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Livsløpsanalyse av norske landbruksaktiviteter og produkter

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MASTER THESIS
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Anne Zimmer Jakobsen

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Environmental Assessment of Norwegian Agricultural Activities and Products
Livsløpsanalyse av norske landbruksaktiviteter og -produkter

Background

In the pursuit for sustainability, knowledge on the environmental impact of products and production systems is essential. This is also valid for food production and consumption, which is among the most essential production systems humans have generated. Here a range of public debates are ongoing, e.g. on organic and locally produced food, and an increased level of knowledge is essential. Life cycle assessment is the prevailing framework to analyze the impact from such complex systems.

The agricultural sector is important with respect to a range of environmental impact categories, such as eutrophication and land occupation and transformation, and climate change where agricultural production contributes around 13.5% of the global greenhouse gas emissions.

There is increasing attention towards impacts associated with food products and an increasing volume of literature addresses the life cycle impacts of food production and coherent agricultural systems. While most products are produced with a relatively narrow range of production technologies worldwide, agricultural production practices are extremely diverse. Comparison of impacts associated with consumption of similar agricultural products produced at different locations and/or under diverging management requires thorough understanding of the individual production practices. Results from locations with other climatic and topographic conditions, as well as countries with other management history, traditions and political incentives on agricultural systems, are not directly transferable, and unique data must be collected.

Aim

The primary objective of this project is to assess the environmental impacts of selected Norwegian agricultural activities, practices and products on a joint and individual level. The secondary objective is to develop a hybrid input-output sector model of the selected agricultural activities.

The analysis should include following elements:

1) Development of LCA inventories covering different regional and production intensity practices.
2) Development of a hybrid LCA and input-output based model of the selected Norwegian agricultural subsectors.
3) Environmental assessment of the sector and individual activities and products.
4) Analysis and Discussion.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

Department of Energy and Process Engineering, February 2012.

Olav Bolland
1/3-2012

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“Environmental Assessment of Norwegian Agricultural Activities and Products”

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Master Thesis

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
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Industrial Ecology Program

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Preface

This report was written to fulfill the requirements for obtaining an Msc. in Industrial Ecology at the Norwegian University of Science and Technology under the Department of Energy and Process Engineering, and represents my master thesis.

The objective of this thesis was to assess the environmental implications of grain production in Norway. In agreement with supervisor Anders Hammer Strømman, the aim of developing a hybrid LCA and input-output based model of selected agricultural subsectors was discarded. This was done as the further scoping of the assignment, in collaboration with bioforsk, rendered this approach to be unnecessary.

I would like to thank all the people that directly or indirectly contributed to the completion of this thesis. Firstly, I would like to thank my supervisor Anders Hammer Strømman, whom has been readily available to guide me through both methodological and technical problems. His guidance and encouragement has been greatly appreciated.

I am also thankful for the extraordinary attention and help I have received from Audun Korsæth and Anne-Grete Roer at Bioforsk. Bioforsk has provided me not only with data, but also with their necessary expertise on agricultural processes. I have greatly appreciated collaborating with both of them.

Lastly, I would like to thank my partner Jon, who has shown interest and support during my work.

Abstract

The agricultural sector have significant environmental footprints, which are expected to increase as the world population continues to grow. The world community therefore has incentives to search for more environmentally friendly production pathways. It is also the goal of the Norwegian government to lower the environmental footprint of the agricultural sector by 2020. As impacts will vary according to climatic and topographic conditions, as well as traditions and political incentives, greater knowledge on environmental impacts specific to Norwegian conditions are important.

This study is focusing on the environmental load associated with cultivating the grains barley, oat and wheat in Norway. By using a lifecycle approach, the footprint associated with producing 1 kg of these species at 94 locations in Norway is assessed. By having a wide system-boundary which includes farm activities, inputs such as machinery, fertilizers and pesticides, as well as emissions associated with the mineralization of soil organic matter, this study wish to provide a basis for assessing average environmental impacts associated with producing 1 kg grain in Norway, as well as assessing variation in loads between regions and species.

The results showed that field emissions contributed greatly to the impacts for all categories, except for those assessing toxicity. It is therefore of interest to further investigate means of lowering these emissions, in particular of N_2O, as it was identified to be the main stressor contributing to climate change potentials. Variation in soil emissions associated with mineralization was also identified as an important source of regional variation in environmental performance. The results further showed that winter wheat was the grain species most often associated with the lowest environmental loads. This was largely explained by the specie having high yields. Agricultural practices enhancing optimal yields can thus be important to lower the environmental impacts from grain production.

Sammendrag

Landbrukssektoren har et betydelig miljømessig fotavtrykk, som forventes å øke ettersom verdens befolkning fortsetter å vokse. Verdenssamfunnet har derfor insentiver til å søke etter mer miljøvennlige produksjonsmetoder. Det er også den norske regjeringens mål å minske belastningen fra jordbrukssektoren innen 2020. Siden konsekvensene av jordbruket avhenger av klimatiske og topografiske forhold, samt tradisjoner og politiske insentiver, vil større kunnskap om miljøbelastning knyttet spesifikt til norske forhold være viktig.

Denne studien fokuserer på miljøbelastningen av bygg, havre og hvete produksjon i Norge. Ved å bruke en livsløpstilnærming, evalueres miljøbelastningen fra kornproduksjon ved 94 gårder i Norge. Ved å ha en bred system-grense, som omfatter gårdsaktiviteter og innsatsfaktorer som maskiner, kunstgjødsel og pesticider, samt utslipp forbundet med humus mineralisering, ønsker denne studien å gi et grunnlag for å kunne vurdere gjennomsnittlige miljøkonsekvenser forbundet med produksjon av 1 kg korn, samt å vurdere mulig variasjon i belastning mellom regioner og arter.

Resultatene viste at utslipp fra åkeren bidro sterkt til miljøkonsekvensene for alle kategorier evaluert, unntatt for toksisitet. Det er derfor av interesse å evaluere mulige tiltak for å minske disse utslippene. Dette gjelder særlig for N_2O utslipp assosiert med mineralisering, da disse utslippene var den viktigste stressoren som bidro til klimaendringer. Utslipp fra åkeren var også den viktigste kilden til geografisk variasjon i miljøbelastningen. Resultatene indikerer også at høsthvete var den kornarten som oftest hadde lavest miljøbelastning, per kg produsert. Dette kan i stor grad forklares ved ved at denne arten hadde et høyt utbytte per hektar. Dette viser viktigheten av jordbrukspraksis som optimaliserer utbyttet for å senke miljøbelastningen, per kg produsert.

Contents

List of Figures

List of Tables

Nomenclature

Table 1: Symbols, acronyms and abbreviations used in this report

AP	Acidification Potential
CCP	Climate Change Potential
CH_4	Methane
CML	Centrum voor Milieuwetenschappen Leiden (Institute of Environmental Sciences Leiden)
CO	Carbon monoxide
CO_2	Carbon dioxide
daa	Dekar (0,1 ha)
DCB	1.4-dichlorobenzene
EP	Eutrophication Potential
eq.	equivalents
FD	Fossil depletion
FE	freshwater eutrophication
FET	Freshwater Ecotoxicity
ha	hectare (0.1 km^2)
HT	Human Toxicity
ICBM	Introductory Carbon Balance Model
IR	Ionizing radiation
ISO	International Organisation for Standardisation
LUC	Land Use Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MD	Metal depletion
ME	Marine Eutrophication
MET	Marine Ecotoxicity
N	Nitrogen
N_2O	Nitrous oxide
NLT	Natural land transformation
NO_3^-	nitrate
OD	Ozone Depletion
P	Phosphorous
P_2O_5	single superphosphate
PAH	polycyclic aromatic hydrocarbons
PMF	Particulate matter formation
POF	Photochemical oxidant formation
POPs	Persistent, organic pollutants
RER	EcoInvent country code for Europe
S. Wheat	Spring Wheat
SN	Statistics Norway (Statistisk Sentralbyrå)

Table 2: Symbols, acronyms and abbreviations used in this report

std	Standard Deviation
TA	Terrestrial acidification
Tg	teragrams
ts30	Soil temperature at 30 cm depth
TET	Terrestrial ecotoxicity
ULO	Urban land occupation
VOCs	Volatile Organic Compounds
WD	Water depletion
WFPS	Water filled pore space
W. Wheat	Winter Wheat

Chapter 1

Introduction

The security of food supply is a pressing issue worldwide. The world population is increasing rapidly, and is likely to have reached 9 billion people by the year 2050. This indicates that a doubling in food-production will be required by this time [1]. Management intensification and land use change are necessary means in order to achieve this goal, and an associated increase in the environmental footprint from agriculture is thus expected [2]. As the current level of foodproduction already contribute with approximately 13.5% of the global green house gas emissions, and also have other environmental impacts in areas such as eutrophication, the world community has strong incentives to search for more sustainable production pathways [3] [4] [5].

The contribution of agriculture to global anthropogenic greenhouse gas (GHG) emissions is estimated to be between 5.1 and 6.1 Gt CO_2eq yr^{-1} [6]. The three main sources of GHG emissions are CO_2, CH_4 and N_2O, where the largest fraction is due to emissions of nitrous oxides (N_2O). The concentration of N_2O in the atmosphere has increased by approximately 20% since preindustrial times, and 70 to 81% of this increase has been linked to the global increase in nitrogen fertilizer use [7] [8] [9].The leaching and run off of fertilizers applied to agricultural land can cause eutrophication of waters, as nitrogen and phosphorous has been identified to be the main limiting nutrients in aquatic ecosystems [10] [11]. Pesticides used in agriculture can also have severe impacts, for instance through their carcinogenic properties [12].

The environmental effects of agricultural processes are thus significant and diverse. It is therefore the goal of the Norwegian government to lower the climate and environmental effect of Norwegian agricultural processes. It has been estimated that the agricultural sector contributes with 7.7 % of the GHG emissions in Norway [13]. The Norwegian government has a goal of reducing this load by 1.1 million tonnes of CO_2-equivalents by 2020 [1]. An actionplan analysis was therefore developed by the Norwegian Pollution Control Authority in 2007 to asses different means of lowering the agricultural climateimpact [14]. This issue was also assessed in white paper 39 [1] and most recently, in "Climate Cure" published by the climate and pollution agency [15].

These publications have however been criticized for having divergent results, implying a lack of knowledge regarding the climate mitigating effect of the different measures they have identified [16]. The White Paper 21 also argue that the estimates of agricultural GHG emissions are in themselves uncertain, especially with regards to emissions of N_2O [17]. It is thus of essence to achieve a better understanding of the environmental impacts associated with agricultural production in Norway, in order to facilitate good decision making.

1.1 Motivation

The White Paper 39 expresses a main goal of reducing the climate and environmental load of agricultural products, per unit produced [1]. By performing life cycle assessments (LCA), insights regarding how to achieve this goal can be obtained. The LCA methodology provides a holistic understanding of agricultural systems by assessing several impact categories associated with the functional unit, independently of which economic sector the emissions occur within [18]. LCAs can in this way provide a stronger basis than sectoral statistics for assessing the possibilities of lowering the environmental impacts across the entire value chain.

There has recently been a growing volume of LCA studies assessing agricultural production pathways. Castanheira et al. (2010), Cederberg et al. (2007) and Flysjö et al. (2011) have all conducted LCA studies on the production of milk [19] [20] [21]. There has also been a few publications concerning the production of grain. These have predominantly focused on the cultivation of the cereal wheat;

Brentrup et al. (2004) identified land use and aquatic eutrophication to be environmental hotspots in their assessment of wheat production, Charles et al. (2006) argue that the quality of the grain should be considered to achieve a more consistent functional unit, while others compare the environmental impact of organically versus conventionally produced grains [22] [23] [24].

The above LCA studies assessing the GHG emissions associated with conventional production of wheat yield results ranging from 303 to 710 kg CO_2-eq/tonne wheat. The divergent results can be explained by differences in system boundaries between studies. It has been shown that indirect emissions of GHG arising from the production of agricultural inputs can contribute with as much as half of the GHG emissions for agricultural crops production [25] [26], and the work of Frischknecht (2007) showed that infrastructure requirements also will contribute significantly to toxicity potential and ionizing radiation for agricultural systems [27]. Some of these studies exclude necessary inputs to the farm or infrastucture-requirements, and thus underestimates the total environmental impact when considering the entire value chain [28]. A more consistent framework for dealing with these inputs would simplify comparisons of results across studies.

Pesticide induced toxicity has previously been confronted as being modeled too poorly within the LCA framework [29] [30]. Pant et al (2004) revealed that the chemical emission models that are commonly used in LCA vary significantly in the characterization factors they produce [31]. Different models have been developed as a response to this in order to achieve more consensus in the estimation of characterization factors for chemicals emissions, such as for instance the USEtox model [32]. The toxicity factors are however still somewhat of a challenge in LCA-studies [33].

The IPCC report that agriculture contributes with approximately 58% of the total antropogenic emissions of N_2O, and has identified N_2O emissions to be the main source of GHG emissions in the agricultural sector [6]. Due to this tremendous impact, it is important that these emissions are modeled with a high degree of certainty. However, as it can be difficult and time consuming to measure these emissions, a standard 0.01 emission factor for N_2O emissions from N inputs have been provided by the IPCC, and this factor is commonly used [34].

The rate of N_2O-emissions from soils are largely region and area specific, as they are influenced by variables such as land cover, soil type, climatic conditions and management practices [34]. A study by Biswas et al. (2008) found that the total GHG emissions associated with the production of 1 tonne of wheat in southwestern Australia decreased by 38% when regionally specific data for soil N_2O-emissions were used, as compared to using the default emissionrate provided by the IPCC [35]. These results makes it apparent that it is of essence to utilise region-specific data for soil N_2O emissions. It is also the advice of the IPCC to use more specific data for N_2O emissions from soil when available [34].

As region specific data can impact the environmental performance of agricultural systems, results can not easily be extrapolated across regions and areas. It is thus of interest to have LCA studies specific to Norwegian agricultural production chains. To benchmark the Norwegian production pathways is important in order to facilitate decision-making and also to be able to assess the performance of Norwegian products as compared to foreign production.

An LCA study is currently in progress which assesses the production of grain at three sites in Norway, performed by Roer et al. at Bioforsk [28]. The study has a large system boundary, and includes both machinery and building requirements as well as impacts associated with pesticides and humus mineralization. This study will be the first life cycle assessment of grain production specific to Norwegian conditions.

There has also been a recent publication regarding GHG emission intensities of crop production in Norway, conducted by Bonesmo et al. [36]. This study provides consistent farm scale data with respect to soil, weather, and farm operations at 95 grain producing farms in Norway. A strength of this study is its evaluation of CO_2 and N_2O-emissions associated with mineralization of soil organic matter (SOM), but it does however not consider the entire life-cycle of grain production systems.

1.2 Objectives

The primary objective of this study is to assess the environmental impacts from production of one kg barley, oat and spring wheat, by means of life cycle assessments. LCA inventories covering different regional and production intensity practices will be developed, by integrating life cycle inventories compiled by Roer et al. (2012) at Bioforsk, with data on soil emission intensities and electricity use at the 95 farms obtained through the study by Bonesmo et al. (2012). In this way, an assessment of the *average* environmental load associated with producing 1 kg grain, as well as *variations* in environmental loads between regions and species can be performed.

The software Arda will be used for all the LCA analysis, using the hierarchical perspective of the ReCiPe method for the impact assessment method. The functional unit in each of the LCA templates is 1 kg of the respective grain specie, at the farm gate. The kruskal wallis test will also be performed on the results, in order to assess both statistically significant differences in environmental loads between grain species, as well as between grain production in the different regions of Norway.

This work is performed in close collaboration with Bioforsk, and this study may be further built upon in a project called "Environmental impact and resource use efficiency of selected food production chains in Norway - a life cycle assessment (LCA) approach", by extending the system boundary to also include the further processing of the grain into bread.

1.3 Content of Study

The remainder of the study will be structured in the following manner;

Chapter 2 will firstly give an introduction to the Norwegian agriculture on a general basis. Further, a review of literature discussing the environmental challenges associated with grain production is included.

Chapter 3 gives an introduction to the life cycle assessment framework.

Chapter 4 contains a description of the compilation of LCI systems used in the present study. Information regarding data inputs and model assumptions are presented here, as well as procedures performed in oder to obtain the results.

The life cycle impact results are then presented in chapter 5, and the main contributors to the various impact-categories are identified. Some brief reflections on the average results and sources of variation in results are also included in this chapter.

Chapter 6 includes a discussion of the results obtained, and the results are compared to external literature. The conclusion of the work is lastly presented.

Chapter 2

Norwegian Agriculture and Environmental Science

2.1 Norwegian Agriculture

Norway has approximately 1 million hectare of agricultural land, of which 31% is used for the cultivation of grain and oilseed crop [13]. The domestic grain-production is approximately 1,2 million tonn per year, which in good years will cover as much as 80% of the Norwegian demand [37] [38].

The land area used for grain production has been decreasing in recent years. This reduction of approximately 30 000 daa per year may however be partially influenced by the transition to a digital map-scheme [38]. The average yield has however continued to increase steadily since 1945 [37]. This has mainly been achieved through improved agricultural procedures with respect to site preparation, fertilization schemes and improved seed selection [38]. As figure 2.1 shows, there are however large fluctuations in the yearly produce. This is strongly related to the varying weather-conditions, which can cause the yearly produce of grain to fluctuate with as much as 50% between years [38].

The topology of Norway is challenging with regards to agricultural practices. Land at high latitudes and altitudes have short growth-seasons, which limits the croptype and yields in such areas. Steep areas are neither suited for agriculture. Large fractions of the area also has a thin soil-cover above the bedrock, or contains too rocky soils to be fit for agricultural purposes [37]. This causes the Norwegian agricultural land to be more fractionated than in other countries, with smaller farms. The average farm in Norway has approximately 7 hectare of land, whereas the average farm size in the EU-15 and the United States are 19 and 170 hectares, respectively [37] [40].

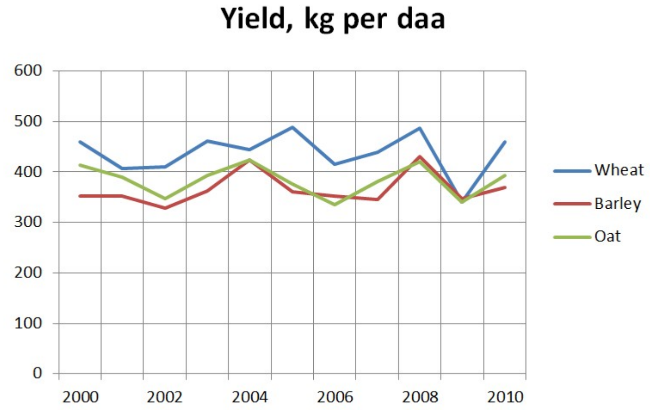


Figure 2.1: The figure shows the yield in kg per daa for the indicated grain species for the last 10 years, based on data provided by Statistics Norway (SN) [39].

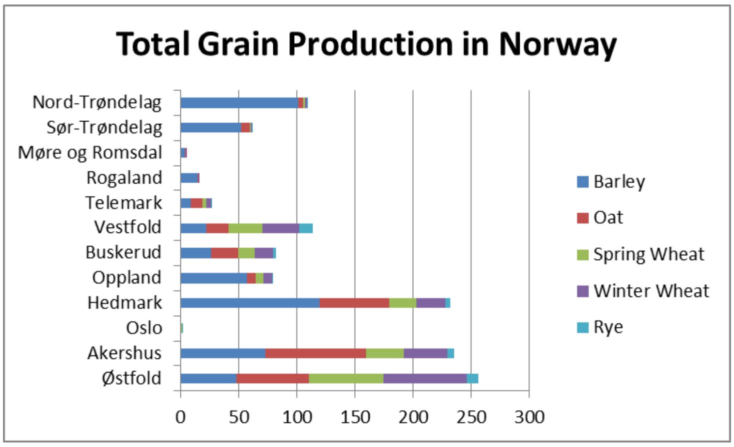


Figure 2.2: The figure shows the county-distribution of crop-production per year, measured in units 1000 tonnes. The graph is based on data provided by the SN, and is the average crop-production per year for the years 2005-2010 [37]

2.1.1 Norwegian Agricultural Policy

Small farming units are associated with less effective production systems and higher costs than larger, more intensive farms [41]. As it can be difficult for Norwegian agricultural products to compete against foreign production, the government has imposed means to protect the domestic food-production. This is done by both a budget support and an import protection. The import protection involves an import duty on agricultural products to be paid as a fixed sum per amount of good, or as a percentage of the goods value, and ensures that the Norwegian agricultural sector can achieve higher prices for their goods on the domestic market than in the international market [42]. The government considers the import protection to be a prerequisite for ensuring a secure appropriation of Norwegian agricultural products and to ensure that the target price level, which is set in the agricultural agreement, is achieved [43]. Values from Statistics Norway (SN) indicate that in 2009, "the import protection constituted 11.1 billion NOK, while the budget support constituted 12.3 billion NOK. The import protection and budget support constituted 66% of the total production value" [37].

As shown in figure 2.2, large fractions of the grain production is located in the southeastern parts of Norway and around Trondheimsfjorden. This is largely due to agricultural policy stimulating the grain-production to be located in the areas best suited for the cultivation with regards to climate and topology, through the governments so-called canalization politics [37].

