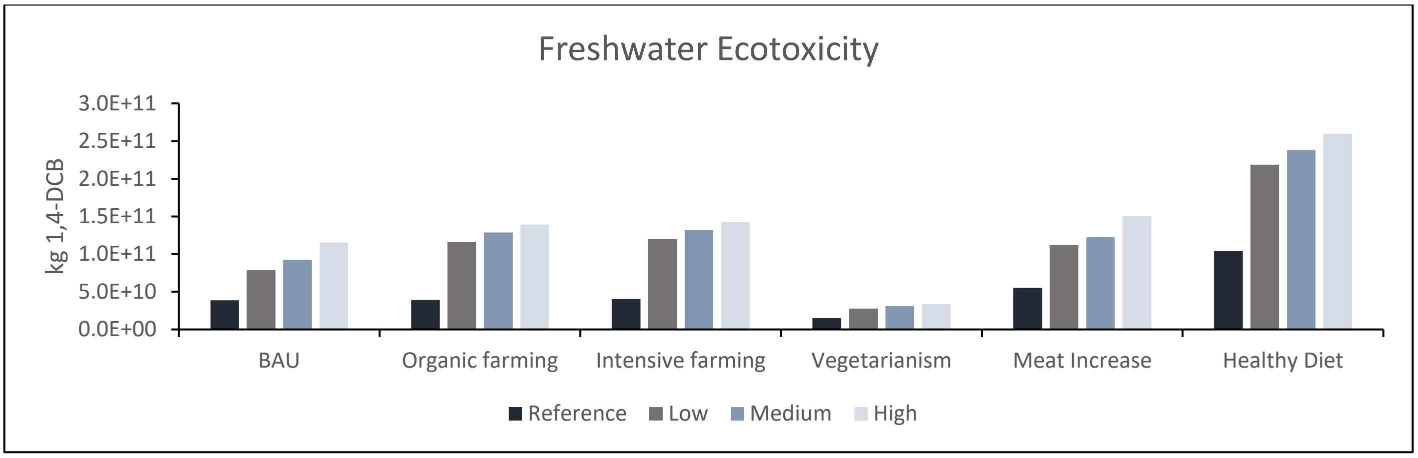

Figure A.6. Midpoint freshwater ecotoxicity impact (in kg 1,4-DCB) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

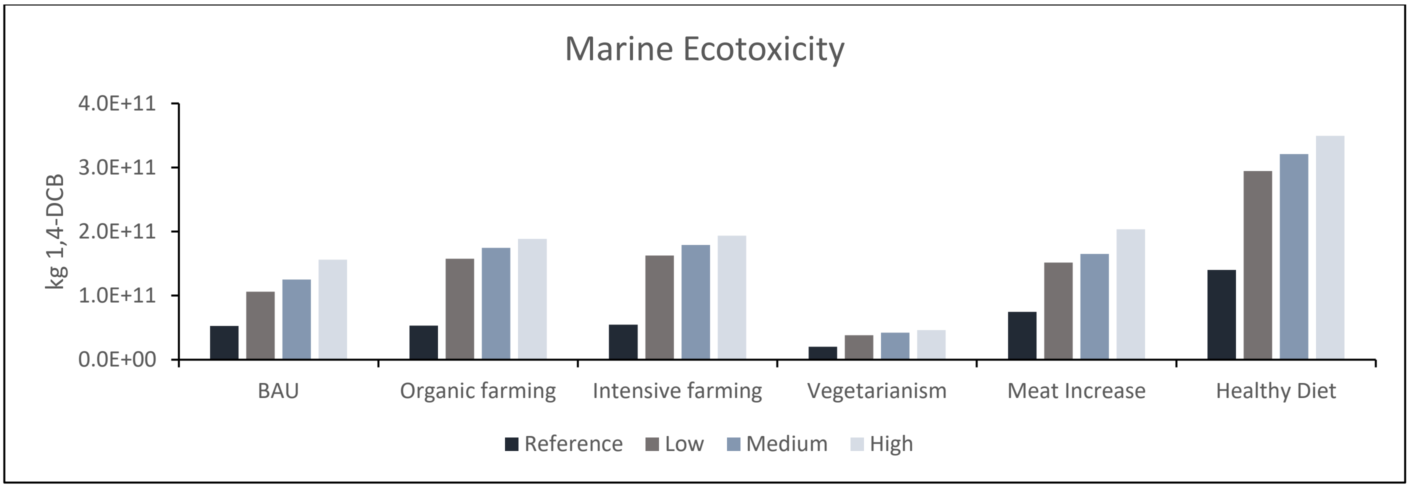

Figure A.7. Midpoint marine ecotoxicity impact (in kg 1,4-DCB) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

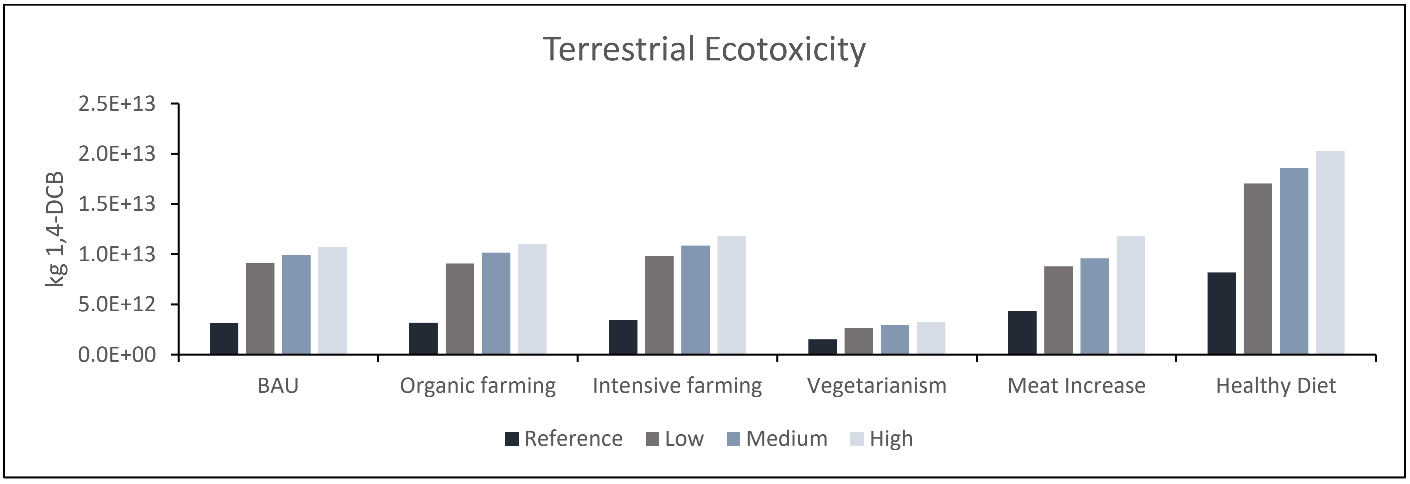

Figure A.8. Midpoint terrestrial ecotoxicity impact (in kg 1,4-DCB) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