2.2 Environmental Stressors

Figure 2.3 shows the direct emissions associated with agriculture in Norway, and also their contribution to global warming. CO_2 is the major stressor in terms of total amount released, but due to the fact that N_2O and CH_4 have 298 and 23 times the climate change potential of CO_2, respectively, these stressors have a larger impacts on the global climate than emissions of CO_2 [44].

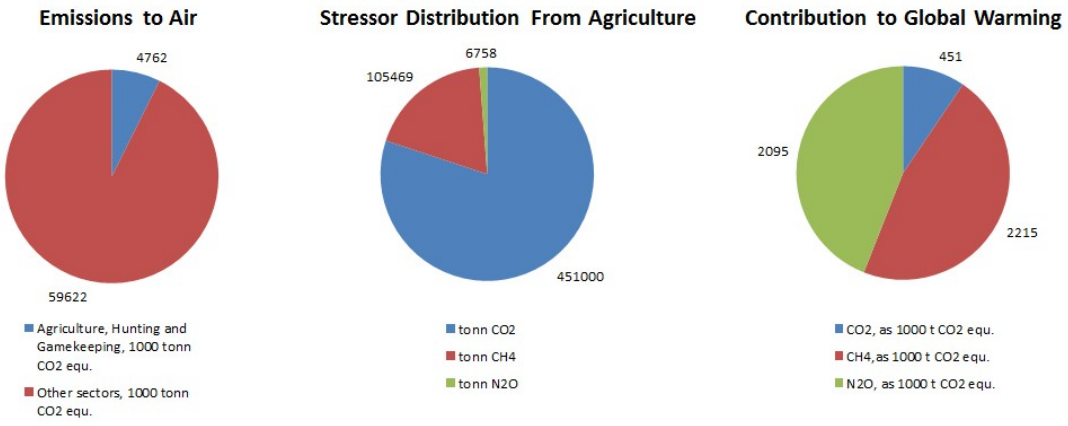


Figure 2.3: The first graph shows the global warming impact of the Norwegian agricultural sector compared to the other sectors, the second graph shows the distribution of stressors emitted from the agricultural sector, and the third graph shows the relative importance of these stressors in generating global warming. The graphs were made based on data provided by SN for the referenceyear 2009.

Agricultural activities are also associated with the potential to cause eutrophication, land transformation and toxic effects [28]. In addition, there are indirect environmental impacts arising from the production of various inputs, such as fertilizer and pesticide production, and through the use of machinery [2] [25]. The following will include a discussion of the environmental implications of the carbon, nitrogen and phosphorous fluxes associated with agricultural production, and will also discuss implications of pesticide use and indirect environmental effects associated with agriculture. As this study focuses on the production of grain, emissions associated with animal husbandry will not be discussed.

2.2.1 Emissions of CO_2

The main sources of CO_2-emissions occurring directly at the farm have earlier been identified to arise from emissions associated with liming, mineralization of soil organic carbon and from diesel consumption [45]. An area of particular interest is the mineralization of soil organic matter. Bioforsk has estimated the carbonreserve in Norwegian agricultural land to be as large as approximately 200 million tons [1]. As mineralization of this carbon results in emissions of CO_2, it is important to understand the cycle of carbon in agricultural soils.

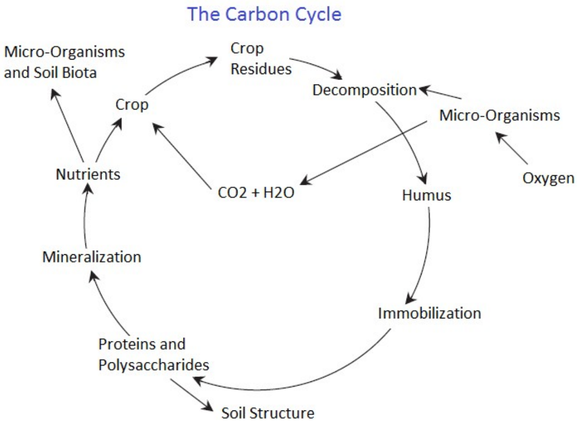


Figure 2.4: The figure shows the carbon cycle for agricultural systems, modified from [46].

As soil organisms use SOM as nutrients, any excess nutrients are released into the soil in a plant available form, in the process called mineralization [46]. Carbon is mineralized in this process. This causes CO_2 to be emitted to the atmosphere, with associated implications for climate change [47]. The carbon-cycle and associated emissions are shown in figure 2.4.

The amount of organic matter in the soils are also an area of focus due to the positive correlation between soil quality and carbon content of the soil [48]. Some of the services provided by SOM are as follows:

A reservoir for nutrients The nutrients are released predominantly in the spring and summer through mineralization, which then benefit the crops [49].

Waterholding capacity Soil aggregates has a positive effect on the soil structure, and increases the waterholding capacity of the soil [50].

Prevention against erosion SOM has also been suggested to help prevent erosion [51], [49].

Soil stabilization Humus stabilizes the soil, by acting as a buffer for fluctuations in soil acidity and nutrient availability [46].

For these reasons, it is important to maintain a healthy SOM content in the soils, but many common agricultural practices accelerate the decomposition of soil organic matter [28] [46]. Such practices include ploughing and tillage [46]. Njøs and Ekeberg (1980) showed that increased tillage depth and frequency diluted the SOM in the upper soil layers of agricultural land in Norway [52].

A study conducted by Riley and Bakkegard (2006) in southeastern Norway, identified the relative decline rate of SOM to be approximately ten percent of the initial percentage per year, for the ten year period the study was conducted [50]. This study also indicated that the SOM level continued to decline until the level of approximately 3% SOM content. Studies in Sweeden and Denmark also indicate that the agricultural soils tend to reach an equilibrium level of approximately 3% SOM-content [53], [54].

There is uncertainty as to which SOM-level will be adequate for maintaining a good soil quality and structure. Riley has argued that the soil stability and water storage capacity will continue to increase up to a SOM level of approximately 6% [55] [56]. Greenland et al. stated that aggregate stability will decline seriously when the SOM level is below 3.4% [57]. Loveland and Webb on the other hand, found little evidence of a general critical SOM threshold when reviewing the literature [58].

It has been estimated that the global quantity of soil organic carbon (SOC) in the 0 to 30 cm layer of the soil is about twice the amount of carbon contained in atmospheric CO_2 [59]. There is therefore, a large interest within scientific and political communities in the possibility of climate change mitigation through increasing this quantity of carbon stored in the soil [60] [61] [48] [62]. For instance, Freibauer et al. estimated that agricultural soils in EU-15 could sequester up to 16 to 19 Mt C per year for the period 2008 to 2012, to be achieved through changes in the management of agricultural soils [63].

Possible Measures to Increase SOM

REDUCED TILLAGE

One of the changes in agricultural practices proposed to sequester carbon in soils is to reduce tillage-rates or no tillage (no-till) [64]. This practice was recommended by several reports published in the last two decades, as minimizing soil disturbance was believed to decreases SOC decomposition rate, which would then also cause decreased transfer of carbon from the soil to the atmosphere [60] [65] [66]. In later times, several articles which are skeptical to whether or not no-till truly increases SOC have been published, and there is thus no clear consensus on the effect of reduced tillage [67] [68] [69] [70]. It has also been argued that the effect of reduced tillage on SOC may be smaller in temperate climates than in tropical environments [71].

Baker et al. (2007) indicated that many studies reporting increased SOC under no-till management had only measured soil C at a depth of 30 cm or less [72]. This can lead to an overestimation of SOC, as bulk density tends to increase under no-till management. If measured at the same depth, a soil with no carbon gain could thus appear to have a gain in mass of C [73]. Under no-till cultivation SOC also tends to be concentrated near the soil surface due to an absence of mixing, which may also lead to SOC overestimation [48].

Some studies have also shown decreased crop yields under no-till management [74] [75]. Ogle et al. found that crop productivity could suffer under no-till management, and that this was in particular the case in cooler and wetter climatic conditions [67]. Other studies however, have identified no such change in productivity, or even an increase in yields, under no-till management regimes [73] [76].

Other issues regarding no-till practices is that seeds are not buried, which can lead to an increased abundance of grass weed species, which implies higher demands on herbicide-use [77]. Soil fungi levels have also been shown to be higher under minimum tillage than ploughed soils [78]. The fungi-genus *Fusarium* can then produce mycotoxins which may decrease yields and also impose a health risk to humans and animals [79]. Norwegian studies have shown a correlation between reduced tillage and increased levels of mycotoxins in the grain produced in Norway [79] [80].

A review by Rochette (2008) concluded that N_2O-emissions would decrease or remain unchanged from conventional tillage in regions with well-drained soil and little rainfall [81]. In wetter environments, such as in Norway, N_2O-emissions increased under reduced tillage as compared to conventional tillage. As N_2O has a global warming potential 298 times larger than CO_2, this increased N_2O can outweigh any possible low-till benefit of increased SOC in terms of GWP under Nordic conditions [48]. No-till implications on N_2O emissions will be further discussed in section 2.2.2.

As this discussion shows, the overall impact of no-till is still under assessment. It does however seem clear that the effect of reduced tillage or no-till must be assessed in the context of soil type and climate, and with respects to more factors than SOC-levels in order to get a holistic answer to the overall effect of this practice.

BIOCHAR

Another possible means of increasing SOC, is though applying carbon to the soil. Manure contains carbon, but a study by Uhlen et al. showed that only 17% of the carbon applied remained in the soil 30-50 years later [82]. In additions, Norway have little livestock farms, and thus available manure, in close visinity to grain producting farms [83]. Another means of applying carbon is therefore under assesment;

Biochar is biomass which is pyrolyzed into charred organic matter, and is receiving attention for its potential for carbon sequestration when applied to agricultural land [84] [85]. As carbon has an estimated residencetime of between hundreds to thousands of years when stored in biochar, application of biochar to agricultural soils will sequester carbon that would have been decomposed and emitted as CO_2 if the plant material had not been pyrolysed [84].

Biochar has also been considered as a potent way of improving soil structure, soil quality and increase crop production [86] [87]. Vaccari et al. (2011) found that biochar applied to soils cultivating durum wheat in a medeterranean climate had a positive effect on biomass production of up to 30%, and showed the viability of carbon sequestration [88].

Biochar might contribute to contaminants accumulating in soils [89], while others are concerned that preemergent herbicides may be less effective on biochar-treated soils [90]. It is also of interest with LCA studies to ensure a carbon benefit over the entire valuechain, when including the production of the biochar [91]. More studies on the effects of biochar on soils in temperate regions is also an area which needs more expertise [48]. The use of biochar does however have an interesting potential for carbon sequestration, and as noted by Powlson (2011), biochar may increase the retention of nutrients and water in soils, which could potentially lower the requirement for N fertilizer application to achieve a given yield, which could then also indirectly contribute to lower GHG-emissions [48].

2.2.2 Emissions of N_2O

Nitrous oxide (N_2O) is a potent greenhouse gas, and according to the IPCC, the climate change effect of 1 kg of N_2O is 298 times that of 1 kg of CO_2 emitted, when considered in a 100 year time-frame [44]. N_2O is emitted from soils and various N inputs, and N_2O is considered to be the most important GHG for agriculture [92]. In addition, N_2O is the single most important ozone-depleting emission [93]. It has been found that arable soils are responsible for approximately 60% of the global anthropogenic emissions of N_2O, and it is thus important to identify means of reducing these emissions [6].

The Haber-Bosch process was invented in the early twentieth century, allowing synthetic nitrogen-based fertilizers to be produced through the reduction of atmospheric nitrogen into ammonia (abiological nitrogen fixation) [95]. This allowed for a dramatic increase in intensive farming, and the development of anthropogenic nitrogen fixation after this invention is shown in figure 2.5. The application of inorganic nitrogen is important to maintain high yields, but it is also widely acknowledged that there is a positive correlation between N_2O-emissions and mineral N fertilizer application [96].

Nitrous oxides are produced naturally by the microbial soil processes nitrification and denitrification [97]. Denitrification is more significant than nitrification in agricultural soils, where N_2O is an intermediate in the reduction of nitrate (NO_3^-) into nitrogen (N_2) [98] [99]:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

This conversion is not always complete, leading to variable amounts of the N to be emitted as N_2O [98]. The main bacteria involved in denitrification are the facultative anaerobic heterotrophs [47].

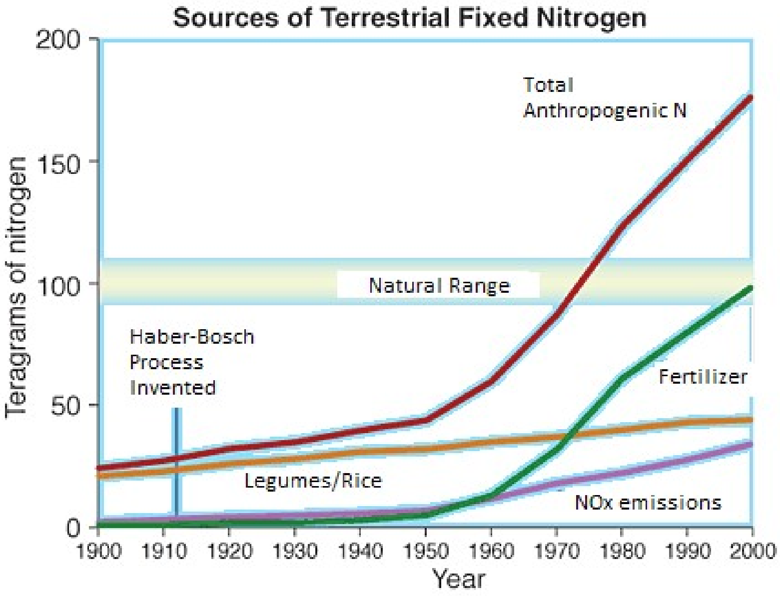


Figure 2.5: The figure shows the development of different sources of nitrogen fixation over time. Modified from [94].

Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) into nitrate (NO_3^-), and nitrous oxides may be produced as a byproduct in this process [96].

NO_3^- is highly mobile and is readily available for plants, NO_3^- is therefore often the major form of N uptake [98]. However, as stated by Subbarao et al (2006), nitrate is also susceptible to losses through leaching and through conversion to gaseous forms [100]. Approximately 5 million tons of N fertilizer were applied for global cereal production in 1996, while the worldwide nitrogen use efficiency for cereal production is only approximately 33% [101]. Figure 2.6 shows N-flows associated with agricultural systems.

The IPCC tier 1 method assumes that 1% of the applied N is emitted as N_2O [34]. This means that 1 kg of N applied is equivalent to 4.65 kg CO_2 emitted in terms of global warming potential [98]. This estimate is however subject to uncertainties, as several environmental factors will causes N_2O emission intensity to vary in space and time [102] [103] [104]. These factors include "soil temperature, soil moisture, soil NO_3^- and NH_4^+ concentrations, and the availability of organic C substrate to micro-organisms" [2]. N_2O-emissions thus vary during the year, and the largest fluxes often occur after fertilizer application [26]. There are also uncertainties as to whether or not it is appropriate to use the emission factor when the crops receive more N than what is required to obtain maximum yields, as emission-rates are not linear to N application under such conditions [105].

Different means of reducing N_2O-emissions from agricultural soils are being

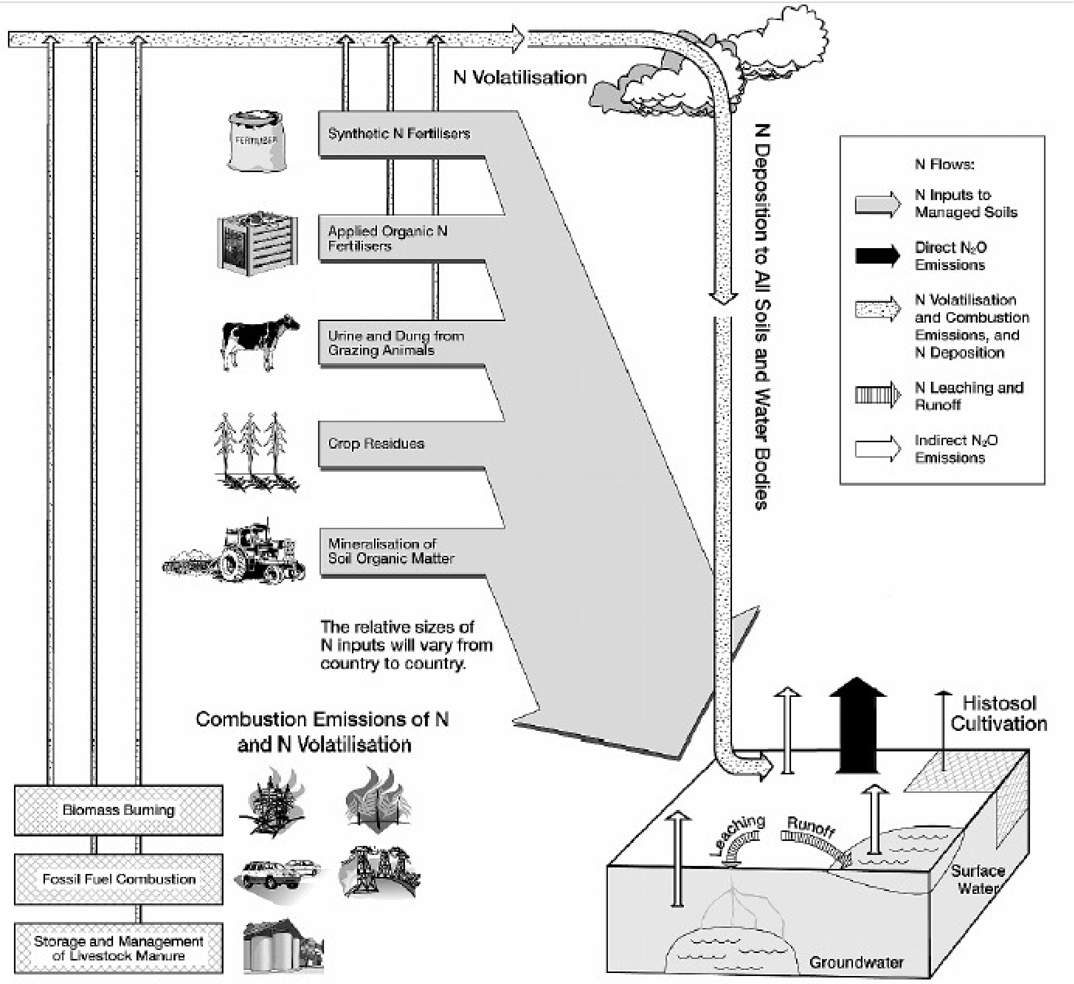


Figure 2.6: Graphical representation of direct emissions as presented by IPCC [34].

discussed. Improved drainage has been identified as one method for lowering N_2O emissions, as this ensures that the aeration in the soil is maintained, even at times with heavy rainfall [106]. Irrigation practices which avoids application of excess moisture can also help minimize N_2O-emission rates [107] [108]. These practices can however, also cause an increase in CO_2-emissions from soils with high contents of SOM [1].

The liming of soils in Norwegian experiments has been reported to reduce N_2O emissions through maintaining an optimal pH level in the soil, but this practice also has a trade-off with associated increases in soil CO_2 emissions [1].

Other proposed means of reducing N_2O emissions from the field is to use urea instead of ammonium nitrate, which has been reported to hold a 50% reduction-potential in N_2O-emissions [109]. This practice can however negatively impact the yield [109].

Precision agriculture are associated with variable rates of application of agricultural chemicals, especially fertilizers [110]. By the use of such technology, more costeffective use of inputs can be achieved, and could help to lower N_2O-emissions to air and waterbodies, as less NO_3^- would be left over in the soil profile [111] [112].

The compaction of soils, for instance through the use of agricultural equipment such as tractors, can reduce the aeration under moist soils [113]. A study by Mosquera et al (2007) found that slight to severe compaction can cause N_2O emissions from the soil to increase by 20-100% [114]. Some report lower N_2O emissions under no-till management [115] [116], while others report greater emissions in soils under no till management than soils being tilled [81] [117]. The variable results can be due to factors such as soil density and watercontent; there have been reports of higher denitrification rates in soils with higher bulk density and water content [106] [118], and the effect of soil compaction on N_2O emissions have been reported to be higher in clay soils than in sandy soils [114].

It has been found that winter N_2O emissions may exceed 50% of the annual emissions [119] [120]. These higher emissionrates may be due to a high product ratio in denitrification and nitrification at lower temperatures [99] [121]. During the winter, N_2O can also be physically trapped in the soil, and this can cause a pulse of nitrous oxide to be emitted shortly after thawing [122] [123]. At this time, the soil often has a high water content, which also enhances denitrification, though increased anaerobic volumes. In addition, "water-soluble organic materials released from frost-sensitive catch crops and green manure may further increase winter emissions" [99]. Other sources however, states that the highest fluxes of N_2O emissions are associated with fertilizer application [36].

The total emissions of N_2O are uncertain, and constitute 80% of the uncertainty in the total Norwegian GHG accounts [1]. Measurements of N_2O emissions in the fields are often measured to be lower than what is derived from the global N_2O budgets, and fluxes from the atmosphere to the soil are neither well understood [124]. Some results indicate that the IPCC factor for N fertilizer emitted as N_2O should be larger [125], or lower [35], and there is a general concensus that further study on N fluxes associated with agriculture is needed [1] [124].

2.2.3 Nitrogen Leaching and Runoff

"Some of the inorganic N in or on the soil, mainly in the NO_3^- form, may bypass biological retention mechanisms in the soil/vegetation system by transport in overland water flow (runoff) and/or flow through soil macropores or pipe drains" [34]. Nitrate leaching is determined by nitrate concentration in the soil, as the NO_3^- present in excess of biological demand will move down through the soil profile [47]. Nitrate leaching is most severe under conditions of minimal plant uptake, and when rainfall is high [126].

In Norway, the effect of nutrient leaching from agricultural land on water-quality has been an important issue since the 1980s. The environmental degradation of coastal zones and open waters, such as observed in the north sea, caused the national authorities to introduce an actionplan to reduce the nitrogen and

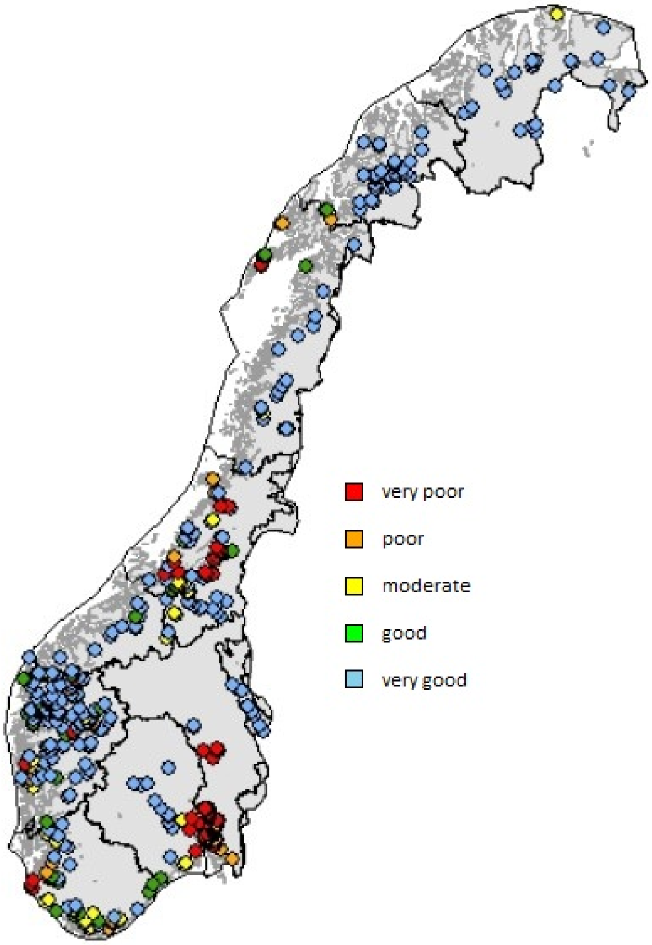


Figure 2.7: The figure shows the state of eutrophication in Norwegian rivers, based on yearly averages of nitrogen-content for the period 1998-2008, as presented by NIVA [127].

phosphorous losses from agriculture. This was to be achieved through improved use of commercial fertilizers and animal manure, and by reducing the transport of nutrients, for instance by reducing autumn tillage [128]. The EU has set a quality theshold of 50 mg nitrate per litre of water [11]. Today, 34% of the monitoring stations in the EU show increasing levels of nitrate pollution, and 15% have nitrate concentrations above the set theshold [11]. This is of concern, as high nitrate levels have healtheffects on humans and also affects ecosystem functioning;

Excessive levels of nitrate in drinking water can cause methaemoglobinemia, which is reduced levels of hemoglobin in the blood [129] [130]. The leaching can also cause eutrophication; enrichment of waters by nitrate can cause an accelerated growth of algae and higher forms of plant life, in particular in combination with increased phosphorous levels, as these are often limiting factors in aquatic systems [131] [132]. Such lakes may be depleted of oxygen, particularly during periods of thermal stratification, when decomposing organic matter accumulates and consumes oxygen [133]. This again causes an undesirable disturbance to the balance of organisms present in the water, and to the quality of the water, in the worst case killing species of higher-order aquatic species [132]. Figure 2.7 shows the areas of rivers with high eutrophication in Norway. This figure shows that the areas associated with agriculture production in Norway generally tend to experience higher eutrophication in associated rivers.

Factors such as soil type, precipitation and nutrient inputs influences the risk of nitrate leaching [134]. The climatic conditions of Norway, characterized by relatively mild winters and surplus winter precipitation, makes the arable soils vulnerable to nitrate leaching if the soil is left uncropped [135] [136]. This may in particular be the case for lighter textured soils, and well drained soils [136] [126]. Results from both field and modeling studies have shown larger leaching losses in fields with course-textured sand than in fields with heavy clay soils, as these have lower water-holding capacities [136] [137], while good drainage enhances the transfer of nitrogen and other compounds, such as pesticides, to watercourses, and thus enhances nutrient losses [138]. It thus seems that conditions which are optimal for lowering N_2O emissions can cause larger N-leaching rates:

$$\text{Sandy Soil} + \text{Good Drainage} \rightarrow \text{Favours N-leaching}$$

$$\text{Clay Soils} + \text{Poor Drainage} \rightarrow \text{Favours N}_2\text{O-emissions}$$

As stated by Borgen (2011), "The most significant mineral N sink in the system is the uptake by growing plants; hence, the leaching potential is largest when plant growth is interrupted, at harvest or by tillage" [47]. This can cause bursts of N mineralization, as the plants do not assimilate mineral N, and also due to the fact that aggregates are broken down by microbial activity at such times [139].

One means of reducing leaching losses of NO_3^- can be through the use of catch crops [140]. The most common catch crop in Norway is grass species, which is sown together with the grain, and thrive after the grain has been harvested [1]. The catch crop will then absorb nitrogen and phosphorous dissolved in the soil, and thus lower the runoff-rate [141]. The risk of loosing the nitrogen stored in this catch crop is assumed to be low, as mineralization and turnover is assumed to be slow in temperate, cool climates [142].

Nitrate leaching is most severe under conditions when rainfall is high [126], and the use of precision farming and appropriate time of plowing can help reduce nitrate runoff [47] [143].

2.2.4 Phosphorous Leaching and Runoff

Phosphate fertilizers are produced from igneous and sedimentary phosphate rock, and approximately 90% of the phosphor processed is used in agriculture [45] [144]. A part of the applied phosphor will be lost to waterbodies through leaching, runoff and soil erosion, which again may cause eutrophication, as phosphor has been identified as the main limiting factor for eutrophication in most European aquatic ecosystems [10][96].

Phosphorous losses are connected with gross soil losses, and erosion is in particular a problem in the south-east of Norway [45] [41]. Phosphorous is transported to rivers in association with fine sediments, and Uhlen et al. (2007) report that "total phosphorous loads from agricultural areas in Norway vary from 0.2 to 2.6 kg ha^{-1} $year^{-1}$ for cereal and grassland areas" [145]. Bechmann and Våje (2002) found large variability in erosion and nutrient loss rates among the ten basins they investigated; "annual P losses varied from around 0.4 kg ha^{-1} in basins with low erosion to around 4 kg ha^{-1} in basins with high erosion and high livestock density" [146]. This P contribution to lakes have caused several lakes in Norway to become eutrophic, such as for instance Vansjøen [147].

The south-western parts of Norway are dominated by silty soils, while clay soils are common in south-eastern Norway, and both these soil types have a high risk of erosion and phosphorus losses [145] [148]. Clay soils are often poorly drained, which can lead to subsurface drainage with associated phosphorus loss [145]. Good field drainage systems can also enhance phosphorus delivery to waters [10]. As discussed in section 2.2.3, one means of lowering particulate P leaching is by growing catch crops [141]. Appropriate application of fertilizer is also an important way to reduce losses of soluble reactive P, especially for sandy soils [148].

Norway has a political target of lowering the phosphorous load in the north sea by 50%, and subsidies and direct payments are used as incentives to achieve this goal [41] [145]. For instance, subsidies are given for reduced autumn tillage, at rates depending on the erosion-risk in the given area [145]. The norm for phosphorus fertilizer application for grain production has also been reduced by 30% in recent years, and is now at rates of 1.4 to 1.75 kg P/daa, depending on the graincrop cultivated [149]. Results from Bechmann and Stålnacke (2005) suggest that subsidies and mitigation measures are useful for reducing P lossrates [150]. Uhlen et al. (2007) also report that "losses have declined in Norway and Sweden as a result of measures to control them" [145].

2.2.5 Pesticide Use

A pesticide has been defined as "any substance or mixture of substances intending for preventing, destroying, repelling or mitigating any pest", and different kinds of pesticides are applied to the crop in order to protect it [96].

The pesticides are applied with the main intent of controlling the population of pest species, but are of environmental concern due to their ability to affect species other than their target [151] [152]. A well known example of this is the eggshell thinning effect of DDT on raptorial and fish eating birds, which lead to DDT being the first pesticide under regulation [153]. Another example is the evidence that pesticides have affected bee-populationsize through airborne drifting, which also illustrates the ecological impacts pesticides can have outside the target area [154]. Most pesticides are also defined as persistent, organic pollutants (POPs), which are known for their ability to bioaccumulate [153]. The food supply for higher taxa can also decrease as the invertebrate populations are reduced within agricultural landscapes [126].

The major groups of pesticides have also been reported to have carcinogenic effects, demonstrated through the increase in cancer frequency in animal, cell cultures and epidemiological lines after exposure to various pesticides [12]. The WHO is also concerned about the toxicity and persistence of long-term exposure to low doses of organochlorine insecticides and organophosphates, as this can cause poisoning [155]. The environmental effects of pesticide use thus impose an optimizationproblem; how to lower the use of pesticides while at the same time securing sufficient yields?

2.2.6 Indirect Emissions

In addition to direct emissions occurring at the farm, there are indirect emissions associated with the production of agricultural inputs. The production of for instance fertilizers, pesticides, fuel and machinery used at the farm can contribute with as much as 50% of the total green house gas emissions [25] [26]. One of the benefits of using the LCA methodology is that such impacts will be accounted for, by including the entire lifecyle for the production of a functional unit.

Chapter 3

LCA Theory

”The objective of a Life Cycle Assessment is generally to perform consistent comparisons of technological systems with respect to their environmental impacts” [156]. In order to achieve this, an LCA considers all aspects of a product system life cycle, including production, distribution, use and disposal. In order to perform life cycle analysis (LCA), the inputs, outputs and environmental impacts of a product system must be compiled and evaluated. The International Organization for Standardization (ISO) has provided a framework for this procedure in the ISO 14040 series [157]. The four phases of an LCA and the respective ISO standards are shown in figure 3.1. The following will give a short introduction into these stages, as well as the mathematics involved with performing an LCA.

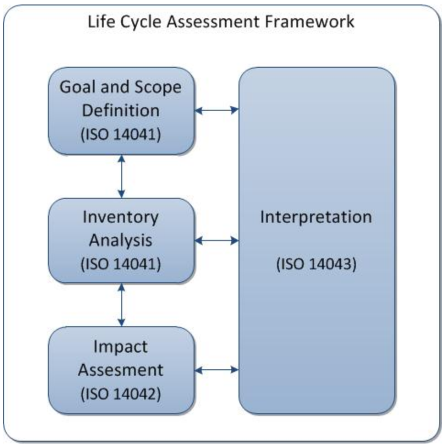


Figure 3.1: The four main stages carried out in an LCA study.

3.1 Goal and Scope Definition

The goal and scope definition stage defines the study. The goal definition should include the intended application and the motivation for carrying out the study.

The scope definition should define the production-system, the functional unit and the system boundary. This includes depicting the allocation procedures used, and the assumptions and limitations of the study.

"The functional unit is the quantified performance of a product system for use as a reference unit" [157]. The functional unit should be consistent with the goal and scope definition, and it must be clearly defined and measurable. This is necessary to ensure the comparability of LCA results [158].

3.2 Life Cycle Inventory Assessment

In the life cycle inventory (LCI) assessment stage the needed data for establishing the requirements and stressors associated with the production system is collected [157]. The material and energy inputs and outputs of the processes must be collected, as well as data on emissions generated. Some of the processes in the system may have multiple outputs, and may therefore require allocation between the multiple outputs.

The LCI is usually divided into two subsystems, which are called the foreground and background system. The foreground system will generally consist of data compiled specifically for the given study, while the background system consists of generic database processes [156].

It can be quite labor intensive to gather the data for the foreground system, it is however important to gather study-specific data to ensure a reliant analysis. It is preferred that a large fraction of the impacts associated with the product-system are generated in the foreground processes [156].

3.3 Impact Assessment

The life cycle impact assessment (LCIA) stage is defined as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product– [157]. The LCIA will result in impact categories, which can be either at midpoint or endpoint level.

To calculate the midpoint indicators, different emissions are assigned to different impact categories. For instance, CO_2 and CH_4-emissions are assigned to the category "climate change". The emissions are then weighted according to their expected impact on the environment by the use of characterization factors. The impact category "Climate Change Potential" is expressed in the unit CO_2-equivalents, where CO_2 and CH_4-emissions have the characterization factor 1 and 23 respectively, using a 100 years perspective [159].

Endpoint indicators are calculated by further processing of the midpoint indicators into damage categories. For instance, the category ”Damage to human health” is measured in disability adjusted life years, and would include, among other midpoint categories, the effects global warming will have on human life.

By translating the midpoint impacts to endpoint units, more uncertainty is added to the impact assessment. These endpoint may however be easier to interpret, especially for stakeholders with little knowledge of the LCA-methodology [160].

The ReCiPe midpointindicators with a hierachical perspective will be used in this study. The hierarchist perspective assumes that impacts may be avoided with proper management, and the choice on what to include in the model is based on the level of scientific consensus [161]. In the current study, the following ReCiPe midpoint indicators will be considered ([162]):

Climate Change Potential (CCP) kg CO_2 eq. To air, global. Expresses the ratio between the increased infrared absorption due to the instantaneous of 1 kg substance and that due to an equal amount of CO_2, integrated over time.

Toxicity Potential kg 1,4-DB eq. Assesses the effects of emissions of toxic substances. The ReCiPe-method offers 4 categories which assess the toxicity to human, terrestrial, marine and freshwater environments.

Eutrophication Potential kg P eq. (freshwater) and kg N eq. (marine). Assesses the potential compounds have to cause algal bloom in waterbodies.

Photochemical Oxidant Formation kg NMVOC. Considers the formation of ground-level ozone, also known as summer smog.

Terrestrial Acidification Potential kg SO_2 eq. Considers the acidifying effects pollutants may have on ecosystems. The major pollutants in this category are SO_2, NO_x and NH_x which may cause acid rain.

3.4 Interpretation

In the interpretation stage the results are evaluated in relation to the defined goal and scope [157]. They may also be subjected to a sensitivity analysis. The results are discussed before a final conclusion is drawn.

3.5 LCA-Mathematics

Table 3.1 gives an introduction to the variables commonly used in LCA. In the interindustry requirements matrix, A, each term a_{ij} shows how much of product i is necessary to produce one unit of product j. Therefore, the A matrix can be seen as a recipe book, where each column contains the requirements for producing one unit of the process in question.

Table 3.1: List of variables used in Life Cycle Assessment

Symbol	*Description*	*Dimensions*	*Determined by*
A	Interindustry requirements matrix	pro*pro	
I	Identity matrix	pro*pro	
y	Final demand vector	pro*1	
S	Stressor matrix	str*pro	
C	Characterization matrix	imp*pro	
L	Leontief Inverse	pro*pro	$L = (A - I)^{-1}$
x	Output vector	pro*1	$x = (I - A)^{-1}y = Ly$
e	Total emissions vector	str*1	$e = Sx$
E	Total emissions by process	str*pro	$E = C\hat{x} = C\hat{Ly}$
d	Total Impacts vector	imp*1	$d = Ce$
D	Total Impacts by process	imp*pro	$D = CE = CS\hat{x}$

The x-vector describes the production output in each node, which is equal to the intermediate demand plus the external demand:

$$x = Ax * y \tag{3.1}$$

This can be rearranges into

$$x = (I - A)^{-1}y = Ly \tag{3.2}$$

where L is called the leontief inverse. The coefficients in L show the amount of output of process i that is required per unit *final demand* of process j.

A given column in the stressormatrix, S, shows the stressors associated with one unit of output of the process in question. Examples of stressors may be land use change or emissions of CH_4. The total stressors associated with a given external demand y, the e matrix, can be calculated by using the S matrix:

$$e = Sx \tag{3.3}$$

The characterization matrix, C, contain "characerization factors which allow us to convert emissions of different substances with the same type of environmental impacts into equivalents" [156]. The midpoint or endpoint indicators can now be calculated by using the appropriate characterization matrices:

$$d = Ce \tag{3.4}$$

It may be of interest to find the stressors and impacts associated with the different processes in the system. This can be done by calculating E and D respectively, by using the formulas shown in table 3.1.

3.6 The Benefits of LCA

LCA is a systematic and comprehensive methods for the assessment of the environmental impacts of technologies, and is beneficial in its inclusion of the entire valuechain [163]. By using the LCA framework, a more holistic understanding of the system's emissions can be achieved, and one avoids focusing on single life-phases of the product, such as the use-phase [156]. The results can be used for comparative or improvement purposes [35]. The results can also be further used to identify the key events in the lifecycle where the environmental impact may be lowered in the most effective way [19].

Chapter 4

Model and Case Description

To make this study as transparent as possible, the most important steps of the system-modeling will be described in this chapter. This includes describing input parameters and the assumptions that have been made. The generic inventory used for the production of 1 kg of grain is also presented.

This study assesses the environmental impact associated with the production of grain at 94 farms located in Norway. Four grain crops are assessed: barley, oats, winter wheat and spring wheat. The inventories for each of the grain species at each farm, totaling 215 inventories, were compiled by integrating life cycle inventories compiled by Roer et al. at Bioforsk, with data on soil emission intensities and electricity use at the 94 farms obtained through the study by Bonesmo et al. (2012), within the so called HOLOS project, which is a collaboration between Norwegian University of Life Sciences (UMB) and the Norwegian Agricultural Economics Research Institute (NILF).

The functional unit in each of the LCA templates is 1 kg of the respective grain specie, at the farm gate. The inventory begins after harvest of the preceding crop and ends after the harvest and drying of the crop in question. The assessment covers processes from cradle to farm gate and includes all activities on the farm related to grain cultivation. The inputs required for production, such as diesel and oil, fertilizer, lime, seeds and pesticides are included, as well as the acquisition of machinery, equipments and buildings.

4.1 Data From the HOLOS Project

The HOLOS project has resulted in a model for calculating the GHG emissions at farm-level, with the main purpose of being used as a decicion-support tool for lowering GHG emissions [164]. The project has collected data on the farms natural resource base. This is an important advantage of their study, as the emissions associated with mineralization of soil organic matter, which has

Table 4.1: The table shows the number of sites for cultivation of the different crop recorded in the HOLOS project. The counties are also assigned to 3 different"areas", which will be further discussed in section 4.2.

County	*Area*	*Barley*	*Oats*	*W. Wheat*	*S. Wheat*	*Total*
Akershus	3	11	13	7	6	37
Buskerud	3	7	10	5	10	32
Hedmark	2	11	6	2	6	25
Nord-Trøndelag	1	10	3			13
Oppland	2	6	1		1	8
Sør-Trøndelag	1	4	2			6
Telemark	3	1	2	1	1	5
Vestfold	3	9	7	4	12	32
Østfold	3	11	17	15	14	57
Total		70	61	34	50	215

previously been shown to be the main contributor to climate change impacts, are largely region and area specific. This study thus provides the strong basis necessary in order to assess *variation* in environmental impacts between Norwegian crop producing farms. The following gives an overview of the data the current study have used from, or modified from, the HOLOS project, and an introduction as to how the HOLOS project calculated these values, as well as possible limitations of the data.

The HOLOS project have data from 95 farms, located in 47 different townships (kommuner). Several farms grow more than one type of grain, resulting in a total of 219 individual crop specific units. 4 of these were ecological grain production, and these were excluded from the present study. This was done in order for the results to unambiguously reflect the impact of conventional grain production. The size of the fields used for the grain cultivation were also based on HOLOS values. Table 4.1 shows the number of farms producing the respective types of grains split according to which county the farm is located within.

The HOLOS project is of particular interest to the current study due to its resolution in parameters varying with local conditions at the farms. Soil survey records for the farms were provided by The Norwegian Forest and Landscape Institute. This included data on layer depth, texture of particles < 2 mm, organic matter content, gravel and bulk density. Detailed data on weather conditions at the farms were also obtained from the daily weather data from the network of The Norwegian Meteorological Institute for the year 2008. The data were interpolated to the geographic midpoint and altitude of each farm, to obtain diurnal mean temperature, relative air humidity, wind speed, cloud cover and precipitation. Estimates for potential evapotranspiration and soil moisture conditions were also calculated. The work performed by HOLOS on obtaining these farm specific data on weather and soil conditions is considered to be an asset for the present study, as regional variation can significantly influence the results of grain LCA studies.

The estimates of soil carbon change were based on the Swedish Introductory Carbon Balance Model (ICBM) [165]. The model requires three variables; crop residues input, humification factor, a combined index of external influences, and two decay constants for old and young soil carbon, which are applied over a 30 year period. Soil moisture and soil temperature will affect the decomposition rate, and weather data for the year 2008 was used for the calculations. As weather conditions can vary significantly between years in Norway, it must be regarded as a weakness that weather data for only 1 year was used in the model for all thirty years. Farm specific input variables are also based on values for the reference year 2008.