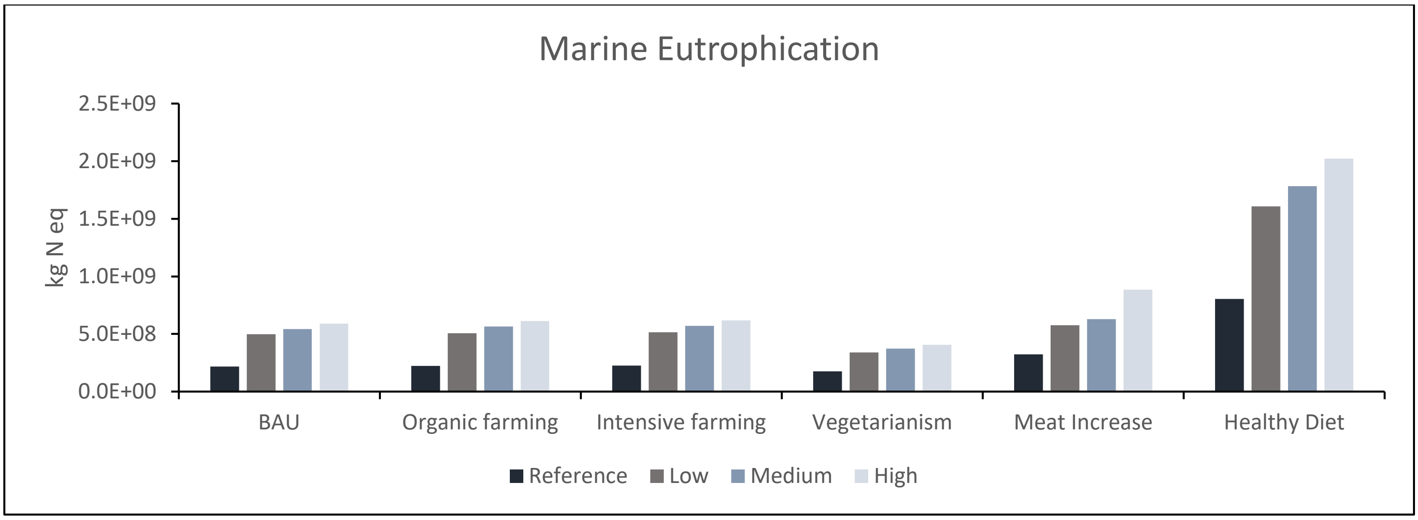

Figure A.9. Midpoint marine eutrophication impact (in kg N eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

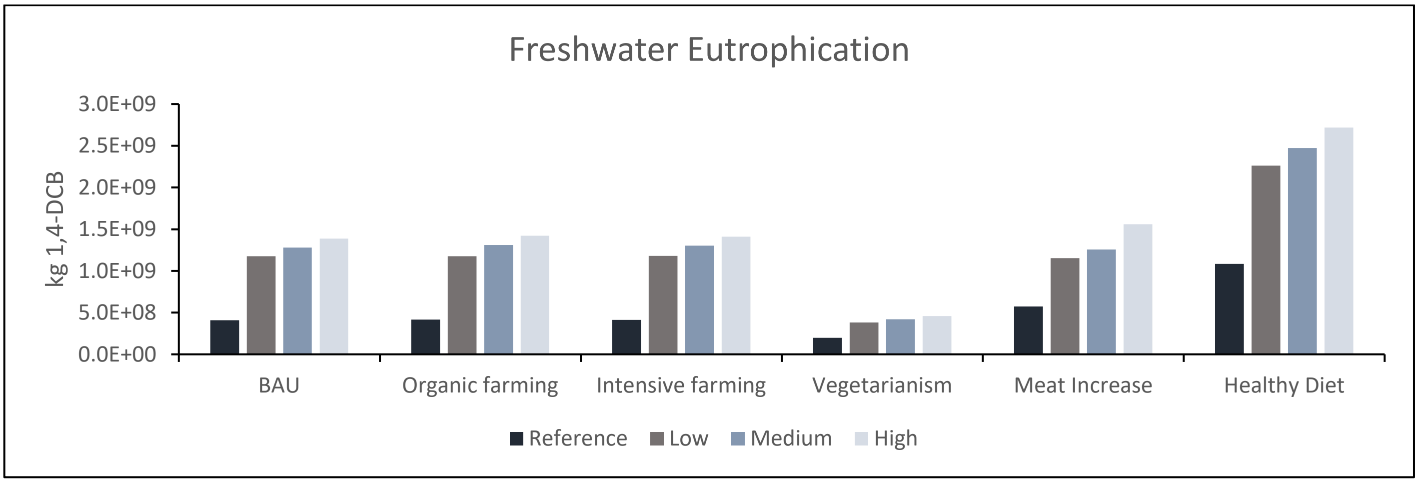

Figure A.10. Midpoint freshwater eutrophication impact (in kg P eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

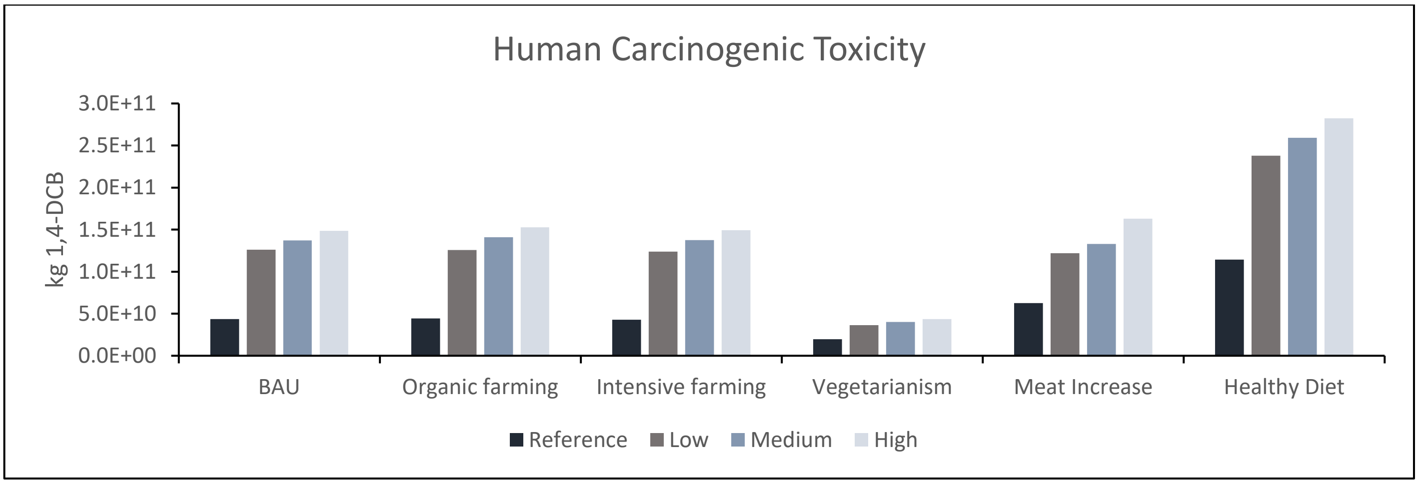

Figure A.11. Midpoint human carcinogenic toxicity impact (in kg 1,4-DCB) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

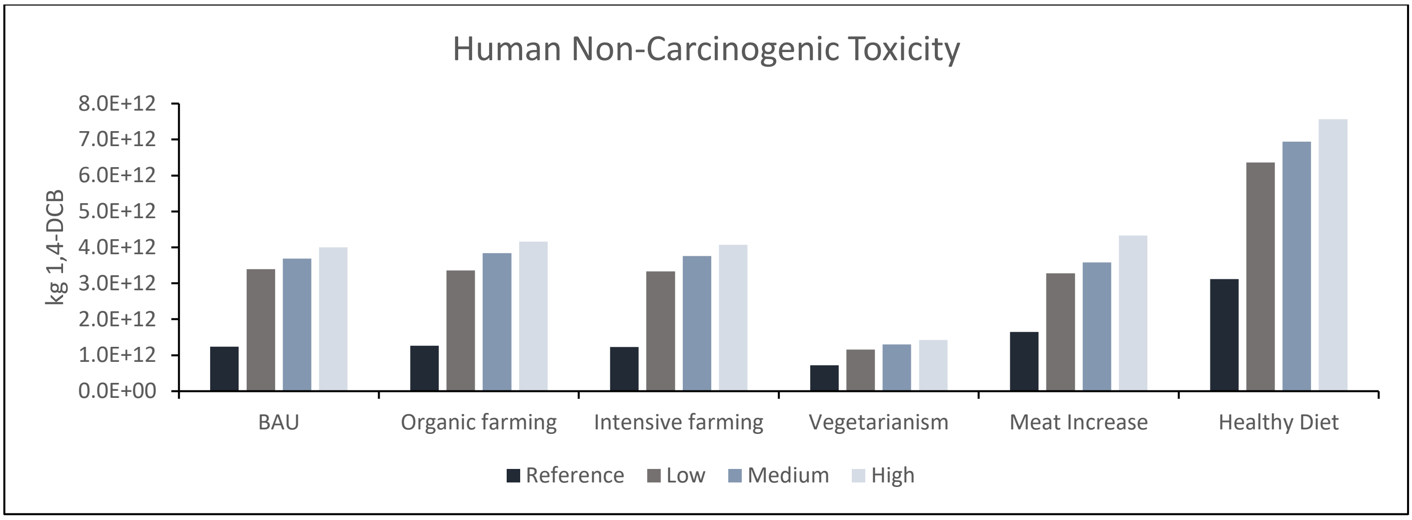

Figure A.12. Midpoint human non-carcinogenic toxicity impact (in kg 1,4-DCB) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

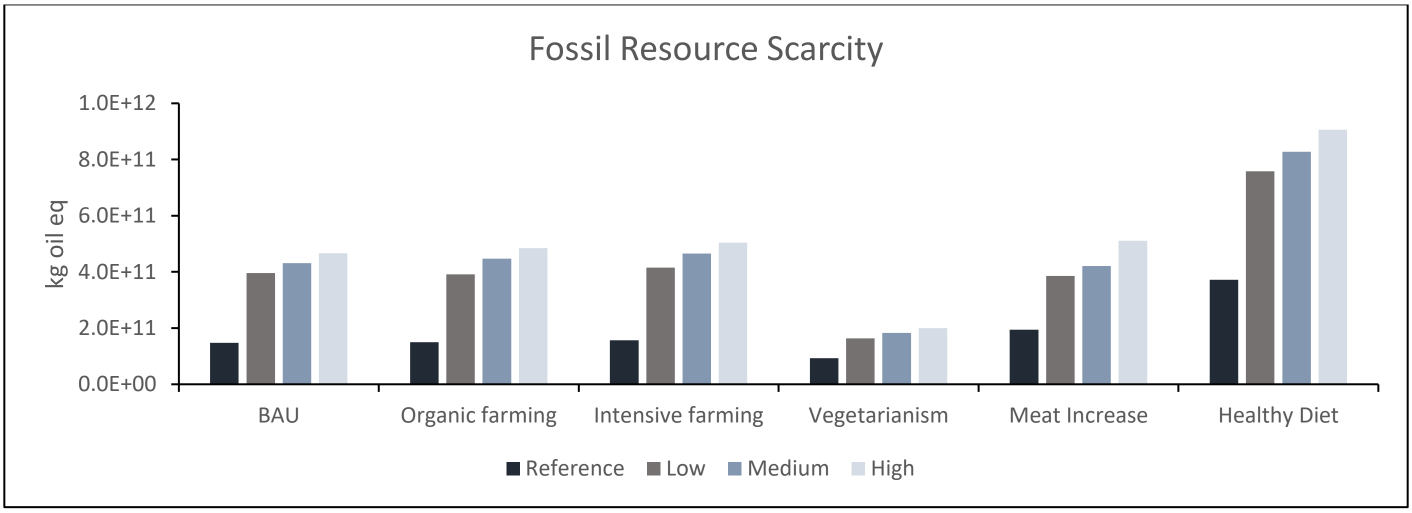

Figure A.13. Midpoint fossil resource scarcity impact (in kg oil eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

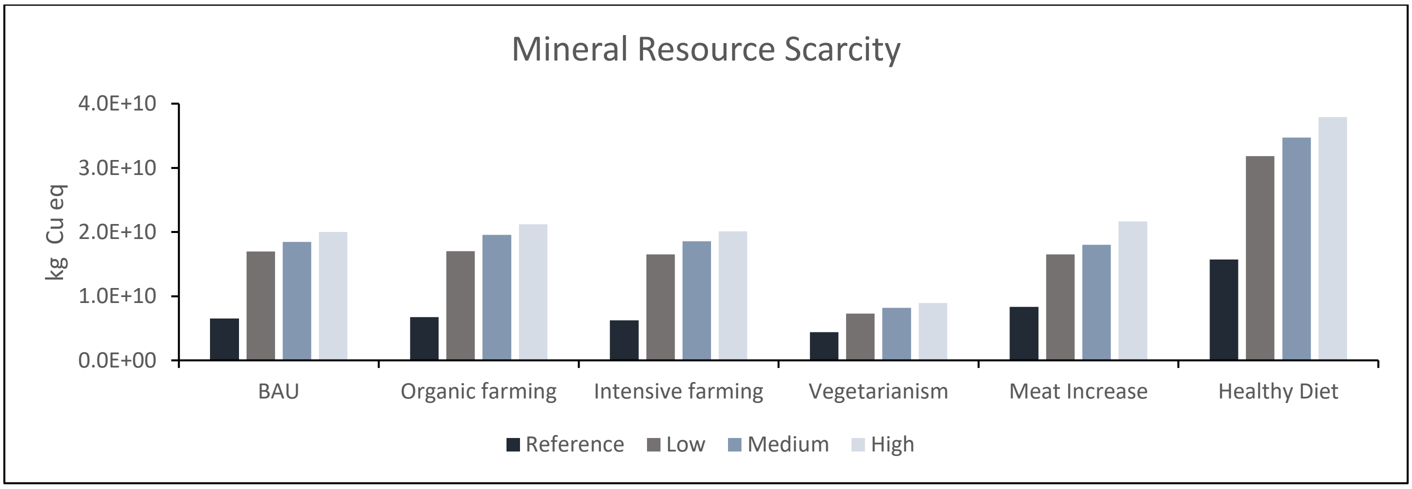

Figure A.14. Midpoint mineral resource scarcity impact (in kg Cu eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

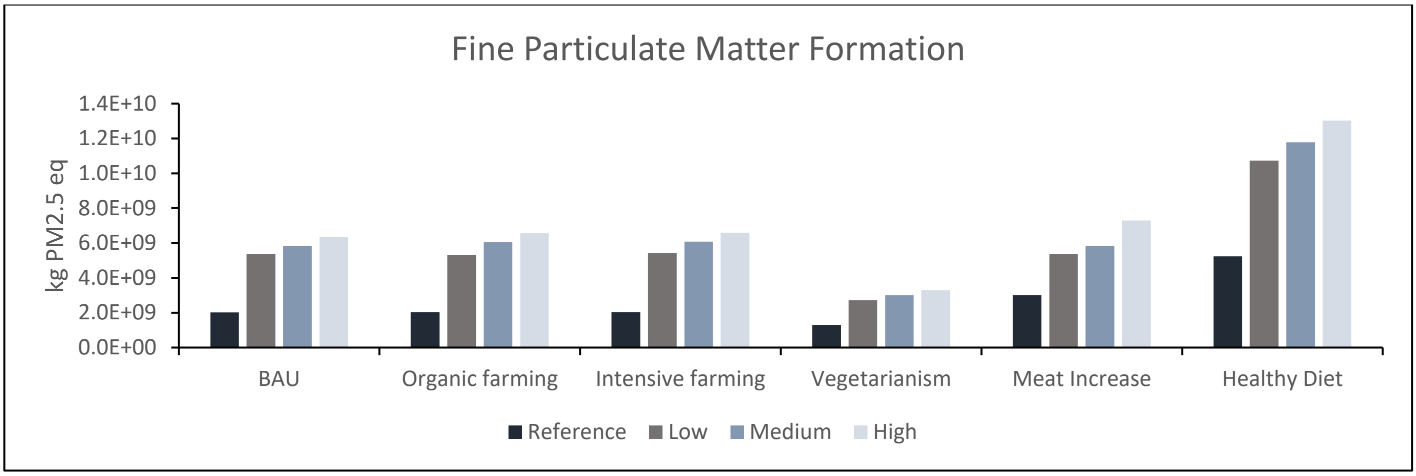

Figure A.15. Midpoint fine particulate matter formation impact (in kg PM2.5 eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