The emissions of nitrous oxides are based on the IPCC tier 1 emission factor, which assumes that 1% of the nitrogen applied will be emitted in the form of N_2O [34]. This emissionrate has however been further modified to consider regional variations in emission intensities. As discussed in section 2.2.2, emissions are affected by soil temperature and soil moisture, and the effect of these variables were included by considering the water filled pore space (WFPS) in the top soil, and the soil temperature at 30 cm depth (ts30). The calculations were based on a model developed by Sozanska et al (2002) [166], resulting in the following linear regression equations;

$$\text{WFPSI} = 0.4573 + 0.01102 * \text{ WFPS} \tag{4.1}$$

$$\text{ts30I} = 0.5862 + 0.03130 * \text{ ts30} \tag{4.2}$$

where WFPSI and ts30I are the relative effects on N_2O emissions. As the emissions vary throughout the year according to climatic conditions and fertilizer application, WPSI and ts30I were also further broken down to reflect the variation between the four seasons. The resulting equation for calculating N_2O emissions from N inputs thus become;

$$N_2O - N(\text{kg ha}^{-1}\text{year}^{-1}) = \sum_{i=1}^{4} 0.01 * (\text{Ntot}_j) * (\text{WFPSI}_j) * \text{ts30I}_j \tag{4.3}$$

On further analysis of the N application rates reported in the HOLOS-project, it was found that the average N application rate was 136 kg N/ha. This is larger than the reported 109 kg N/ha which is the average for grain production in Norway [1]. The HOLOS project used economic data from the year 2008 to estimate application-rates, without taking into consideration that the entire quantum purchased might not be applied that respective year. In fact, in the fall 2007, the international fertilizer prices were beginning to rise. As Norway had significantly lower prices compared to the world market, Yara speculated that the farmers were hoarding fertilizers this year to save money [167]. 116 000 tonnes of fertilizers were sold this year, as compared to 80 000, 82 000 and 96 000 tonnes the three following years [167]. It therefore seems likely that hoarding indeed took place this year, and it is therefore of concern that the HOLOS project assumed that all purchased fertilizer was applied within the respective year. As these data thus seem unrealistic, it was chosen to use data on fertilizer rates obtained from the bioforsk project instead. Although this involves lower resolution, the extreme values observed for some of the farms in the HOLOS dataset will be avoided.

Equation 4.3 was therefore updated in the current study. Ntot_j was replaced by data from the Bioforsk data, while the influence of local conditions was kept from the HOLOS project. By doing this adjustment, the average emission intensity of N_2O caused by nitrogen application was reduced from 4.1 to 3.9 kg N_2O/ha. By doing this procedure, the current study obtained data on N_2O emissions adjusted for regional variation and nitrogen application rate.

HOLOS provided data on the individual farm costs of fuel, which they had distributed onto farm area. The electricity use per hectare could thus be calculated as this price divided by the average consumer price of electricity. The average price of electricity was obtained from SN, and set to 89.3 øre/kWh for the year 2008 [168].

In the HOLOS project, data on yield at the farms are based on economic data from the Norwegian Farm Accountancy Survey (NILF) for the year 2008. As the conversion from monetary to physical flows will introduces uncertainties, it is of interest to do an assessment of how the yields reported compare to the average yields in the county. The average yields for the counties with grain production in Norway was therefore calculated based on SN statistics, over the 6 last years. It was found that most data in the HOLOS dataset, more than 65%, lie within the range ± 20% of this average yield. It is expected that the yields in the dataset will vary around the average value. The largest difference was however 63% higher than the average, found for spring wheat grown in Telemark. This issue will be adressed in section 4.3.1.

It was only within the scope of the HOLOS project to consider emissions occurring at the farm, and the project thus does not have a life-cycle perspective regarding emissions associated with grain production. The study also only assessed one environmental impact; climate change potential. By integrating the work performed by bioforsk on establishing life cycle inventories for grain production, these shortcomings can be overcome.

4.2 Data From Bioforsk

Bioforsk is currently working on a project funded by the Norwegian Research Council, with the title "Environmental impact and resource use efficiency of selected food production chains in Norway - a life cycle assessment (LCA) approach". In this project, the environmental impacts and resource use efficiencies related to food production in Norwegian agriculture will be assessed by considering the production of bread, milk and selected bovine meat [45]. The LCA inventories regarding the production of the following grains at three locations in Norway have already been established within this project;

- Barley and autumn wheat production in Trøndelag [45]
- Barley, oats and spring wheat production in Stange [169]
- Barley, oats, spring wheat and winter wheat production in Follo [170]

For each of the areas, a farm representing the ”typical” cereal producing farm was identified and used for establishment of the life cycle inventories. The farm within the region which best fulfilled the following criteria was chosen to represent the model farm;

1. The farm should lie on the dominant soil type in the area
2. Crops grown on the farm and their relative distribution should correspond fairly well with the average of the cereal farms of the region
3. The farm should have a size close to the average

The system is described in terms of resources and management using local advisory recommendations, and will thus reflect the variation between regions in Norwegian crop production. The field work processes included in the inventories are ”ploughing, levelling with simultaneously stone picking, combined sowing and fertilization, drumming, first spraying (herbicides and insecticides), split fertilization, second spraying (fungicides and growth regulation), threshing (including cutting of straw) and spraying against couch grass in autumn after harvest (every third year)” [28]. The inventories also include liming of the soil, which is assumed to occur every 8th year, and drying of the grain down to a moisture content of 15%. A schematic drawing of these processes is shown in figure 4.1.

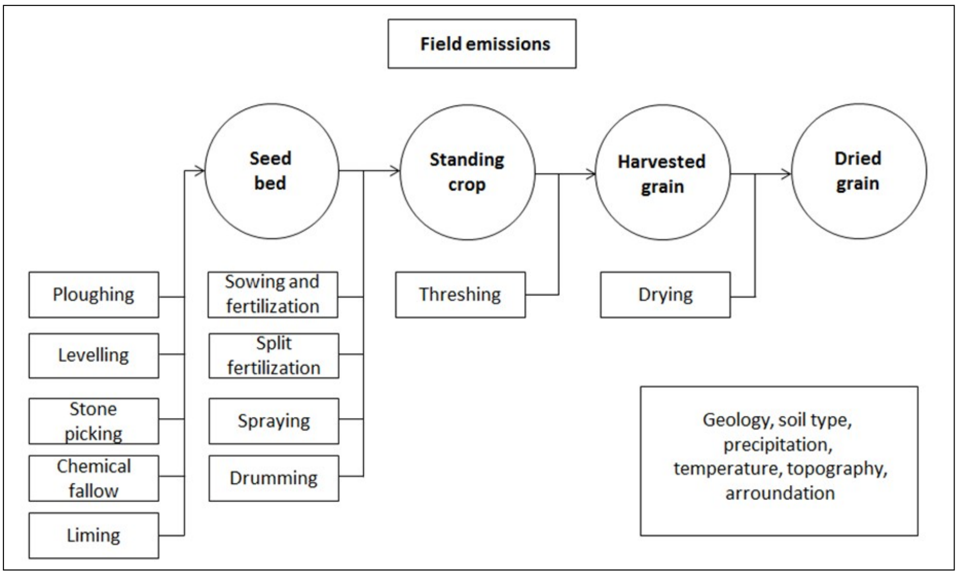


Figure 4.1: The figure shows a schematic presentation of processes and products and their relationships in the life cycle inventory for a typical grain producing farm. The figure is taken from Roer et al. (2012) [28].

In alignment with the recommendation of the ISO standard on life cycle assessments [157], not only the use-phase, but also the production and acquisition of equipment, diesel and oil, fertilizer, lime, seeds and pesticides were included in the inventories. A strong advantage of the inventories established by bioforsk, is that they also consider the manufacturing of buildings and machinery required to perform the farm operations. Although it is recommended that capital goods should be included when assessing the climate change impacts and toxic effects of farm operations [27], such requirements have often been neglected in life cycle inventories, as addressed in section 1.1.

The buildings included in the inventories are a location for drying the grains with size 200 m^2, and a shed, size 300 m^3, for the machinery, both assumed to have a lifetime of 30 years. The production of equipment required at the farm is also included in the inventories. This equipment includes reversible plough, leveller, loader, stone rake, seed drill, roller, sprayer, disc spreader and a trailer.

"Machinery included three tractors of different age and size (5 yrs/90 kW, 15 yrs/60 kW, 35 yrs/45 kW) and a combined harvester (15 yrs/95 kW) (...) For the tractors and thresher, lifetime was set to 15 years, somewhat longer than that suggest in Ecoinvent (12 years), since this was assumed to be more realistic for this type of farm" [28].

Operation-time of the machinery, as influenced by the transport length between the machine shed and the fields, will have implications for emissions related to diesel use. The expected fuel consumption at the three model farms has been based on the average transport distance, found by weighting the distances from the farm to the center of the fields with the respective field sizes. Bioforsk has also calculated the diesel and lubrication oil requirements for all field work processes by modeling the number of man hours needed to perform the various operations with the available equipment under the given conditions, while also considering the workload associated with the work. Please refer to Henriksen and A. Korsæth (2011) [45] for further information regarding these calculations.

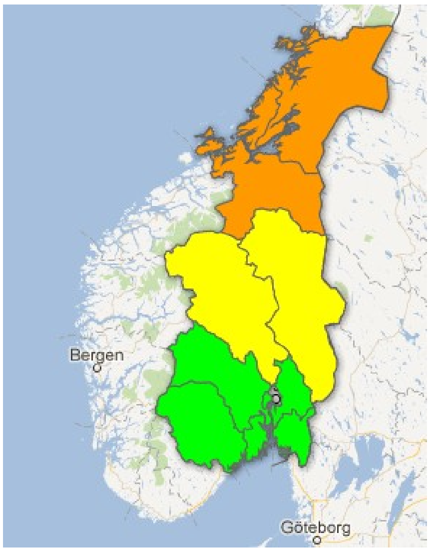


Figure 4.2: The figure shows the three geographical areas used to assign data from Bioforsk. Throughout this report, the orange area will be called area 1, yellow area 2, while the green area will be called area 3.

Table 4.2: The table gives an overview of the matlab scripts made in the current study.

Filename	*Description*
Read Inn	File for reading in data specific to the farms or graintype from excel
Templatemaker	Calculates required variables and makes the LCA templates
Arda Robot	Runs the templates automatically in Arda, and saves the results as .mat
Result Management	Formats and rearranges the 215 results
Average Yield	Calculates the average yield and production over 6 years in Norway

Some input data in the bioforsk project are constant in all the three inventories across both grain specie and location. The data that vary between the three studies performed by bioforsk will be used by assigning each of the HOLOS farms to a region, according to the areas shown in figure 4.2. The Trøndelag inventory will represent farms located within area 1, the Stange inventory will represent area 2, while the Follo inventory will represent farms within area 3. Some variables from the bioforsk project vary both with area and grain specie. These variables are listed in table B.1, and concern fertilizer and optikas use, as well as transportation by tractor and tresher. P runoff and lime application is assumed to be independent of grain-specie, and thus only vary according to the location of the farm. These variables are shown in table B.2. The variables assumed to only vary according to grain specie are associated with the production and use of various pesticides, as well as variables used to calculate the nitrogen content of crop residues. Please refer to table B.3 for further details on these values. Seed requirements per ha were assumed to be 200 kg/ha for barley, based on Trøndelag and Stange data, while the remaining cereals were assumed to require 230 kg seeds/ha, based on Østfold-data.

The inventories collected by bioforsk does not have data on winter wheat production in Stange. The variables associated with this scenario needed to be estimated. This was done by using the ratio of the respective variables between the grains cultivated in Østfold, and applying these ratio's to estimate values for the missing data.

By using criteria for selecting the model farms, and by considering local management practices, Bioforsk has provided inventories which are well suited for representing their respective regions. By adding data on farm level from HOLOS, a good basis for representing grain production in Norway across regions can be achieved. When this data is used for LCA inventories, the average environmental impacts from producing 1 kg of grain can be assessed.

4.3 Model Description of the Current Study

In order to integrate data from the two project, a base LCA template was made, structured in such a way that each template will represent one grain specie at the respective farm. 5 matlab script were also written, and their name and function is indicated in table 4.2. The following includes a description of the work and calculations performed.

Table 4.3: The table shows the total production of the cereals in the current system and in Norway in total, measured in tonnes. The percentage of the production covered in the current study is also presented.

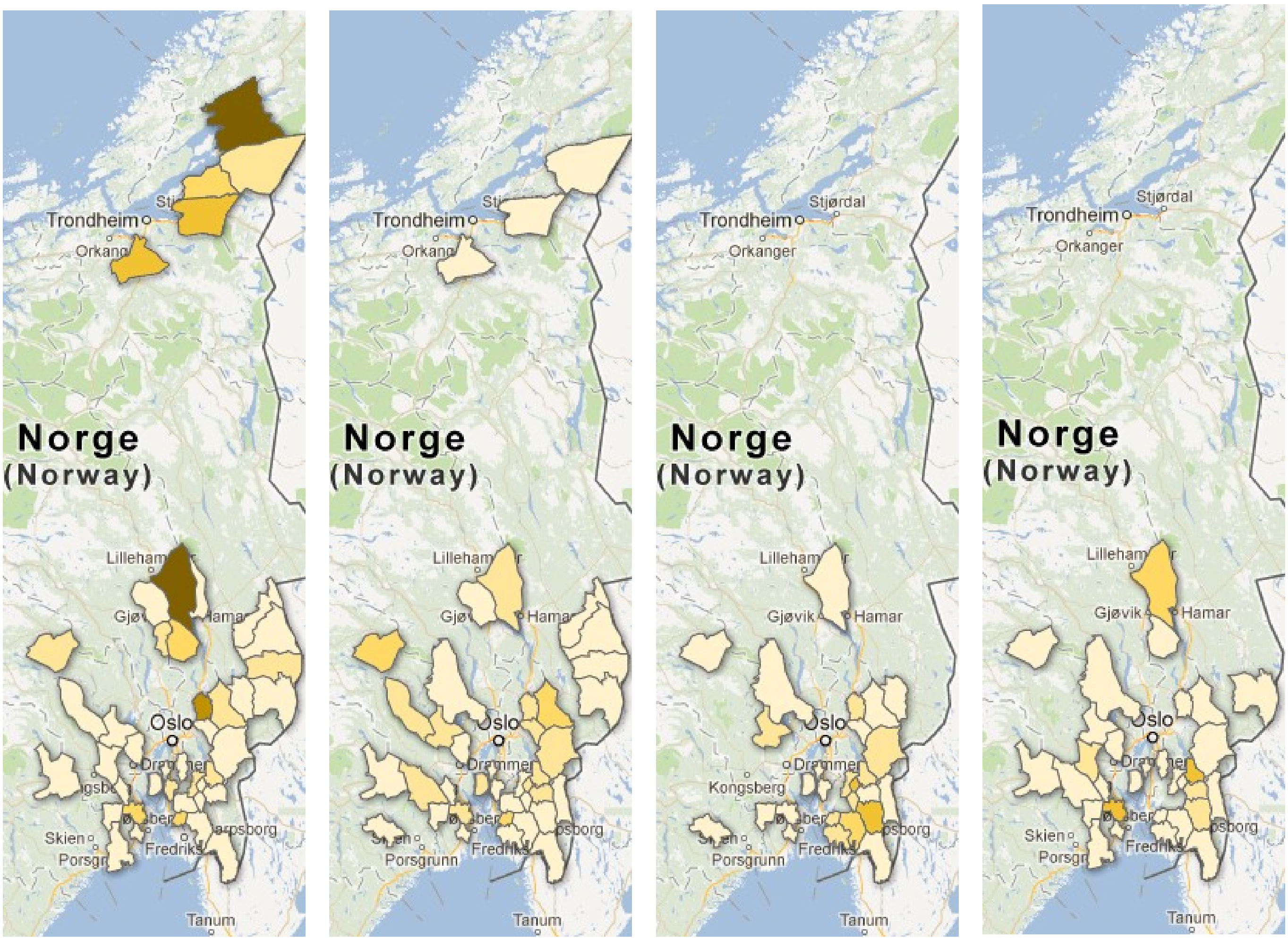
Tonnes Produced	*Barley*	*Oats*	*Winter Wheat*	*Spring Wheat*	*Sum*
Current System	4423	2679	2443	2208	11753
Total Norway	527413	281804	196274	175256	1180747
Percent	0,8	1,0	1,2	1,3	1,0

4.3.1 Finding Average Yield

There are two issues with using the yields reported for the farms in the HOLOS project. The yields provided in the HOLOS project show a less consistent co-variation with fertilizer application rate than what is expected and commonly observed (personal comment, Bioforsk). The reason for this might be that both fertilizer rate and yields were calculated from monetary data and converted to quantities based on unit prices. Another reason for concern is that the present study is using fertilizer rates provided by bioforsk. Farms in the HOLOS project which originally had both low fertilizer use and yields, would thus end up having a high environmental load per kg produced when the fertilizer rates were updated with larger values provided by bioforsk, while keeping the low yield originally used in the HOLOS-project. It thus seems wise to discard the yields reported by the HOLOS project, and rather replace these with the average yield reported for the township in which the farm is located. In order to do so, the average yield and yearly production for the years 2005 to 2010 in Norway was calculated, based on data from SN. Appendix C contains the matlab code used to perform these calculations.

SN does not provide mass data on spring and winter wheat production separately, but rather provides the total kg of wheat produced. They do however provide data on land area used for the production of winter and spring wheat, which can be used to estimate the production of the spring and winter wheat. Bioforsk has performed work on identifying the ratio between spring and winter wheat with a yearly resolution. They also consider regional variation, and the ratio vary between the north eastern part of Norway and the southeastern part. By applying this ratio, the production of winter and spring wheat was estimated. The values will be subject to uncertainties, as the ratio between spring and winter wheat production in reality will vary with a spatial resolution greater than the two regions provided by bioforsk.

To give an indication of the relative size of the production at the study sites, the average total yearly produce for the last 6 years of the respective cereals in Norway was also calculated, based on data from SN. Table 4.3 shows the total production on the farms in the current study, and compares this to the total production in Norway. The production in the current study represents approximately 1 % of the total Norwegian production for all the grain species assessed. Figure 4.3 gives a visual representation of which of the counties have the largest production, measured in ton grain, for the dataset used in the present study.



(a) Barley (b) Oat (c) W. Wheat (d) S. Wheat

Figure 4.3: The figure shows how many kg grain are produced in the different townships. The production varying between 6.9 and 493 tonnes in the different townships. The resolution is six intervals, where the darkest colors indicate the high end of the interval.

4.3.2 Making Templates

The base template that will be used to make each of the 215 LCA templates is based on the templates made by Bioforsk, but is restructured to only contain one type of grain per template. A flowsheet visualizing how the foreground is structured is shown in figure 4.4, while the actual foreground is shown in figure 4.5. The yellow data-points in this figure indicates the data-points which will vary according to farm and grain specific variables. Non-colored data-points are based on values from bioforsk, and are assumed to be constant.

The structure of the backgroundsystem is shown in appendix A, where gray data-points indicates that they are permutated across templates. In total, 40

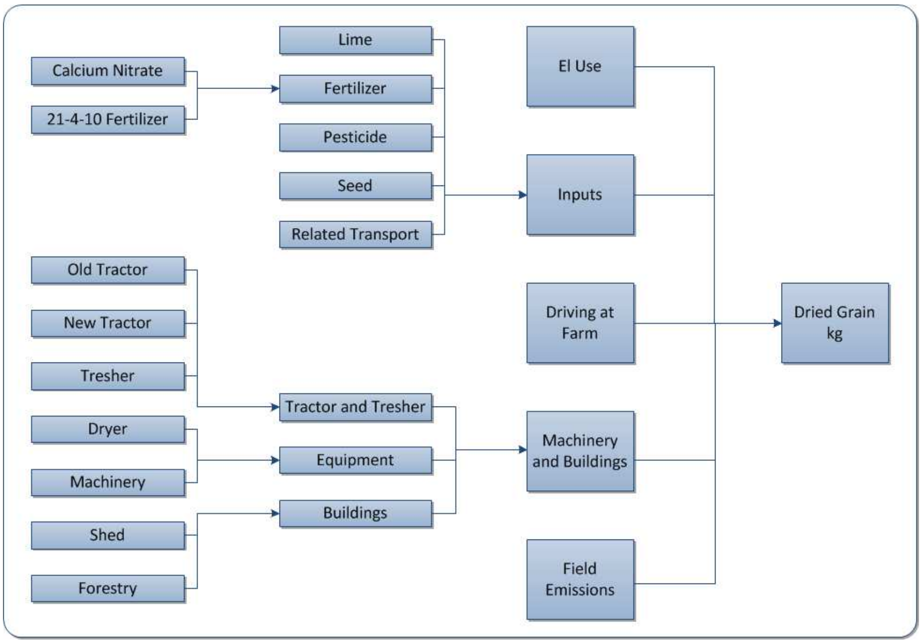


Figure 4.4: The figure shows how the foreground is structured in the current study.

data-points in the templates will be updated for each individual LCA, of which 14 is located in the foreground. The templates will in this way be able to reflect site and grain specific variation in environmental load associated with the functional unit, 1 kg of dried grain. The following will go through the required calculations performed in order to obtain variables for the templates.

N_2O-emissions When additional N is added to the soil, the nitrification and denitrification rates are enhanced [34]. Direct emissions of N_2O include emissions arising from applied synthetic fertilizer (F_{SN}). There are also direct N_2O-emissions arising from the decomposition of the nitrogen in crop residues (F_{CR}) and due to N-mineralization (F_{SOM}).

The N content in fertilizer and optikas is 21.6% and 27% repectively, and F_{SN} could thus easily be identified. The nitrogen content of crop residues (F_{CR}) was calculated by using N-content of above ground as well as below ground residues, and the relationship between below-ground to aboveground biomass. The N mineralization-rate was calculated by assuming that the N mineralization will occur at a fixed ratio of the C-mineralization:

$$F_{SOM} = \text{Soil C/CN-ratio}$$

where Soil C is kg carbon in the soil per hectare, and was provided by the HOLOS project, and CN_{ratio} is the ratio between C and N content in the soil, and is set to 10 in accordance with the IPCCs recommendation.

In order to integrate the regional adjustments in emission intensities identified in the HOLOS project, the Ntot$_j$ in equation 4.3 was replaced by the nitrogen application rate obtained from the bioforsk project. Appendix C.3 shows further details of how these calculations were performed in matlab.

A visual representation of how the N_2O emissions vary between regions and grain species cultivated is shown in figure 4.6. Here, the average amount of N_2O released per ha at the farms are presented at township level. It is however important to remember that some of the townships are represented by few farms. In the most extreme cases, as is the case for the township Kongsvinger in Hedmark county, the value presented is based on data from one single farm. The maps does however give some interesting insights;

The emissions are higher for the cereal winter wheat. Winter wheat cultivation is associated with the highest N application per ha, as presented in table B.1, which contributes to the higher emission intensity. Winter wheat also has the highest water filled pore space, and the temperature in the soil is also lower during winter wheat cultivation, than for the other grain species. As discussed in section 2.2.2, these factors can contribute to higher nitrification and denitrification rates in the soil. These factors thus also contribute to winter wheat cultivation being associated with the highest rates of N_2O emissions.

There is one township that stands out with high N_2O emissions associated with spring wheat production - Råde, located in Østfold. This township is represented by only one farm, which has a N_2O emission intensity of 6.3 kg/ha.

Field Emissions of NH_3 and NO_X Nitrogen volatized as NH_3 and NO_X is calculated according to the IPCC recommendations as:

$$N - vol = F_{SN} * 0.1 \tag{4.4}$$

$$NH_3 = NH_3 - N * 0.02/14 * 17 \tag{4.5}$$

$$NOx - field = NO_x - N * 0.98/14 * 46 \tag{4.6}$$

where 0.1 is the fraction of mineral fertilizer which is volatized as either NH_3 or NO_X. 0.02 and 0.98 is the ratio between the two stressors, and was set according to recommendations from bioforsk.

There are also emissions of NO_X associated with diesel-use at the farms. These emissions are calculated by using the CO_2 emissions from tractor and tresher transportation identified in B.1:

$$NO_X - diesel = CO_2 - diesel/2.6391 * avg - prep/1000 \tag{4.7}$$

where avg-prep is the average required soil preparation associated with seedbed preparation, standing crop and harvesting, measured as g NO_X/L. 2.6391 is the factor required to convert the CO_2 emissions from diesel into liters of diesel.

N Leaching and runoff The leaching and runoff rate of nitrogen was calculated by using the emission-factor provided by the IPCC. This factor assumes that 30% of the nitrogen added to or mineralised in managed soils is lost through leaching and runoff;

$$N_{runoff} = (F_{SN} + F_{CR} + F_{SOM}) * 0.3 \tag{4.8}$$

Field Emissions of CO_2 Lime is applied to agricultural land, in order to reduce soil acidity and thereby improving plant growth. Carbonate limes release bicarbonate as they dissolve, which later evolves into CO_2 and water. It is assumed that the land is limed every eight years, at intensities dependent on the region in which the farm is located. The application rates are provided by bioforsk, while the IPCC provides a default emission factor of 0.13 for dolomite, which is used to estimate the CO_2-emissions associated with liming;

$$CO_2 - liming = limeadded * EF_{dolomite} * (44/12) \tag{4.9}$$

where the unit is kg CO_2 $ha^{-1}yr^{-1}$.

The HOLOS project provide the data required for including CO_2 emissions from mineralization of soil carbon. The project did however not include emissions associated with liming of agricultural soils, which is common practice in Norwegian agriculture. The total field emissions of CO_2 were thus found by adding the HOLOS data on CO_2 emissions, with the CO_2 emissions associated with liming. A visual representation of how the CO_2 emissions vary between regions and grain species cultivated is shown in figure 4.7. Here, the average amount of CO_2 released per ha at the farms are presented at township level.

When investigating CO_2 field emission intensities between farms, they are in the range from negative 250 to 1700 kg CO_2 per ha. The fact that some farms have negative values, indicates that a net accumulation of carbon to the soil is taking place at these locations. As discussed in section 2.2.1, this increase in SOM will benefit the total GHG balance of the system, as it is a source of carbon sequestration.

Machinery and Buildings The machinery and buildings required at each farm is assumed to be the same as at the farms modeled by bioforsk. As the infrastructure requirements are added on a per hectare basis, farms of larger size will have a lower machinery and building requirement per ha cultivated.

4.3.3 Arda Robot

The results of each inventory was calculated by using the software ARDA. In order to run each of the 215 templates through this software automatically, a so-called "Arda-robot" was made. InputEmu is a Java-based function, which emulates user inputs via keyboard and mouse. By using this function in matlab, a script could be written which automatically performs the emulations required by the ARDA gui in order to run the individual LCAs.

The InputEmu function is sensitive to the keyboard locale, and the inputEmu utility is programmed specifically for the US QWERTY keyboard. The function thus had to be modified in order to perform the required emulations when using a Norwegian keyboard. This was the case for obtaining the correct characters when using the shift key. The Norwegian characters æ ø å were altogether avoided by removing them from filenames at the beginning of the script.

The code for uploading and running the 215 LCA inventories through ARDA is presented in appendix C.4. In addition to the code presented here, the script required for running structural path analysis and for saving the results as .xls rather than .mat files have also been made and are available.

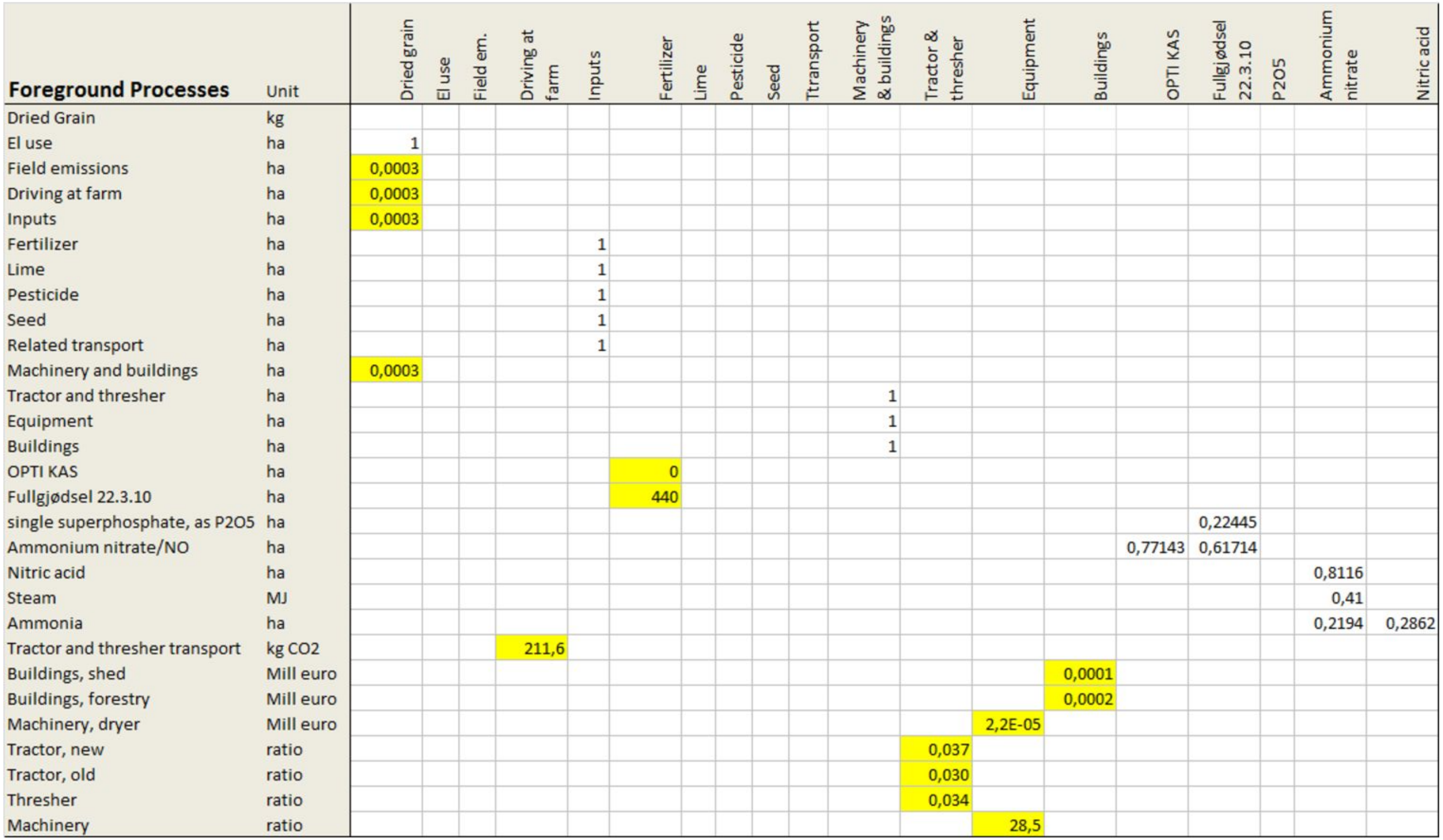
4.3.4 Management and Statistical Analysis of the Results

In order to systematize the results into a more tangible structure, the matlab script "Results management" was made. Here, the total impact vectors (d) are collected from each of the result files and structured into matrices, according to area and grain specie. The results broken down on foreground processes, and the total impact from producing the grain type at the farms are collected. Summary statistics regarding production of the four grain types are also calculated, including the weighted mean, median, and standard deviation.

In order to test for significant differences in environmental loads associated with producing the four different cereals, a statistical test called kruskal-wallis was also be performed. The possibility of statistically significant regional differences in impacts was also assessed, by using the three areas presented in figure 4.2.

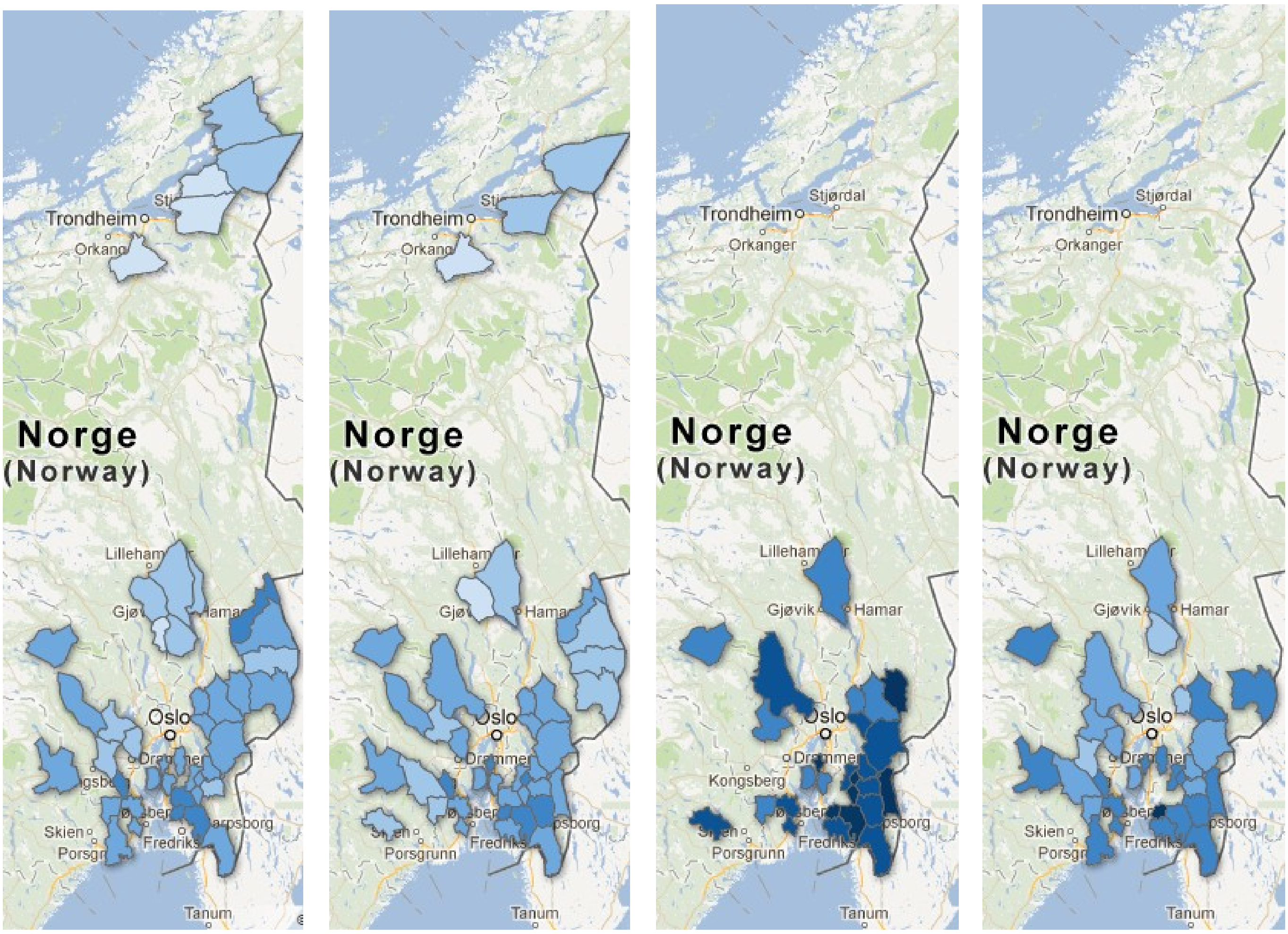
The kruskal-wallis test is a non-parametric method which evaluates the hypothesis that all samples come from populations that have the same median, against the alternative that the medians are not all the same [171]. By using this non-parametric test, one avoids making the assumption that the samples come from populations with normal distributions, which is an assumption in the more commonly used ANOVA test (variance analysis). The use of non parametric tests are necessary in the present study, as the results show tendencies towards a lognormal distribution, rather than a normal distribution. The confidence level 0.95 was used for all assessments.

In order to determine which pairs are significantly different from each other, the "multcompare" function in matlab was used by providing the stats structure obtained from the kruskal-wallis test.



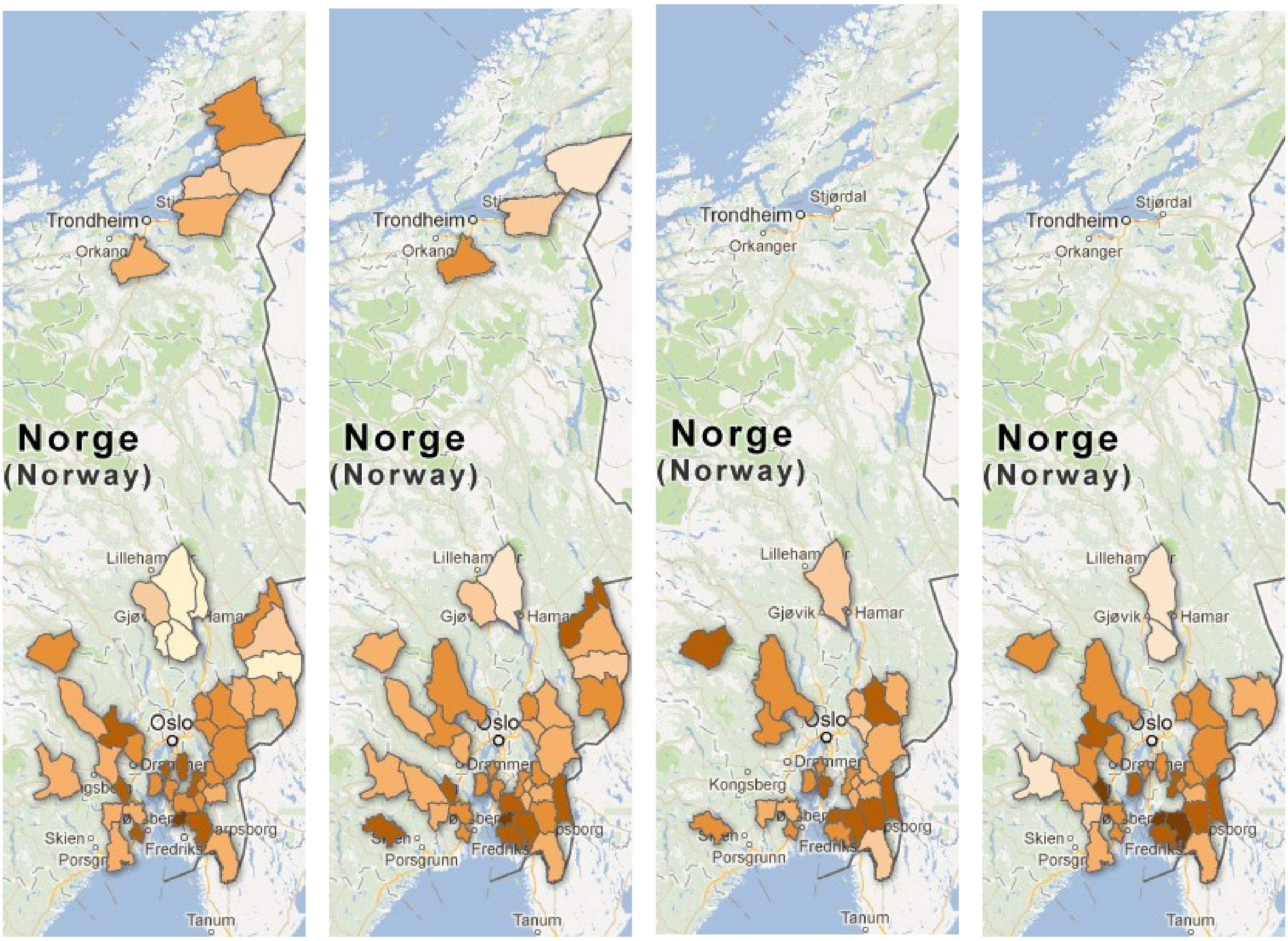
Foreground Processes	Unit	Dried grain	El use	Field em.	Driving at farm	Inputs	Fertilizer	Lime	Pesticide	Seed	Ttransport	Machinery & buildings	Tractor & thresher	Equipment	Buildings	OPTI KAS	Fullgjødsel 22.3.10	P2O5	Ammonium nitrate	Nitric acid
Dried Grain	kg																			
El use	ha	1																		
Field emissions	ha	0,0003																		
Driving at farm	ha	0,0003																		
Inputs	ha	0,0003																		
Fertilizer	ha					1														
Lime	ha					1														
Pesticide	ha					1														
Seed	ha					1														
Related transport	ha					1														
Machinery and buildings	ha	0,0003																		
Tractor and thresher	ha											1								
Equipment	ha											1								
Buildings	ha											1								
OPTI KAS	ha						0													
Fullgjødsel 22.3.10	ha						440													
single superphosphate, as P2O5	ha																0,22445			
Ammonium nitrate/NO	ha															0,77143	0,61714			
Nitric acid	ha																		0,8116	
Steam	MJ																		0,41	
Ammonia	ha																		0,2194	0,2862
Tractor and thresher transport	kg CO2				211,6															
Buildings, shed	Mill euro														0,0001					
Buildings, forestry	Mill euro														0,0002					
Machinery, dryer	Mill euro													2,2E-05						
Tractor, new	ratio												0,037							
Tractor, old	ratio												0,030							
Thresher	ratio												0,034							
Machinery	ratio													28,5						

Figure 4.5: Foreground system. Yellow values indicates that these values are permutated for each of the 215 inventories



(a) Barley (b) Oat (c) W. Wheat (d) S. Wheat

Figure 4.6: The figures show the regional variation in field emissions of N_2O associated with producing the various grain species. Kg N_2O emitted per hectare is shown, varying between 2.8 to 7 kg. The darkest colors indicate the high ends of these intervals.



(a) Barley (b) Oat (c) W. Wheat (d) S. Wheat

Figure 4.7: The figures show the regional variation in field emissions of CO_2 associated with mineralization of soil organic carbon. Kg CO_2 emitted per hectare is shown, varying between *negative* 250 to 1700 kg. The darkest colors indicate the high ends of these intervals.

Chapter 5

Results

This chapter will present the results for the impact categories climate change, terrestrial acidification, eutrophication, photochemical oxidant formation and toxicity potential. These impact categories were chosen due to their reported general implication in agricultural systems. Tables with all the ReCiPe hiearchical midpoint impact-categories are however presented in appendix D.

As the farms with the largest production should be weighted more heavily when assessing the average impacts associated with the production of 1 kg of grain, the average and standard deviation is calculated with weighting according to production. The effect of weighting the results is always a reduction in environmental load, for all impact categories. This indicates that larger production volumes in general are associated with lower impacts, per kg produced. The weighted standard deviations are also between 6 to 33% lower than the unweighted standard deviations.