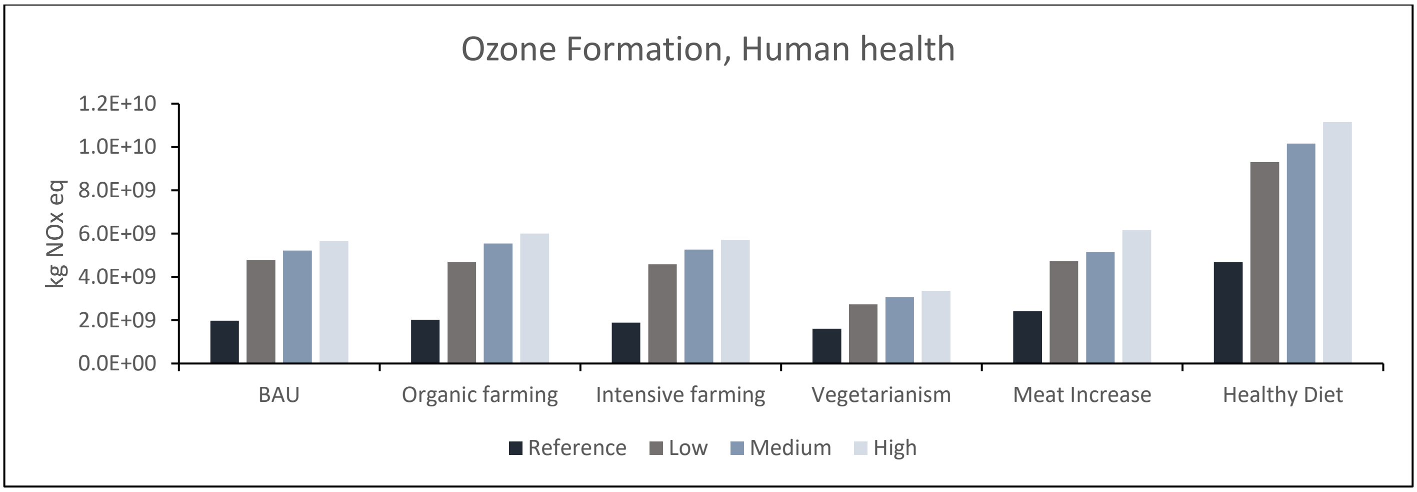

Figure A.16. Midpoint ozone formation impact on human health (in kg NOx eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

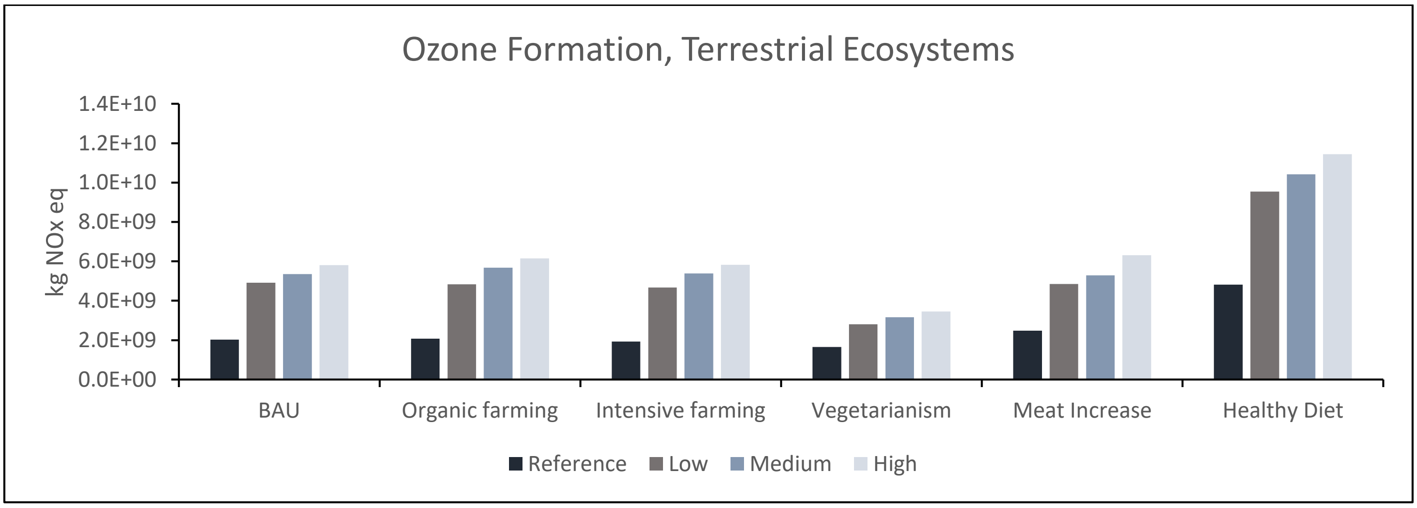

Figure A.17. Midpoint ozone formation impact on terrestrial ecosystems (in kg NOx eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

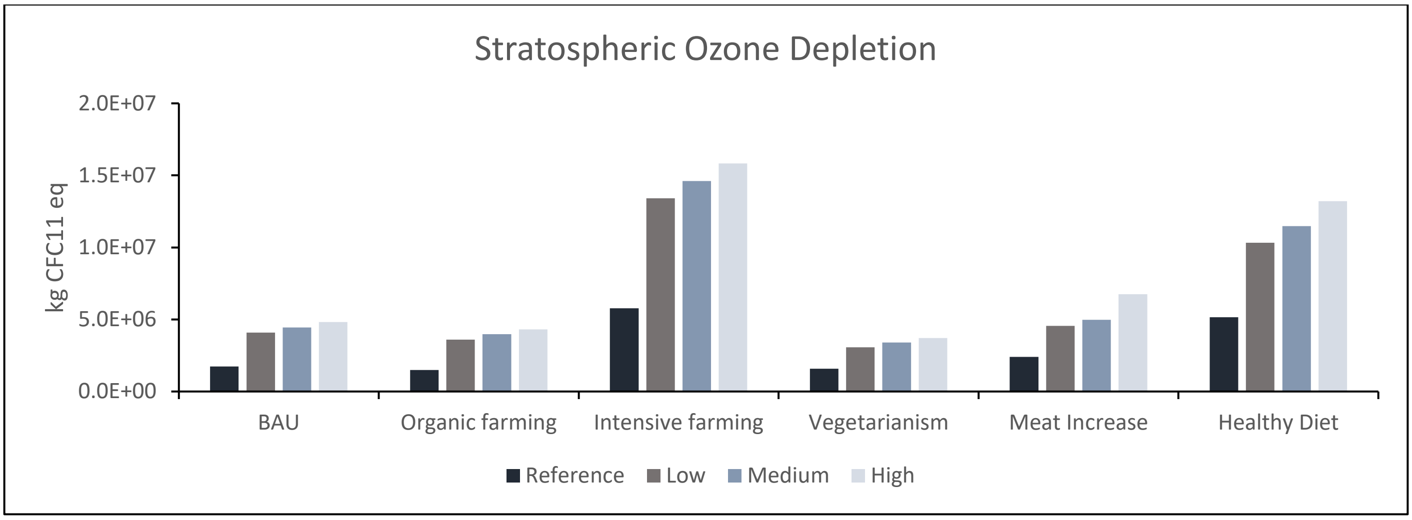

Figure A.18. Midpoint stratospheric ozone depletion impact (in kg CFC11 eq) for the scenarios studied (BAU, organic and intensive farming, vegetarianism, meat increase and healthy diet) and its population growth projections (low, medium, and high).