The results will be presented in empirical cumulative distribution plots, broken down on impacts associated with electricity use, field emissions, driving at farm, inputs required at the farm and machinery and buildings. It was chosen to present the results in this manner as it allows for reflection upon the *variation* in environmental impacts associated with producing 1 kg grain. As these plots are weighted according to production, the weighted average environmental load associated with the production may be identified as the environmental load where y equals 0.5 in these figures. The weighted average load from producing the grains are also presented in table 5.1, to simplify the identification of these values.

The results obtained from performing the kruskal-wallis analysis will also be presented in this section. The confidence level 0.95 was used for all statistical assessments.

Table 5.1: The table shows the weighted average load associated with producing 1 kg of the respective grains.

Impact Category	*Unit*	*Barley*	*Oat*	*W. Wheat*	*S. Wheat*
Climate Change	kg CO2 eq	0,93	0,98	0,92	0,99
Terrestrial Acidification	g SO2 eq	7,96	7,92	7,85	8,04
Marine Eutrophication	kg N eq	0,015	0,015	0,016	0,016
Freshwater Eutrophication	g P eq	0,54	0,67	0,56	0,61
Photochem. Ox. Formation	g NMVOC	11,7	11,7	12,0	12,2
Terrestrial Ecotoxicity	g DCB eq	0,072	0,087	0,056	0,068
Marine Ecotoxicity	g DCB eq	2,79	2,76	1,88	2,50
Human Toxicity	kg DCB eq	0,14	0,13	0,09	0,12
Freshwater Ecotoxicity	g DCB eq	2,94	3,89	1,95	2,58

5.1 Climate Change

The weighted average climate change potentials associated with producing 1 kg of barley, oat, winter and spring wheat, are 0.93, 0.98, 0.92 and 0.99 kg CO_2 eq./kg grain, respectively. As shown in figure 5.1, field emissions are the main contributor to the climate change potential for all cereals assessed. Field-emissions of N_2O contribute more to CC potential than field emissions of CO_2, on average about twice as much. Refer to the figures 4.6 and 4.7 to see how N_2O and CO_2 soil-emissions vary between the different regions.

As observed in figure 5.1, large variations in climate change impacts are observed for the different cereals, and the weighted standard deviations for the 4 cereals vary between 0.19 and 0.28. The main sources of variation is with regards to field emissions of N_2O, and in impacts arising from machinery and building requirements at the farms.

The reason why 1 kg of barley have less climate change impacts occurring through field emissions than the other cereals, are due to lower N_2O-emissions. Barley and oat cultivation both have a slightly lower total application of nitrogen per ha than fields growing wheat, but regional variation in N_2O emissions as influences by soil temperature and moisture, is a larger contributor to this variation. The climatic conditions in northern Norway favors lower N_2O emissions. As no wheat production is located in the assigned area 1 in figure 4.2, wheat production does not benefit from this. Barley production however, have more production located further north in Norway than the other grain species, and 31 % of the production of barley is located within area 1 in the current study. This explains the lower contribution to climate change from field emissions for the cereal barley.

The climate change impacts associated with infrastructure and machinery requirements at the farms are relatively stable across grain species, except for the cereal winter wheat. As the infrastructure requirements at each farms is added on a per ha basis, farms with large areas and high yields will have a lower impact associated with machinery and buildings requirements. This fact can explain why winter wheat have lower impacts from machinery and buildings, as this crop is never the sole crop grown at a farm. This rational will also hold

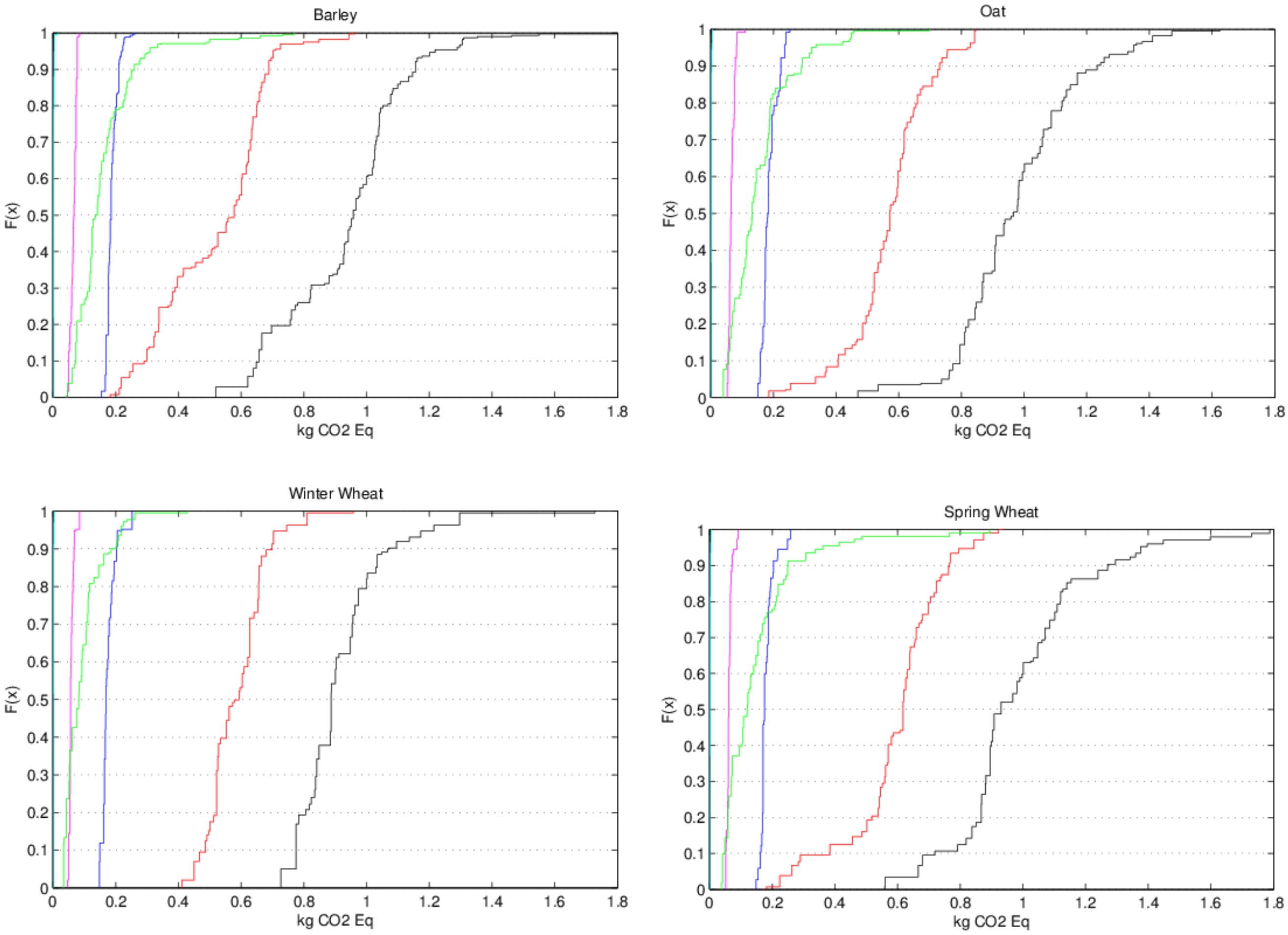
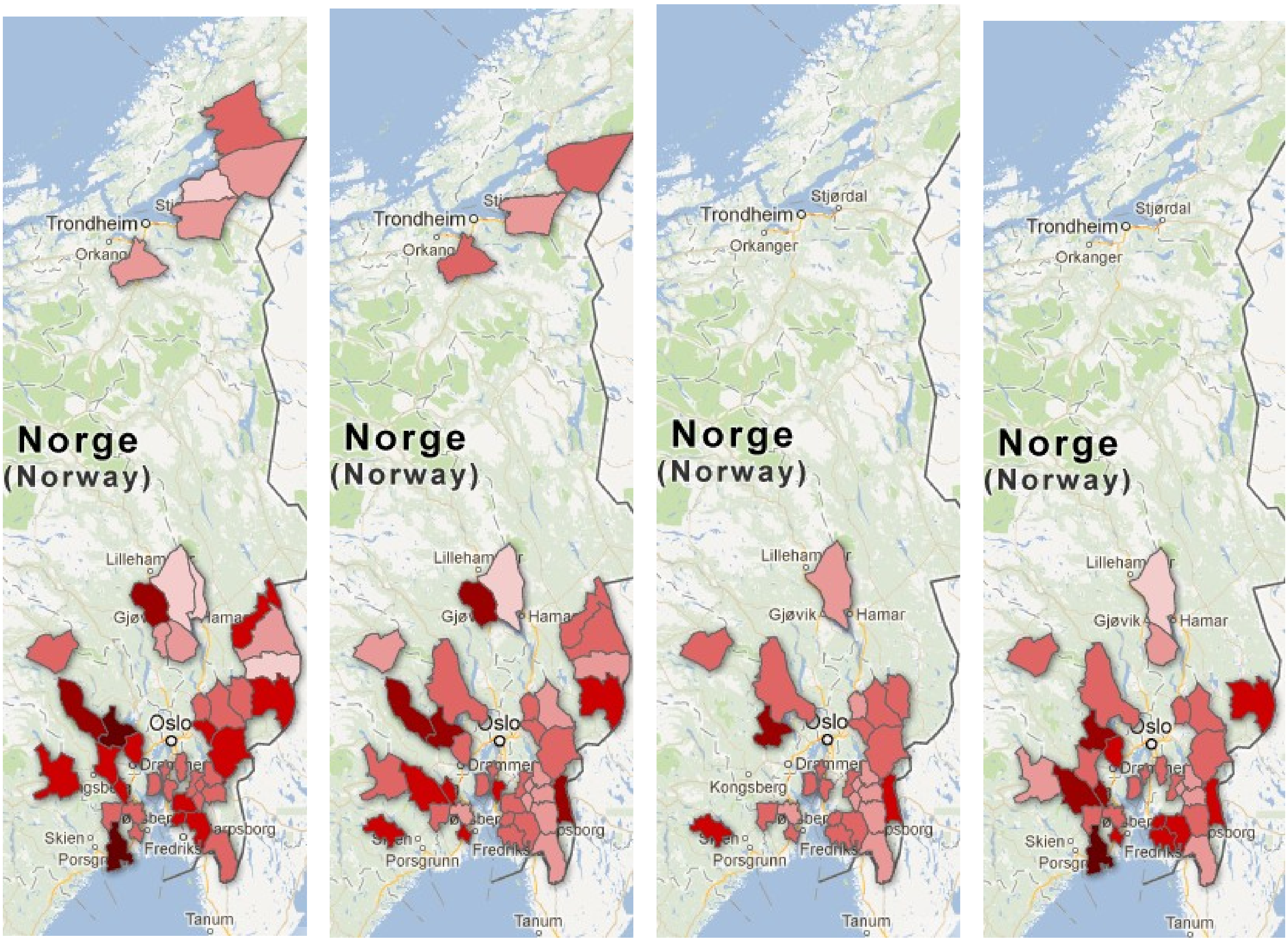


Figure 5.1: The figures show the cumulative distribution function for climate change, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total climate change potential from producing 1 kg grain.

for several of the other impact categories assessed. This also explains why there is less variation in the climate change impact at the farms producing winter wheat with respects to infrastructure requirements, as shown in figure 5.1. If considering barley, on the other hand, this crop is grown as the sole crop at 16 out of the 70 farms at which barley is cultivated. If some of these farms are small and also have a low yield per ha cultivated, this will cause the machinery and building requirements to be higher per kg grain produced. This results in the observed long upper tail for this foreground process in figure 5.1, for the cereal barley.

The contribution from inputs required at the farms is relatively stable across grain species. The production of nitric acid and ammonia required for fertilizers is the largest source of impacts associated with inputs to the farms.



(a) Barley (b) Oat (c) W. Wheat (d) S. Wheat

Figure 5.2: The figures show the regional variation in climate-change potential from producing the various grain species, ranging from 0.5 to 1.7 kg CO_2eq/kg grain. The darkest colors indicate the high ends of these intervals.

In order to assess the variation in environmental impacts at a regional level, the climate change potential from producing 1 kg of grain are also presented in maps, with a resolution at township-level. For illustrative purposes, the representation is based on the weighted average climate change potential in each township. From the figures in 5.2, it seems that the results vary significantly between the different townships. It is however important to remember that some of the townships are represented by few farms, and the maps should thus only serve as a starting point for investigating possible regional trends. For instance, with regards to all grain species, the climate change potential associated with grain-production in the townships located in the counties Hedmark and Oppland are all low, and a possible reason for this can be low field emissions of CO_2 in these areas;

12 out of the 94 farms have a net carbon accumulation in the soil. 16 LCA templates were based on these farms, of which 14 were located in the counties Hedmark and Oppland. This can explain why the climate change impact in the townships Hamar, Ringsaker, Østre Toten and Vestre Toten in general are in the lower range of the scale, for all cereal. At the other end of the scale, farms in the county Østfold are in general overrepresented, with the township Råde having the highest soil carbon emissions per ha.

The field emissions of N_2O were also identified as an important contributor to climate change potential. In section 4.1 the average amount of N_2O released per ha in the townships were presented. By comparing the intensities in figure 4.6 and 5.2, we observe that there is not always a strong correlation between CC and N_2O emissions, as is to be expected; N_2O-emissions are not the sole contributor to CC potential. In addition, the N_2O emission intensities are presented on a per ha basis, while the CC potentials are presented per kg produced. The ha required to produce 1 kg will vary according to yields, and there is not necessarily a strong covariation between yields and field N_2O emissions.

The statistical analysis showed that the production of barley in area 3 was associated with a significantly higher climate change potential per kg produced, than producing barley in both area 1 and 2 ($p= 0.0009$ and $p = 0.0032$, respectively), when using the significance level 0.05. It was also found that producing spring wheat in area 3 is associated with a significantly higher climate change potential per kg produced, than in area 2 ($p=0.0008$). No other statistically significant differences were found when comparing climate change potentials between the three areas. There was neither any significant difference in climate change potential between the different grain species.

5.2 Acidification

Terrestrial acidification is measured as kg SO_2-equivalents released per kg grain produced. Field emission stressors contributing to this impact category are NH_3 and NO_X, and are associated with the use of mineral fertilizers. Ammonia has an acidification potential of 2.45 kg SO_2 eq. per kg released, while 1 kg NO_X emissions are characterized to 0.56 kg SO_2 eq, when using the ReCiPe hierarchical method. 98% of the nitrogen volatized is assumed to be in the form of NO_X, and only 2% in the form of ammonia. This results in NO_X dominating this impact category, despite the fact that ammonia has a higher acidification potential per kg released.

Figure 5.3 shows the results for the impact category terrestrial acidification. The weighted average terrestrial acidification potentials associated with producing 1 kg of grain is very stable across grain species, as they are all within the narrow range from 0.0079 to 0.008 kg SO_2 eq./kg grain.

Emissions of sulfur dioxide is associated with the production of inorganic fertilizers, and is the main contributor to the impacts associated with inputs required at the farm. Driving at the farm also contribute to terrestrial acidification, through the refining and combustion of diesel associated with farm operation.

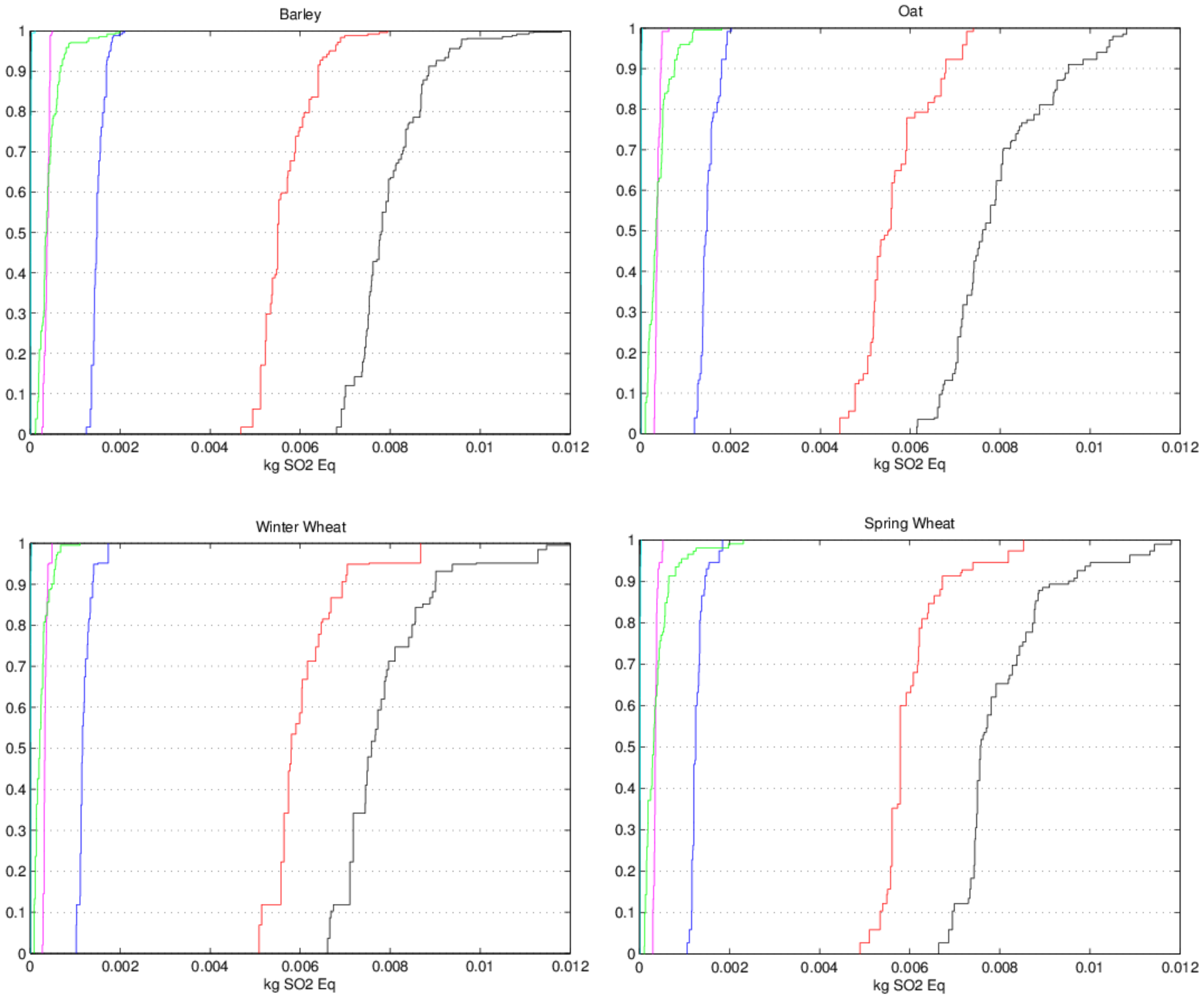


Figure 5.3: The figures show the cumulative distribution function for terrestrial acidification, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total terrestrial acidification potential from producing 1 kg grain.

The statistical analysis showed that the production of barley in area 3 was associated with a significantly higher terrestrial acidification potential per kg produced, than producing barley in both area 1 and 2. No other significant differences in terrestrial acidification potentials were found, across both location and grain species.

5.3 Eutrophication

The CML-method offers two impact categories associated with eutrophication, marine eutrophication and freshwater eutrophication. Only a short presentation of marine eutrophication potentials will be included, while the results for freshwater eutrophication will be present in more depth.

5.3.1 Marine Eutrophication

Marine eutrophication is measured as kg N-equivalents, and this category is completely dominated by field emissions. Most of this contribution is caused by nitrogen runoff to rivers. NO_X and NH_3 emissions to air however also contribute with approximately 10% to the impacts. Little variation between grain species are observed for this impact category, as the weighted mean is between 0.015 and 0.016 kg N eq./kg grain for all grain species.

Several statistically significant differences were found with regards to marine eutrophication potentials generated from producing 1 kg of grain. Again, it was found that the production of barley in area 3 was associated with a significantly higher marine eutrophication potential per kg produced, than producing barley in both area 1 and 2. Both the production of oat and spring wheat in area 2 are associated with a significantly lower level of marine eutrophication than area 3.

5.3.2 Freshwater Eutrophication

The weighted average freshwater eutrophication potentials associated with producing 1 kg of barley, oat, winter and spring wheat, are 0.54, 0.67, 0.56 and 0.61 g P eq./kg grain, respectively. As shown in figure 5.4, the impacts are generated predominantly from direct field-emissions, which arises from emissions of phosphate. The phosphate emission rate to rivers are assumed to vary only with the location of the farms in this study, and is based on the three areas assigned for use of bioforsk values. The fact that barley have a lower emission intensity of phosphate thus reflect that barley has a larger fraction of its production occurring in the northern parts of Norway than the other grain species, as is in accordance with figure 4.3.

There are also indirect emissions from the production of single superphosphate (P_2O_5) needed at the farm, which adds all the potential observed as "inputs" in figure 5.4. The contribution observed from the foregroundprocess "machinery and buildings" is associated with the required disposal of farm machinery at end of life.