APPENDIX A.6
Sensitivity Analysis

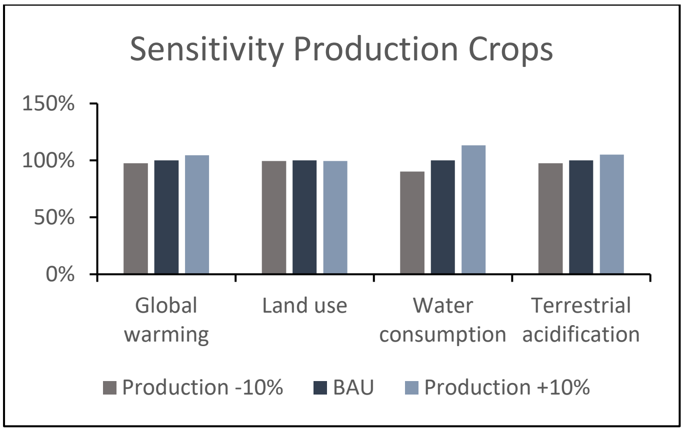

Figure A.19. Sensitivity analysis of crop production in modelling: 10% increase and decrease of production inputs.

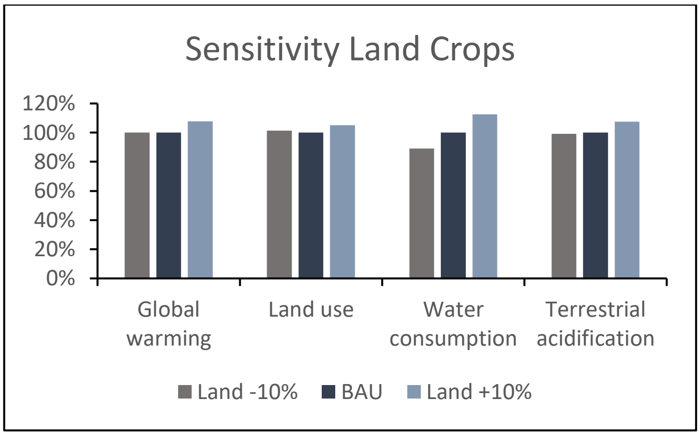

Figure A.20. Sensitivity analysis of crop land in modelling: 10% increase and decrease of land inputs.

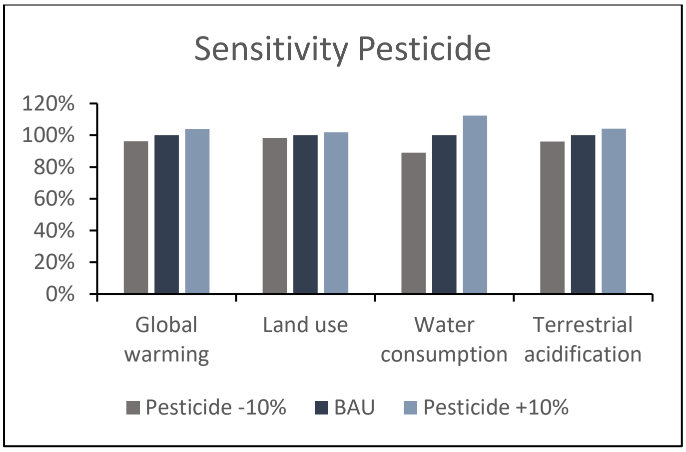

Figure A.21. Sensitivity analysis of pesticide use in modelling: 10% increase and decrease of pesticide inputs.

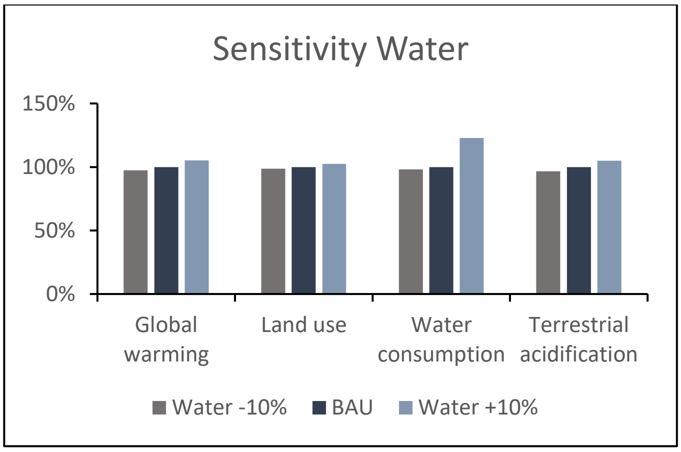

Figure A.22. Sensitivity analysis of water use in modelling: 10% increase and decrease of water inputs.

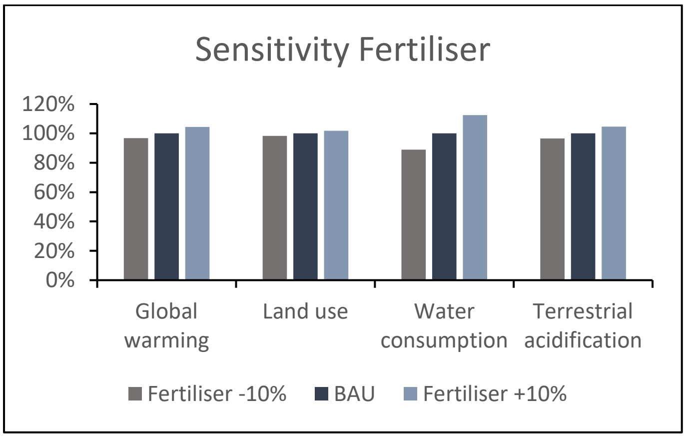

Figure A.23. Sensitivity analysis of fertiliser use in modelling: 10% increase and decrease of fertiliser inputs.

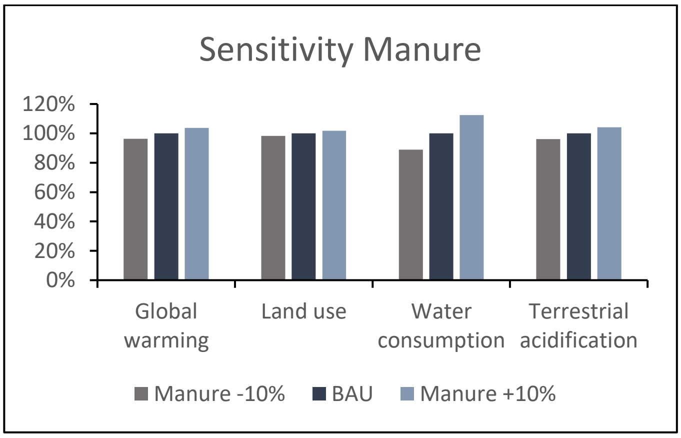

Figure A.24. Sensitivity analysis of manure use in modelling: 10% increase and decrease of manure inputs.

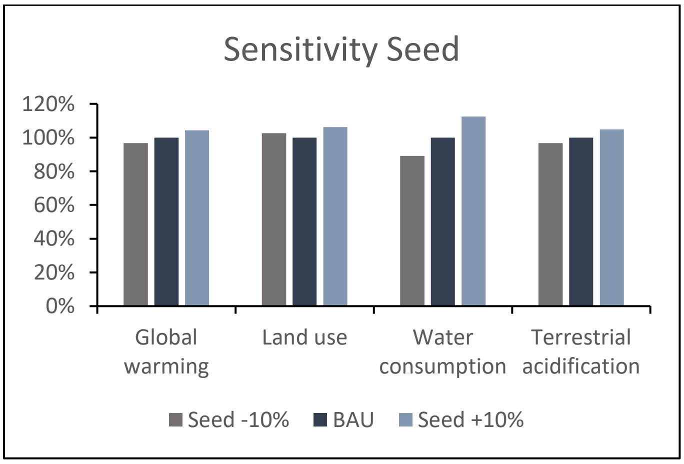

Figure A.25. Sensitivity analysis of seed use in modelling: 10% increase and decrease of seed inputs.

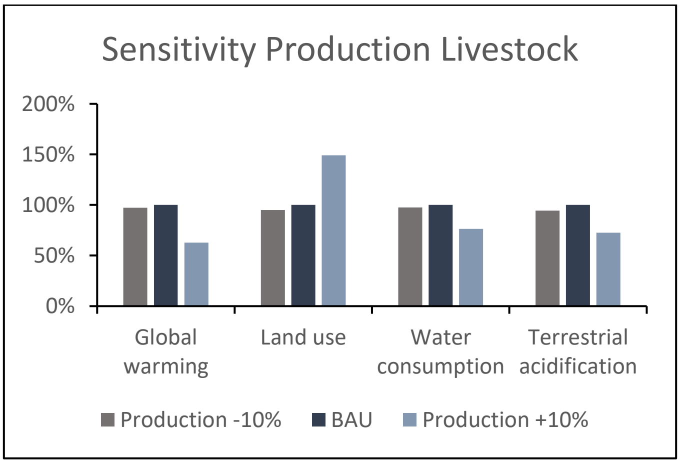

Figure A.26. Sensitivity analysis of livestock production in modelling: 10% increase and decrease of production inputs.

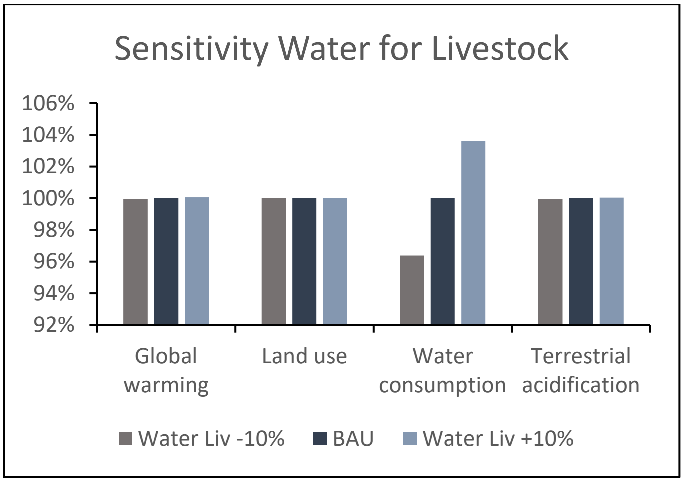

Figure A.27. Sensitivity analysis of livestock water use in modelling: 10% increase and decrease of livestock water inputs.

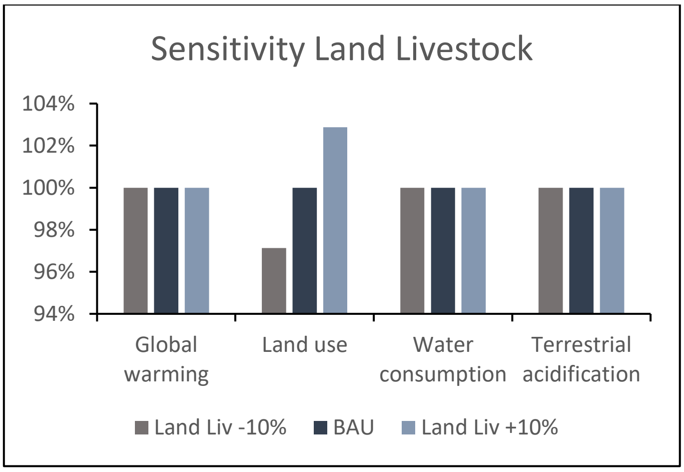

Figure A.28. Sensitivity analysis of livestock land in modelling: 10% increase and decrease of land input

Appendix B: Raw Data

APPENDIX B.1
Irrigation Water

Area	Commodities	Item	Year	Unit	Value	Water m3	Water/commodity
EA	Cereals	Maize	2013	ha	16113052	7580964788	10989592306
		Sorghum	2013	ha	5229543	2460426575	
		Wheat	2013	ha	2015365	948200943	
	Roots and tubers	Cassava	2013	ha	4064652	1912361711	3262586322
		Potatoes	2013	ha	895401	421273602	
		Sweet potatoes	2013	ha	1974450	928951010	
	Pulses	Beans	2013	ha	5372855	2527852859	2820549705
		Peas	2013	ha	622116	292696845	
	Treenuts	Nuts	2013	ha	78600	36980197	36980197
	Oil crops	Sunflower seed	2013	ha	2013225	947194103	2743239451
		Groundnuts	2013	ha	2943445	1384849556	
		Coconuts	2013	ha	873981	411195792	
	Vegetables	Tomatoes	2013	ha	142401	66997672	137069499
		Onions	2013	ha	148935	70071827	
	Fruits	Bananas	2013	ha	1402269	659747881	726497606
		Oranges	2013	ha	86786	40831595	
		Pineapples	2013	ha	55088	25918131	
	Sugar crops	Sugarcane	2013	ha	563348	265047326	265047326
MA	Cereals	Maize	2013	ha	5497332	319021625	527775039
		Sorghum	2013	ha	2166725	125739564	
		Millet	2013	ha	1430482	83013850	
	Roots and tubers	Cassava	2013	ha	6134554	356000945	390884494
		Sweet potatoes	2013	ha	382199	22179804	

		Yams	2013	ha	218909	12703745	
	Pulses	Beans	2013	ha	1713514	99438786	100162040
		Peas	2013	ha	12463	723254	
	Treenuts	Nuts	2013	ha	415	24083	24083
	Oil crops	Groundnuts	2013	ha	2348440	136284864	157511143
		Cottonseed	2013	ha		0	
		Sesame seed	2013	ha	365768	21226279	
	Vegetables	Tomatoes	2013	ha	83470	4843938	6095110
		Onions	2013	ha	21560	1251172	
	Fruits	Bananas	2013	ha	367353	21318260	27082296
		Pineapples	2013	ha	61510	3569553	
		Citrus	2013	ha	37815	2194483	
	Sugar crops	Sugarcane	2013	ha	415	24083	24083
NA	Cereals	Wheat	2013	ha	7408124	676573804	1449695941
		Maize	2013	ha	1237165	112988583	
		Sorghum	2013	ha	7228112	660133555	
	Roots and tubers	Potatoes	2013	ha	433948	39631876	48730399
		Sweet potatoes	2013	ha	23624	2157548	
		Yams	2013	ha	76000	6940976	
	Pulses	Beans	2013	ha	39644	3620632	11229585
		Peas	2013	ha	83314	7608953	
	Treenuts	Nuts	2013	ha	2347	214348	214348
	Oil crops	Olives	2013	ha	3406520	311112799	716212346
		Groundnuts	2013	ha	2252356	205704584	
		Sesame seed	2013	ha	2183269	199394963	
	Vegetables	Tomatoes	2013	ha	312954	28581660	47839123
		Onions	2013	ha	210859	19257463	
	Fruits	Oranges	2013	ha	253307	23134181	76980262
		Dates	2013	ha	373257	34089050	
		Grapes	2013	ha	216329	19757031	
	Sugar crops	Sugarcane	2013	ha	223505	20412405	20412405
SA	Cereals	Maize	2013	ha	3039779	6000844128	7189909005
		Wheat	2013	ha	519186	1024927884	
		Barley	2013	ha	83145	164136993	
	Roots and tubers	Potatoes	2013	ha	73635	145363251	191229616
		Sweet potatoes	2013	ha	23234	45866365	
	Pulses	Beans	2013	ha	65480	129264421	134067420
		Peas	2013	ha	2433	4802998	
	Treenuts	Nuts	2013	ha	5466	10790460	10790460
	Oil crops	Soybeans	2013	ha	516500	1019625437	2163424078
		Sunflower seed	2013	ha	507236	1001337325	
		Rape and mustardseed	2013	ha	72165	142461316	
	Vegetables	Onions	2013	ha	25790	50912178	69014725
		Tomatoes	2013	ha	9170	18102546	
	Fruits	Grapes	2013	ha	108617	214421406	370476412
		Oranges	2013	ha	54232	107059684	