Phosphate has the characterization factor 0.33 for freshwater eutrophication potential, as this is the molecular weight of phosphorous (31 g/mol^{-1}) divided by the molecular weight of phosphate (95 g/mol^{-1}). As the emissions per ha only depend on location of the farm, the resulting cumulative distribution plot shown in figure 5.4 has a stepwise nature. Farms in region 1 will have a freshwater-eutrophication potential of approximately $0.3 * 10^{-3}$, region 2 of

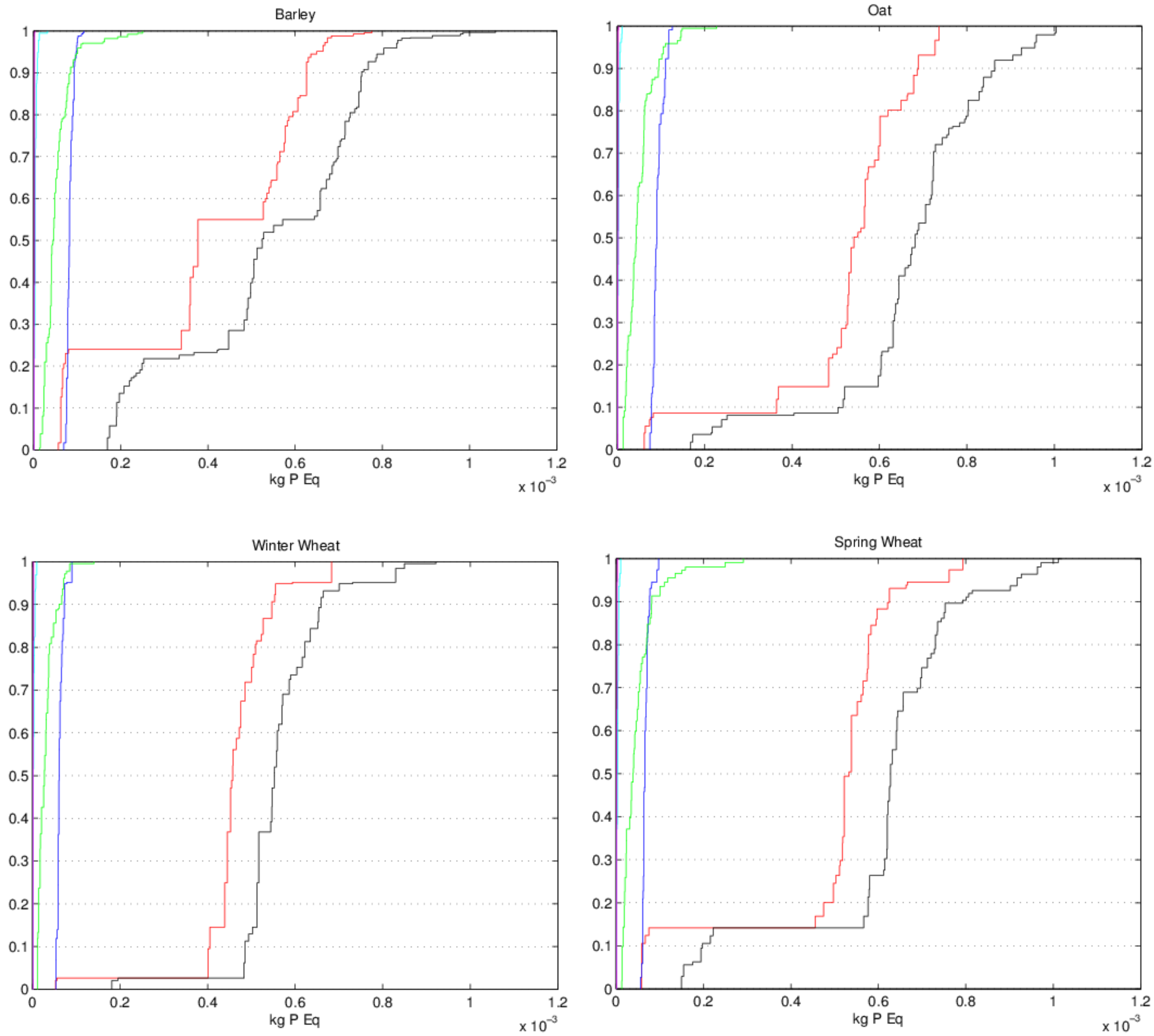


Figure 5.4: The figures show the cumulative distribution function for freshwater eutrophication, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total climate change potential from producing 1 kg grain.

$0.06 * 10^{-3}$ and region 3 $0.5 * 10^{-3}$ kg P eq. per kg grain. The area required to produce 1 kg of grain will vary according to the yield, which smoothen out the stepwise buildup.

The freshwater eutrophication potentials from producing 1 kg grain in area 1 and 2 were significantly lower than the potential generated in area 3, for the grain species barley and oat. The potentials generated were also significantly higher in area 3 than in area 2 for the production of winter and spring wheat. This is a direct consequence of the assumption that P-leaching vary only with the location of the farms in this study, and is based on the three areas assigned for use of bioforsk values. The production of oats produced significantly higher freshwater eutrophication potentials than the production of winter wheat and barley, when assessed at a significance level of 0.95.

5.4 Photochemical Oxidant Formation

The photochemical oxidant formation potential of producing 1 kg grain is measured as kg non-methane volatile organic compounds (NMVOC), and above 80% of the impacts in this category is caused by field emissions, as presented in figure 5.5. It is more specifically caused by emissions of nitrogen oxide associated with the volatilization of nitrogen applied to the fields. As spring and winter wheat cultivation is associated with optikas as well as fertilizer application, the total N applied to these fields are slightly higher than at fields growing barley and oats. If the increased use of nitrogen is not perfectly correlated to yields achieved, this can explain why wheat production is associated with slightly higher impacts associated with field emissions of NO_X.

The contribution from the foreground process "driving at farm" is caused by NO_X-emissions associated with the combustion of diesel, while the contribution from "inputs" are caused by the production of fertilizers. The production of agricultural machinery required at the farms also contribute to photochemical oxidant formation, in the range of 3-4% for the different cereals.

As observed in figure 5.5, spring and winter wheat have a larger upper tail than the other two species. As the total nitrogen applied to these fields are larger per hectare, fields with low yields will impact the results more for wheat than for barley and oats.

Few significant differences regarding this impact category were found. The production of barley in area 3 had significantly higher photochemical oxidant formation potentials than barley production in area 1 and 2. The difference for this impact category is also significantly higher for spring wheat than for oats.

5.5 Toxicity

The ReCiPe method provides four categories measuring toxicity potentials, measured as kg 1.4-dichlorobenzene (DCB) equivalents. A short introduction to the results of all these impact-categories will be included, while terrestrial ecotoxicity and human toxicity potential also is presented graphically.

The production of pesticides and fertilizers contribute significantly to all of these impact categories. The herbicide glyphosate is the pesticide which has the highest toxicity impact for all grain-species. The application of glycosate, which

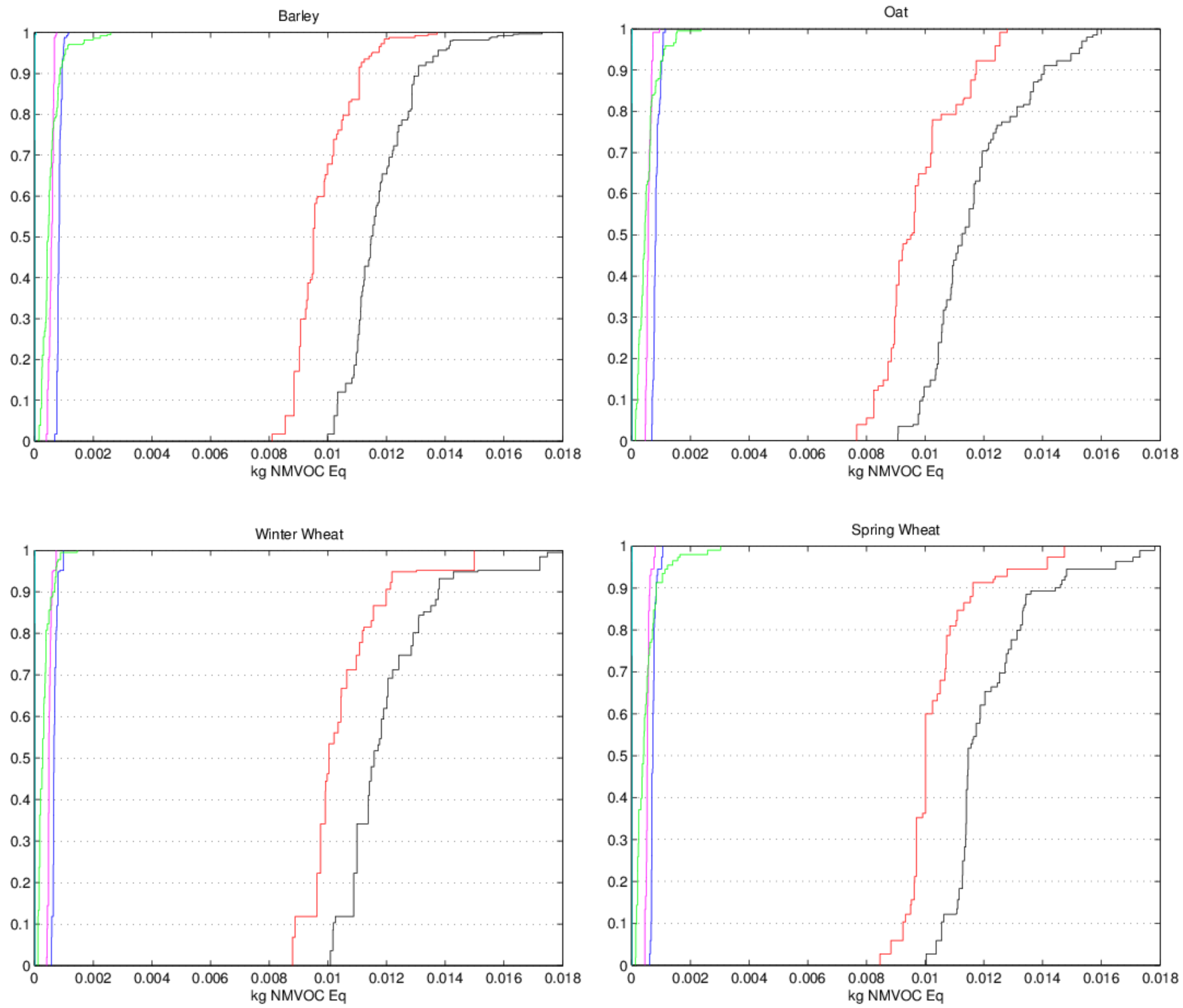


Figure 5.5: The figures show the cumulative distribution function for photochemical oxidant formation, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total photochemical oxidant formation potential from producing 1 kg grain.

is assumed to be 0.93 kg/ha for all grain-types, is particularly influential for the impact category terrestrial ecotoxicity, where it contributes with approximately 8 % of the total, varying according to kg produced per ha.

5.5.1 Terrestrial Ecotoxicity

The weighted average terrestrial ecotoxicity potentials associated with producing 1 kg of barley, oat, winter and spring wheat, are 0.072, 0.087, 0.056 and 0.068 g 1.4 DCB eq./kg grain, respectively. Terrestrial ecotoxicity are associated with the use of tractor and threshers at the farms, and 18-21% of the potentials are generated in the foregroundprocess "driving at farm", when considered as the weighted average for each cereal. The refining of the diesel required for the transportation also contribute to terrestrial ecotoxicity potential.

When considering the foreground process "inputs", the two largest impacts are due to the production of the P_2O_5 and ammonia required for fertilizer production. As shown in table B.3, 0.4 kg growth-regulator is required per ha of oat cultivated. Barley only require inputs of 0.02 kg growth regulator per ha, while wheat-production is not associated with any inputs of growth regulators. For the cultivation of oat, the production of growthregulators significantly increase the terrestrial ecotoxicity, as observed in the foreground process "inputs" in figure 5.6. Besides growthregulators applied to oats, glycosate is by far the dominating pesticide with regards to creating terrestrial ecotoxicity potentials, with impacts varying around 5.5 E-6 kg DCB eq./kg grain.

All grain species have significantly different terrestrial ecotoxicity potentials associated with producing one kg grain, except for the production of barley and spring wheat.

5.5.2 Marine Ecotoxicity

The weighted average marine ecotoxicity potentials associated with producing 1 kg of barley, oat, winter and spring wheat, are 2.8, 2.8, 1.9 and 2.5 g 1.4 DCB eq./kg grain, respectively. This impact category is dominated by the foreground-processes "machinery and buildings" and "inputs" for all cereal. The impacts associated with machinery arise from the necessary disposal of nickel smelter slag associated with the production of steel used to make the machinery. The largest contributors to "inputs" are the P_2O_5 and ammonia required for producing inorganic fertilizers required at the farms. For the cereal oat, the production of growth regulators also impact the marine ecotoxicity potential.

The production of winter wheat is associated with significantly lower marine ecotoxicity potential than the cultivation of barley and oat. This is due to lower impacts associated with infrastructure and machinery requirements, due to reasons addressed in section 5.1.

5.5.3 Human Toxicity

The results for the impact category human toxicity are shown in figure 5.7. Similarly to marine ecotoxicity, this impact category is dominated by the stages "machinery and buildings" and "inputs". The impacts from machinery production arise from the disposal of sulfidic tailings associated with copper requirements for producing farm machinery. The two largest contribuors in the stage

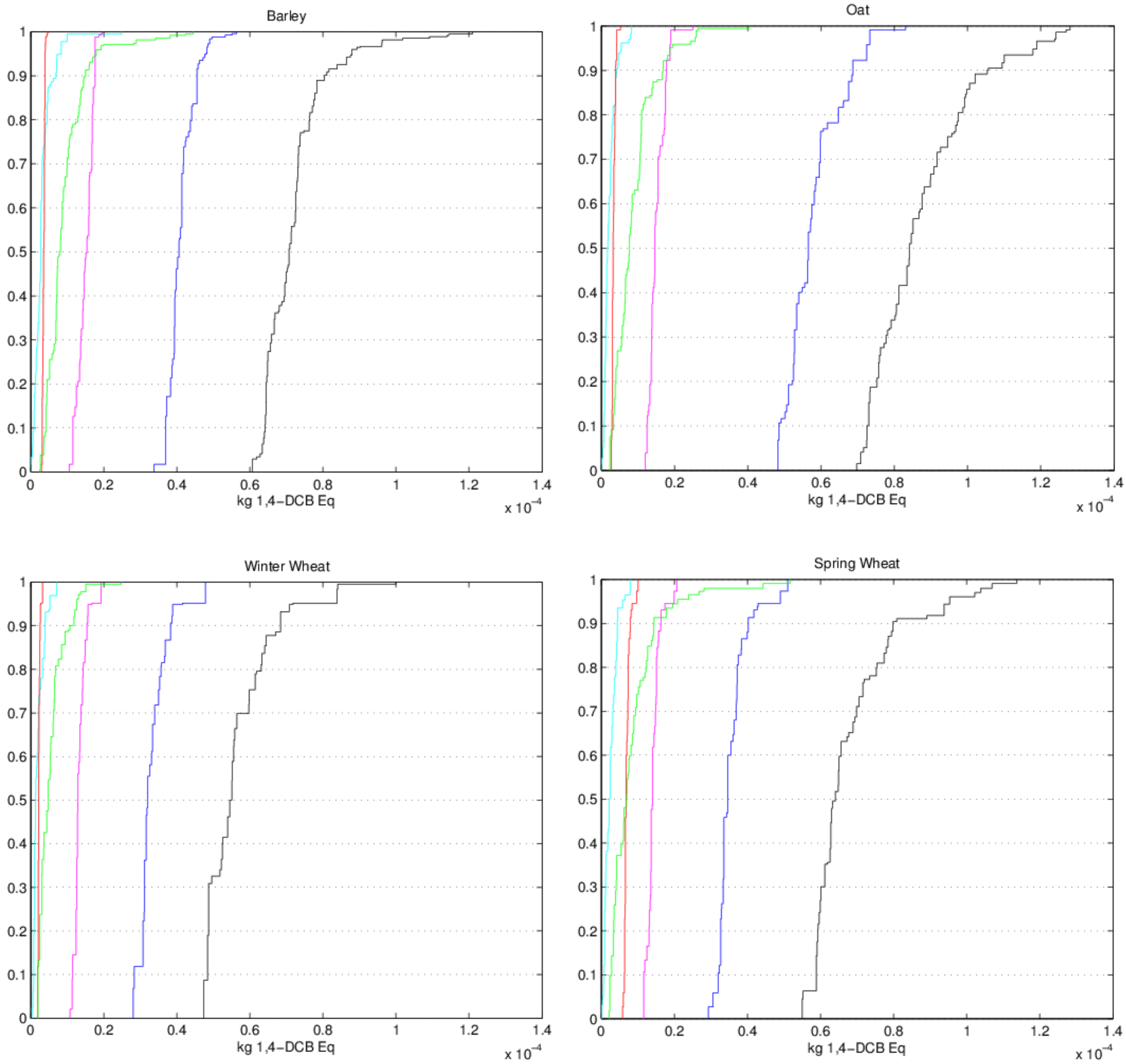


Figure 5.6: The figures show the cumulative distribution function for terrestrial ecotoxicity, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total terrestrial ecotoxicity potential from producing 1 kg grain.

”input” are emissions associated with P_2O_5 and ammonia production required for inorganic fertilizers used. The need for glyphosate at the farm also add to impacts associated with impacts arising from inputs required at the farm, as phosphorouscloride is required in the production of glyphosate.

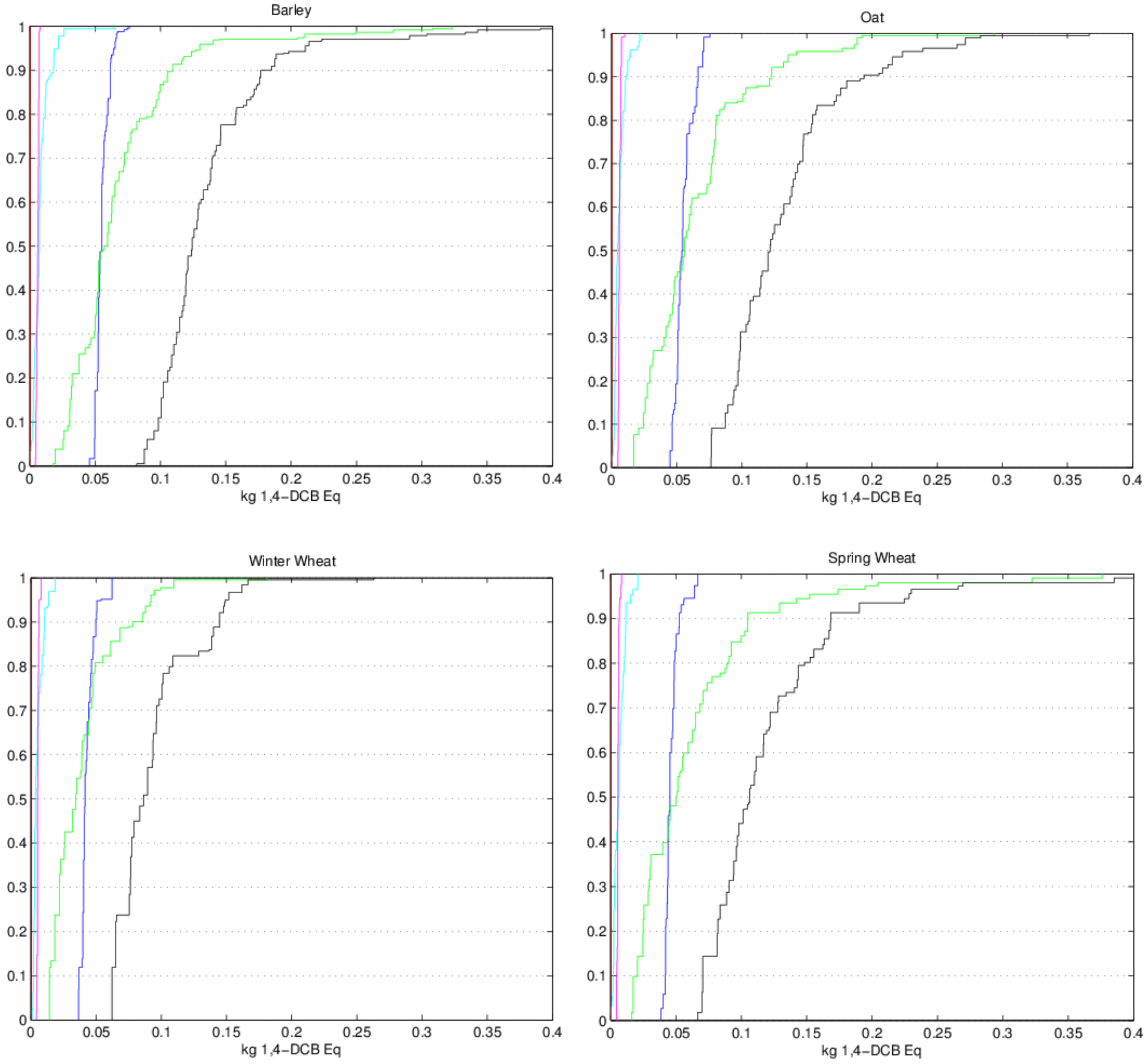


Figure 5.7: The figures show the cumulative distribution function for human toxicity, broken down on the 5 foreground-processes. The colors represent; cyan - electricity use, red - field emissions, magenta - driving at farm, blue - inputs and green - machinery and buildings. The black line represents the total human toxicity potential from producing 1 kg grain.

The production of winter wheat is associated with significantly lower human toxicity potential than the cultivation of barley and oat, as was also the case for marine ecotoxicity.