		Apples	2013	ha	24819	48995322	
	Sugar crops	Sugarcane	2013	ha	322186	636029121	636029121
WA	Cereals	Maize	2013	ha	11207000	1367738425	4607161530
		Sorghum	2013	ha	13245153	1616481191	
		Millet	2013	ha	13298091	1622941915	
	Roots and tubers	Cassava	2013	ha	9149281	1116607762	2138010213
		Sweet potatoes	2013	ha	1676357	204588015	
		Yams	2013	ha	6692829	816814437	
	Pulses	Beans	2013	ha	723971	88355756	92740769
		Peas	2013	ha	35930	4385013	
	Treenuts	Nuts	2013	ha	30903	3771502	3771502
	Oil crops	Groundnuts	2013	ha	6332061	772785147	772785147
		Palm kernels	2013	ha		0	
		Cottonseed	2013	ha		0	
	Vegetables	Tomatoes	2013	ha	638468	77920694	141001664
		Onions	2013	ha	516874	63080970	
	Fruits	Bananas	2013	ha	1387849	169377568	197587860
		Citrus	2013	ha		0	
		Pineapples	2013	ha	231150	28210292	
	Sugar crops	Sugarcane	2013	ha	158239	19311998	19311998

APPENDIX B.2

Manure Applied to Soils

Area	Commodity	Item	Year	Unit	Value	Manure kg	Manure/commodity
EA	Cereals	Maize	2013	ha	16113052	127926927	185446683
		Sorghum	2013	ha	5229543	41519097	
		Wheat	2013	ha	2015365	16000659	
	Roots and tubers	Cassava	2013	ha	4064652	32270636	55055346
		Potatoes	2013	ha	895401	7108889	
		Sweet potatoes	2013	ha	1974450	15675821	
	Pulses	Beans	2013	ha	5372855	42656899	47596086
		Peas	2013	ha	622116	4939188	
	Treenuts	Nuts	2013	ha	78600	624032	624032
	Oil crops	Sunflower seed	2013	ha	2013225	15983669	46291495
		Groundnuts	2013	ha	2943445	23368998	
		Coconuts	2013	ha	873981	6938828	
	Vegetables	Tomatoes	2013	ha	142401	1130569	2313014
		Onions	2013	ha	148935	1182445	
	Fruits	Bananas	2013	ha	1402269	11133084	12259469
		Oranges	2013	ha	86786	689023	
		Pineapples	2013	ha	55088	437362	
	Sugar crops	Sugarcane	2013	ha	563348	4472609	4472609
MA	Cereals	Maize	2013	ha	5497332	26328040	43555926
		Sorghum	2013	ha	2166725	10376965	
		Millet	2013	ha	1430482	6850921	

	Roots and tubers	Cassava	2013	ha	6134554	29379849	32258699
		Sweet potatoes	2013	ha	382199	1830443	
		Yams	2013	ha	218909	1048408	
	Pulses	Beans	2013	ha	1713514	8206429	8266117
		Peas	2013	ha	12463	59688	
	Treenuts	Nuts	2013	ha	415	1988	1988
	Oil crops	Groundnuts	2013	ha	2348440	11247242	12998992
		Cottonseed	2013	ha		0	
		Sesame seed	2013	ha	365768	1751751	
	Vegetables	Tomatoes	2013	ha	83470	399758	503014
		Onions	2013	ha	21560	103256	
	Fruits	Bananas	2013	ha	367353	1759342	2235033
		Pineapples	2013	ha	61510	294586	
		Citrus	2013	ha	37815	181105	
	Sugar crops	Sugarcane	2013	ha	415	1988	1988
NA	Cereals	Wheat	2013	ha	7408124	36874263	79010551
		Maize	2013	ha	1237165	6158043	
		Sorghum	2013	ha	7228112	35978245	
	Roots and tubers	Potatoes	2013	ha	433948	2159995	2655878
		Sweet potatoes	2013	ha	23624	117589	
		Yams	2013	ha	76000	378293	
	Pulses	Beans	2013	ha	39644	197330	612029
		Peas	2013	ha	83314	414699	
	Treenuts	Nuts	2013	ha	2347	11682	11682
	Oil crops	Olives	2013	ha	3406520	16956103	39034621
		Groundnuts	2013	ha	2252356	11211201	
		Sesame seed	2013	ha	2183269	10867317	
	Vegetables	Tomatoes	2013	ha	312954	1557742	2607302
		Onions	2013	ha	210859	1049560	
	Fruits	Oranges	2013	ha	253307	1260847	4195537
		Dates	2013	ha	373257	1857903	
		Grapes	2013	ha	216329	1076787	
	Sugar crops	Sugarcane	2013	ha	223505	1112506	1112506
SA	Cereals	Maize	2013	ha	3039779	33512233	40152669
		Wheat	2013	ha	519186	5723798	
		Barley	2013	ha	83145	916637	
	Roots and tubers	Potatoes	2013	ha	73635	811794	1067938
		Sweet potatoes	2013	ha	23234	256145	
	Pulses	Beans	2013	ha	65480	721888	748711
		Peas	2013	ha	2433	26823	
	Treenuts	Nuts	2013	ha	5466	60260	60260
	Oil crops	Soybeans	2013	ha	516500	5694186	12081829
		Sunflower seed	2013	ha	507236	5592055	
		Rape and mustardseed	2013	ha	72165	795588	
	Vegetables	Onions	2013	ha	25790	284323	385419
		Tomatoes	2013	ha	9170	101095	

	Fruits	Grapes	2013	ha	108617	1197455	2068958
		Oranges	2013	ha	54232	597884	
		Apples	2013	ha	24819	273619	
	Sugar crops	Sugarcane	2013	ha	322186	3551960	3551960
WA	Cereals	Maize	2013	ha	11207000	38514176	129733161
		Sorghum	2013	ha	13245153	45518529	
		Millet	2013	ha	13298091	45700456	
	Roots and tubers	Cassava	2013	ha	9149281	31442582	60204276
		Sweet potatoes	2013	ha	1676357	5760998	
		Yams	2013	ha	6692829	23000695	
	Pulses	Beans	2013	ha	723971	2488012	2611489
		Peas	2013	ha	35930	123478	
	Treenuts	Nuts	2013	ha	30903	106202	106202
	Oil crops	Groundnuts	2013	ha	6332061	21760874	21760874
		Palm kernels	2013	ha		0	
		Cottonseed	2013	ha		0	
	Vegetables	Tomatoes	2013	ha	638468	2194170	3970469
		Onions	2013	ha	516874	1776298	
	Fruits	Bananas	2013	ha	1387849	4769507	5563881
		Citrus	2013	ha		0	
		Pineapples	2013	ha	231150	794374	
	Sugar crops	Sugarcane	2013	ha	158239	543807	543807

APPENDIX B.3

Energy Use

Area	Commodity	Item	Gas-diesel oil	Fuel oil	Coal	Electricity	Natural gas	Energy for irrig.
EA	Cereals	Maize	3458	134	6481	1116		844
		Sorghum						
		Wheat						
	Roots and tubers	Cassava	1027	40	1924	331		251
		Potatoes						
		Sweet potatoes						
	Pulses	Beans	887	34	1663	286		217
		Peas						
	Treenuts	Nuts	12	0	22	4		3
	Oil crops	Sunflower seed	863	34	1618	279		211
		Groundnuts						
		Coconuts						
	Vegetables	Tomatoes	43	2	81	14		11
		Onions						
	Fruits	Bananas	229	9	428	74		56
		Oranges						
		Pineapples						

	Sugar crops	Sugarcane	83	3	156	27		20
MA	Cereals	Maize	268	0	0	83	0	25
		Sorghum						
		Millet						
	Roots and tubers	Cassava	199	0	0	62	0	18
		Sweet potatoes						
		Yams						
	Pulses	Beans	51	0	0	16	0	5
		Peas						
	Treenuts	Nuts	0	0	0	0	0	0
	Oil crops	Groundnuts	80	0	0	25	0	7
		Cottonseed						
		Sesame seed						
	Vegetables	Tomatoes	3	0	0	1	0	0
		Onions						
	Fruits	Bananas	14	0	0	4	0	1
		Pineapples						
		Citrus						
	Sugar crops	Sugarcane	0	0	0	0	0	0
NA	Cereals	Wheat	155985	1806	0	17712	688	4015
		Maize						
		Sorghum						
	Roots and tubers	Potatoes	5243	61	0	595	23	135
		Sweet potatoes						
		Yams						
	Pulses	Beans	1208	14	0	137	5	31
		Peas						
	Treenuts	Nuts	23	0	0	3	0	1
	Oil crops	Olives	77063	892	0	8750	340	1984
		Groundnuts						
		Sesame seed						
	Vegetables	Tomatoes	5147	60	0	584	23	133
		Onions						
	Fruits	Oranges	8283	96	0	941	37	213
		Dates						
		Grapes						
	Sugar crops	Sugarcane	2196	25	0	249	10	57
SA	Cereals	Maize	26207	0	0	217475	0	2518
		Wheat						
		Barley						
	Roots and tubers	Potatoes	697	0	0	5784	0	67
		Sweet potatoes						
	Pulses	Beans	489	0	0	3910	0	47
		Peas						
	Treenuts	Nuts	39	0	0	326	0	4
	Oil crops	Soyabeans	7886	0	0	65438	0	

		Sunflower seed						
		Rape and mustardseed						
	Vegetables	Onions	252	0	0	2088	0	24
		Tomatoes						
	Fruits	Grapes	1350	0	0	11206	0	130
		Oranges						
		Apples						
	Sugar crops	Sugarcane	2318	0	0	19238	0	223
WA	Cereals	Maize	2465	0	0	149	0	159
		Sorghum						
		Millet						
	Roots and tubers	Cassava	1144	0	0	69	0	74
		Sweet potatoes						
		Yams						
	Pulses	Beans	50	0	0	3	0	3
		Peas						
	Treenuts	Nuts	2	0	0	0	0	0
	Oil crops	Groundnuts	414	0	0	25	0	27
		Palm kernels						
		Cottonseed						
	Vegetables	Tomatoes	75	0	0	5	0	5
		Onions						
	Fruits	Bananas	106	0	0	6	0	7
		Citrus						
		Pineapples						
	Sugar crops	Sugarcane	10	0	0	1	0	1

APPENDIX B.4
Feed for Livestock

Area	Item	Cattle (tonnes)	Poultry (tonnes)	Sheep and Goat (tonnes)
EA	Rice (Milled Equivalent)	106816	335	11849
	Barley and products	11669	37	1294
	Maize and products	3112027	9768	345205
	Millet and products	14362	45	1593
	Sorghum and products	63731	200	7069
	Cassava and products	4566162	14332	506506
	Potatoes and products	728862	2288	80850
	Sweet potatoes	304291	955	33754
	Sugar cane	58345	183	6472
	Beans	26031	82	2887
	Soybeans	49369	155	5476
	Cottonseed	8976	28	996
	Plantains	13464	42	1494
	Milk - Excluding Butter	433548	1361	48092
	Pelagic Fish	40393	127	4481

MA	Maize and products	705398	2779	106822
	Millet and products	21638	85	3277
	Sorghum and products	288218	1136	43646
	Cassava and products	8592013	33851	1301136
	Sweet potatoes	22504	89	3408
	Yams	55393	218	8389
	Sugar cane	65779	259	9961
	Plantains	26831	106	4063
	Milk - Excluding Butter	8655	34	1311
	Pelagic Fish	60586	239	9175
NA	Wheat and products	5906956	118831	1574213
	Rice (Milled Equivalent)	90159	1814	24027
	Barley and products	2599838	52301	692861
	Maize and products	8356011	168099	2226889
	Oats	112699	2267	30034
	Millet and products	45079	907	12014
	Sorghum and products	542507	10914	144579
	Potatoes and products	38862	782	10357
	Sugar cane	980866	19732	261402
	Sugar beet	155446	3127	41427
	Vegetables	59070	1188	15742
	Dates	38084	766	10150
	Milk - Excluding Butter	1153411	23203	307386
	Pelagic Fish	28758	579	7664
SA	Wheat and products	31829	369	4803
	Barley and products	17205	199	2596
	Maize and products	4135131	47900	623969
	Oats	6882	80	1038
	Millet and products	6882	80	1038
	Sorghum and products	25807	299	3894
	Potatoes and products	186670	2162	28168
	Soybeans	6882	80	1038
	Vegetables	43872	508	6620
	Milk - Excluding Butter	133336	1545	20120
	Pelagic Fish	57635	668	8697
WA	Wheat and products	15488	149	4363
	Rice (Milled Equivalent)	167271	1612	47117
	Maize and products	4107428	39595	1156978
	Millet and products	715547	6898	201555
	Sorghum and products	869653	8383	244963
	Cassava and products	25195165	242875	7096960
	Potatoes and products	46464	448	13088
	Yams	3559925	34317	1002758
	Sugar cane	21683	209	6108
	Soybeans	47239	455	13306
	Milk - Excluding Butter	85959	829	24213
	Pelagic Fish	713999	6883	201119

APPENDIX B.5

Water for Livestock

Area	Item	Year	Water req. L
EA	Cattle and Buffaloes	2013	1412568660625
	Poultry Birds	2013	34662941130
	Sheep and Goats	2013	918109518469
MA	Cattle and Buffaloes	2013	352863038250
	Poultry Birds	2013	10868818890
	Sheep and Goats	2013	313101603563
NA	Cattle and Buffaloes	2013	406950490250
	Poultry Birds	2013	64004994750
	Sheep and Goats	2013	635466233700
SA	Cattle and Buffaloes	2013	180196238625
	Poultry Birds	2013	16319284320
	Sheep and Goats	2013	159320171756
WA	Cattle and Buffaloes	2013	614829305250
	Poultry Birds	2013	46336725180
	Sheep and Goats	2013	1014754592138