5.5.4 Freshwater Ecotoxicity

The weighted average freshwater ecotoxicity potentials associated with producing 1 kg of barley, oat, winter and spring wheat, are 2.9, 3.9, 1.9 and 2.6 g DCB eq./kg grain, respectively, where the foreground processes "inputs" and "machinery and buildings" yet again are the main contributors. Glycosate production is the input which has the largest overall contribution to this category. This is not the case for the cereal oat, where the production of growth-regulators are associated with larger freshwater ecotoxicity impacts. Barley also have impacts arising from the production of growth-regulators, but as this grain species use only 0.02 kg growth regulator per ha as compared to 0.4 kg used on oats crop, this contribution is less significant. The production of P_2O_5 also contribute to the potential associated with inputs to farm.

The impacts under "machinery and buildings" are due to disposal of waste associated with the production of farm machinery. Nickel smelter slag disposal is the largest contributor, while disposal of sulfidic tailings comes second.

The freshwater ecotoxicity potential associated with the cultivation of oat is significantly larger than production of the other grain species, when using a significancelevel of 0.95. The production of barley is also associated with significantly larger freshwater ecotoxicity potential than the production of winter wheat.

Chapter 6

Discussion

The two species barley and winter wheat were associated with the lowest climate change potentials, with loads of 0.93 and 0.92 kg CO_2eq./kg grain, respectively. The reason for these two species achieving the lowest impacts are however explained by differing mechanisms;

The low climate change impact from barley production is largely explained by low N_2O-emissions associated with the cultivating of this crop. Compared to the other species, the cultivation of barley is to a larger extent located in more northern parts of Norway, and 31% of the barley production is located within the area 1 introduced in figure 4.2. The temperature and moisture content in the soils of this region tend to favor lower N_2O emissions.

Low N_2O emissions can not explain the reason for winter wheat achieving the lowest climate change potentials, as no wheat production is located in area 1. In fact, as shown in figure 4.6, winter wheat cultivation is associated with higher N_2O emissions from N-mineralization than the other species, on a per ha basis.

The result can be explained by the fact that the emissions of both CO_2 and N_2O associated with mineralization are presented on a per *hectare* basis. As winter wheat have higher yields than the other grain species, less of the emissions are attributed to each *kg* grain produced for the case of winter wheat cultivation. The average yield associated with winter wheat is 4590 kg/ha for the farms assessed in the current study, whereas the yields for barley, oat and spring wheat are 3750, 3855 and 4010 kg/ha, respectively. If the functional unit of the analysis had rather been per hectare, the climate change results would thus be less favorable for winter wheat, than when using a functional unit related to mass.

The impacts regarding toxicity and terrestrial acidification were also lower for winter wheat than for the other grains assessed. Fertilizer and pesticide application are applied per ha, and high yields will therefore again benefit winter wheat with regards to these impact categories, where the production of pesticides and fertilizers are important contributors. Also, the machinery and building requirements are important contributors to especially the impact categories human and marine toxicity. The impacts associated with infrastructure requirements are shared between all grain species cultivated at the individual farms, according to ha used for the cultivation of the grain in question. High yields and the fact that winter wheat is never the sole crop cultivated at a farm, therefore results in this crop having lower toxicity and acidification potentials than the other cereals.

The production of wheat was allocated to the species spring and winter wheat based on ratios provided by bioforsk, and as explained in section 4.3.1, there are some uncertainties regarding the use of these ratios. Further investigations of the ratio between spring and winter wheat production would therefore be of interest, before concluding that winter wheat production is more environmentally friendly on a general basis.

The results of the kruswal wallis test showed that production in area 3, as presented in figure 4.2, often had significantly higher environmental loads than production in area 1 and 2. This region neither benefits from low CO_2-emissions, as was the case for area 2, or by having low N_2O emissions, as was the case for area 1. This area is also associated with the highest P leaching.

The cultivation of barley was especially associated with higher environmental loads in area three than in area 1 and 2, for which climate change, terrestrial acidification, marine eutrophication, freshwater eutrophication and PCOF potentials were all significantly higher in area 3, when using a confidence level of 0.95. It therefore appears that barley cultivation is associated with lower environmental impacts in more northern parts of Norway. As shown in figure 2.2, the national production of barley is largely located around the Trondheimsfjord area, where the largest productions occur in Hedmark and Nord-Trøndelag. With regards to environmental considerations, this distribution of barley production in Norway seems sensible.

The bioforsk project have collected data for representing the "typical" cereal producing farm in their life cycle inventories. The present study has assumed that some of the data from these inventories may be used to represent production at either all of the farms modeled in the current study, or for farms within the regions assigned in figure 4.2. For instance, it is assumed that all farms will require the same amount of ploughing per hectare, and that they will have the same shed on site. This will not necessarily be the case, and this assumption can thus be considered as a limitation of the present study. Possible variation in these processes are however not likely to be central contributors to the environmental loads associated with grain-production, and it is thus considered to be fair assumptions to make nonetheless.

The fertilizer application rates are however also obtained from the bioforsk project. Large impacts are associated with fertilizer production and application, and it would therefore be of interest with greater resolution, preferably at farm-level, regarding these values, rather than assuming a constant fertilizer application rate for all farms within one of the three regions. The loss rate of P and N applied to the fields are also estimated with low resolution, and as these emissions are the main contributors to freshwater and marine eutrophication, further investigations of these flows are also of interest.

The HOLOS project ran the ICBM model over a time span of thirty years in order to estimate CO_2 emissions from mineralization of soil organic carbon, but weather data from the year 2008 was used repeatedly for all thirty year in this model. As weather conditions will vary between years, the estimate soil CO_2-emissions could be strengthened by using unique weather data in this model for each year. As emissions from agricultural soils have proven so important for the environmental load, it is a concern indeed if these flows are not modeled with a high degree of certainty.

As addressed in section 3, it is preferred to have larger fractions of the impacts associated with the product-system generated in the foreground processes. On average, 56% of the impacts contributing to the impactcategory climate change are generated in the foreground system. For the impact categories regarding eutrophication, PCOF and acidification, between 72 and 99% of the impacts are generated in the foreground-systems, which is regarded to be satisfactory.

For the categories assessing toxicity potentials, the fractions of impacts modeled in the foreground systems are however low. The highest ratio is 6%, for the impact category terrestrial ecotoxicity. In addition, the toxicity impact categories have previously been confronted as being modelled too poorly within the LCA framework, as adressed in section 1.1. In the current study, it was also assumed that the emissions of pesticides would only affect the compartment "soil". There is however some evidence that pesticides will also impact water bodies and air [172]. As the mechanisms influencing these emissions are very complex, it was considered beyond the scope of this study to address these implications further. These three issues combined render less confidence in the results regarding toxicity than the other impact categories.

The foreground processes "field emissions" was associated with the largest variation in impacts between farms. These emissions are influenced by geographical parameters, such as soil type and weather conditions, and it can therefore be somewhat challenging to reduce these impacts at farms with high loads. Possible means of reducing field emissions were addressed in section 2.2.

The foreground process "machinery and buildings" was also a main source of variation in impacts between farms. The lifetime of machinery is not fixed, and by using them longer than the expected lifetime assumed in the present study, the associated impacts could be lowered. However, as stated by Roer et al. (2012), as new tractors exploit diesel better than old ones, a cut-off point between old and new machinery will eventually be reached [28]. If the machinery could be used to cover the needs of larger land areas, each kg grain would be attributed less of the impacts associated with this foreground process. The Norwegian topology can often put stains on the maximum field sizes, and neighboring farms are often not in close vicinity. Enlarging the field areas or sharing of equipment between farms is therefore not necessarily possible. The strain on the machinery could also become too large with such a solution.

The cultivation and harvesting of grain are associated with GHG-emissions from fossil energy-sources, originating from the diesel used in machinery. Transportation of inputs are also associated with combustion of diesel. Lower emissions could be achieved by using biofuels with low lifecycle GHG-emissions rather than using fossil energy sources. However, these emissions have little overall impact on the climate change category. Combustion of conventional diesel are

Table 6.1: The table shows comparisons of results from different grain producing chains evaluated by life cycle assessments in literature, with regards to climatechange and acidification potentials associated with producing 1 kg of grain.

Grain	*Study*	*Location*	*Year*	*Climate Change* g CO_2 eq	*Terr. Acidification* g SO_2 eq.
Wheat	This study	Norway		950	7,9
	Roer et al [28]	Norway	2012	735	6,1
	Williams et al [23]	UK	2010	700	3,3
	Biswas et al. [35]	Australia	2008	304	
	Nielsen et al [173]	Denmark	2007	710	5,3
	Pelletier et al. [22]	Canada	2008	382	10,2
Barley	This study	Norway		931	8,0
	Roer et al. [28]	Norway	2012	795	6,3
	Nielsen et al [173]	Denmark	2007	650	5,8
Oats	This study	Norway		977	7,9
	Roer et al. [28]	Norway	2012	765	5,6
	Nielsen et al [173]	Denmark	2007	570	6

however also associated with emissions of nitrogen oxides. By switching to use of biofuels in the machinery, lower impacts in the PCOF category could also be achieved, as biofuels have lower NO_X-emissions during combustion than fossil fuels.

6.1 Result Robustness

Comparison of results with other LCA studies may be difficult due to the use of different indicators, system boundaries, allocation-methods and differences in geographically dependent variables, but from table 6.1, it becomes apparent that the weighted average for climate change and terrestrial acidification potential in the present study are in the high range compared to results reported by other sources. The following discussion seeks to identify possible reasons for the divergent results.

An interesting comparison to make, is between the results obtained in the bioforsk study, presented in Roer et al. (2012) [28], and the current study, which have also obtained data from the same project.

The study by Roer et al. is based on the model farm located in Stange, whereas the results of the current study presented in table 6.1 are based on the weighted average environmental load, which is calculated independent of geographic location. As data provided by bioforsk and the HOLOS project have also been fused, and as the entire system will be affected by including these values in the foreground systems, it is expected that the two studies will have somewhat different results.

Differences in yields between the studies will also contribute to possible variations in the results. The yields used by Roer et al., are 4690, 4760 and 5460 kg grain/ha, for barley, oats and spring wheat, respectively. In the current study, the average yields across all farms and areas, for the same grain species, are 3750, 3855 and 4009 kg grain/ha.

The lower yields used in the present study will cause all impact categories to be higher than in the study conducted by Roer et al. (2012), as the yield will affect how much of the impacts are assigned per kg grain produced. If the results in table 6.1 had rather been presented with weighed averages for only farms located within area 2, the difference would be less, as the average yield in area 2 is higher for the different cereals, than the average yield calculated based on all farms.

Field-emissions of CO_2 and N_2O are the two largest contributors to the impact category climate change, and the HOLOS project provided data on emissions intensities for both of these in the current study. Although 12 farms in the current study have a net accumulation of soil carbon, the average soil emissions of CO_2 are in the same range across the two studies. The current study does however, always have higher emissions of the stressor N_2O than the study by Roer et al (2012). As N_2O is a more potent greenhouse gas than CO_2, this difference in emission intensities explains in large part the larger climate change impacts found in the current study.

As shown in table 6.1, the present study is also associated with higher terrestrial acidification associated with cultivation of the cereals. This may seem surprising, as the impacts are mainly associated with the production and use of fertilizers, which are values provided by bioforsk. It is however only the farms assigned to area 2 in the present study which will have the same application rate of fertilizers as the study by Roer et al, as only this area is based on Stange-values. The differences in yields between the two studies will also cause some of the differences in impacts. If the functional unit had rather been per hectare, and if only the results from farms in area 2 had been compared to the results in the study by Roer et al (2012), there would be less differences with regards to this impact category.

The remaining impact categories have results in the same range in both studies, but for reasons already adressed, the impacts tend to be a bit higher in the present study. Regarding eutrophication potentials, larger differences in impacts are however observed;

The freshwater eutrophication loads reported by Roer et al are in the range from 1.4 to 1.6 $* 10^{-4}$ kg P/kg grain, whereas the present study have results in the range 5.4 to 6.7 $* 10^{-4}$ kg P/kg grain. The difference can be explained by the fact that impacts are largely dependent on geographical location of the farms. The P application is the lowest in area 2, where 0.8 kg phosphate is emitted to river waterbodies per ha grain cultivated, as compared to 3.7 and 6.4 kg phosphate in area 1 and 3, respectively. As a means of exemplifying the effect of regional variation, the freshwater eutrophication potential for barley production in the current study would be reduced to 2.0 $* 10^{-4}$ kg P-eq/kg, when only farms within area 2 are considered. This is much closer to the 1.6 $* 10^{-4}$ kg P-eq/kg reported by Roer et al. (2012). The remaining difference in results can be explained by the studies having differences in yields.

The current study is also associated with higher marine eutrophication, due to higher leaching and runoff rates of N. Roer et al report 36.1 kg nitrogen emitted to rivers per ha barley, oat and spring wheat cultivated. The average nitrogen emitted in the current study for area 2 is however 43, 38 and 50 kg/ha for barley, oat and spring wheat respectively. This, in addition to the lower yields, explains why the current study have 60 to 100% higher marine eutrophication potentials than what was reported by Roer et al (2012).

Williams et al (2010) report lower climate change potentials generated by wheat production than the current study, as indicated in table 6.1. This can be explained by the fact that Williams et al. used a long term approach in their study, so that the changes in soil carbon status, and its associated CO_2-emissions, were not included. In addition, the yield used in the UK study is 7.7 tonnes/ha, while the yields for wheat production in the current study vary between 3 and 4.6 tonnes/ha. The higher yields may also partly explain why Williams et al. report lower acidification potentials than the current study. It however also seems that Williams et al. have not included soil emissions of NO_X in their study, which will explain the differences in impacts.

The study by Biswas et al. (2008) [35] report significantly lower CO_2 eq. and SO_2 eq. associated with producing 1 kg of wheat, than what the present study found. This study was conducted in Australia, considering wheat produced on semi-arid and arid lands. The study utilized regionally specific data for field emissions of N_2O, which gave the total soil N_2O emissions to be 0.11 kg N/ha/year. This is much lower than the emission intensities reported from other areas and climatic conditions, and causes the emissions to be 85% lower than if the IPCC default emission factor of 0.01 had been used. Despite the fact that Biswas et al. has used the older characterization factor for N_2O emissions of 310, as opposed to the factor of 298 used in the present study, the stressor N_2O only contribute with 22% of the total CC potential. This is very different from our results, where N_2O is the largest stressor contributing to climate change.

Biswas et al. (2008) have also excluded CO_2 emissions associated with liming, as lime was not applied to the fields in the year the study was conducted, but rather the year before. Our study on the other hand, includes the impacts associated with liming. This provides another explanation as to why the current study have higher climate change impacts.

The system boundary in the study by Biswas et al. (2008) does not include the production of buildings. The emissions of CO_2 due to changes in soil organic matter were neither assessed. Taking these differences in system boundaries into consideration, it seems reasonable that the present study have higher environmental impacts associated with wheat production than what was reported by Biswas et al. (2008).

Pelletier et al. conducted an LCA study aiming at identifying potential reductions in environmental impacts associated with a hypothetical national transition from conventional to organic production of four field crops in Canada. As shown in table 6.1, the climate change potential associated with conventional wheat production was lower in Canada than in the present study. This can in part be explained by differences in system boundaries; Pelletier et al have not included inputs and emissions associated with the production and maintenance of farm machinery and infrastructure as well as transportation of inputs, nor were possible emissions of CO_2 due to changes in SOM content. It is expected that some of the differences can also be explained by higher yields and higher intensity agriculture in Canada than in Norway, but the resources used in the Pelletier study is not available to make such comparisons.

The terrestrial acidification potential on the other hand, were found to be higher in the Pelletier study. Both studies have followed the IPCC tier 1 guidelines, but Pelletier et al. have assumed that 90% of the N volatized to be emitted as NO_X, while 10% is emitted as NH_3. The present study have assumed the split between NO_X and NH_3 to be 98/2%. Ammonia has 4.4 times the acidifying potential as NO_X, per kg released. The difference in allocation between these two stressors can thus explain the higher acidification potential reported by Pelletier et al.

Lastly, Nielsen et al. (2007) have excluded capital good requirements, such as buildings and machinery, pesticides and most other chemicals from their assessments, presented in table 6.1. This can in part explain the higher impacts associated with the current study. It was however difficult to find documentation on the field emission intensities used in the studies by Nielsen et al., and further analysis as to differences in results thus become difficult. As they do not provide full details regarding their farming system, it is not clear what systematic differences there might be between the studies.

To summarize, the present study have results in the high range for the impact categories climate change and acidification when compared to other LCA studies assessing grain production systems. Throughout the discussion, it however becomes apparent that these results can be justified by differences in system boundaries. The higher results can be explained by the inclusion of infrastructure requirements and soil emissions associated with changes in SOM, and also partially by having lower yields associated with its production pathway, when compared to other studies.

6.2 Implications and Conclusion

215 LCAs may seem adequate to represent the grain production in a small country such as Norway, but as the data is further subgrouped according to species and geographical location of the farms, the sample-sizes are not large in statistical terms. The utility of the results hence become somewhat limited. Still, we try to introduce some key insights into the results, and some results were indeed found to be statistically different from each other.

It is the goal of the Norwegian government to reduce the environmental load from the agricultural sector by 1.1 million tonnes of CO_2 equivalents by 2020. To reflect on the order of magnitude of this value, the climate change potential generated in total from production at the 94 farms in the present study is roughly 11 thousand tonnes of CO_2-equivalents. The total production at the farms in this study thus represent only 1 percent of the CO_2-equivalents that the Norwegian government wish to *reduce*. In addition, the results of this studies also includes impacts arising from other sectors, and a reduction in these impacts would not contribute to reaching the governments goal. It thus seems that achieving a 1.1 million ton reduction in CO_2 equivalents by 2020 is a grand challenge indeed.

As farms have different crop-rotations, the environmental load associated with the production of 1 kg grain will vary. The present study has only considered farms without pasture as part of the rotation. Farms which have pasture as a part of the crop rotation is likely to have lower or no humus mineralization, and are thus expected to have a lower climate change impact per kg produced. The results in the present study can thus not be used to consider the climate-change effect of grain-production in Norway in a general manner, nor be used to scale up from 1% to cover the entire grainproduction in Norway. The results are only relevant for grain producing farms without livestock.

It would be of interest with Norwegian LCA studies assessing grain production at farms also involved with livestock husbandry, as to assess the environmental influence of having pasture as part of the crop production. The total impacts associated with grain production in Norway could then also be estimated, by using a bottom-up approach.

This study is only relevant for weather conditions experienced at the present. The projected global warming is expected to have negative implications for the environmental performance of agricultural systems. A larger variation in yields between years is expected, due to more extreme weather [174]. Periods of heavy rainfall can cause erosion and associated leaching of soil nutrients [1]. Milder winters can result in more freeze-thaw events, which also will increase the risk of erosion and runoff [175]. As discussed in section 2.2.2, thawing may also enhance denitrification-rates. These scenarios show the importance of assessing the emissions associated with agriculture, and identify areas of focus for reducing the total environmental load, as to lower global warming. It will also be important to asses and adapt the Norwegian agricultural practices continuously, in order to obtain optimized production during these times of a changing climate.

The White Paper 21 argue that the estimates of agricultural GHG emissions are uncertain, and that emissions of N_2O is a key factor introducing this uncertainty [17]. The N_2O-emissions associated with N mineralization increased by 18-112%, when using regional estimates rather than the standard 0.01 emission factor for nitrogen applied provided by the IPCC. This confirmes the need for site-specific estimates regarding these emissions. The inclusion of CO_2 emissions associated with changes in soil organic carbon also proved to be an important contributor to climate change potentials, and other LCA studies should stive to include these emissions in their assessments. There however needs to be a level of certainty in these site-specific estimates, as they are likely to significantly alter the results with respects to certain impact-categories. Continuous monitoring of N_2O emissions from soils by using so-called ”climate towers” (masts with sensitive instruments) does not exist in Norway at present. As measuring of in particularly N_2O is workintensive, expensive and can result in discontinuous data, further development and use of technologies measuring these emissions will be important for improving these estimates.

As the world population continues to grow, there is a need to *increase* the global food production volumes, and it is therefore of little interest to recommend a reduction in production volumes at farms associated with high environmental impacts. More intensive grain production at larger farms could make the production more efficient and lower the environmental loads per kg produced, but as discussed in section 2.1, this is not necessarily an option for grain production in Norway. The Norwegian topology places a strain on field sizes, and there are also political incentives to maintain production in the rural areas, to secure amongst other employment and the cultural heritage in these areas. Possible means of reducing the emissions should rather be assessed. Emissions associated with mineralization was an important contributor to global warming. As discussed in section 2.2, several means of lowering soil emissions of CO_2 and N_2O have been suggested, such as reduced tillage, application of biochar to agricultural soils and improved drainage. As appeared from this discussions, there is no strong consensus regarding the mitigating potential for the various strategies, and further research regarding these approaches is of interest.

To summarize, this study assessed the average, and variation in, environmental loads associated with producing four grain species at different locations in Norway. The results showed that field emissions contributed greatly to the impacts for all categories, except for those assessing toxicity. It is therefore of interest to further investigate means of lowering these emissions, in particular of N_2O, as it was identified to be the main stressor contributing to climate change potentials. The results also showed that winter wheat was the grain species most often associated with the lowest environmental loads. This was largely explained by the specie having high yields. Agricultural practices enhancing optimal yields can thus be important for lowering environmental impacts per kg grain produced. Variation in soil emissions associated with mineralization was an important source of regional variation in environmental performance. Production in area three often had significantly higher environmental impacts associated with grain production. This was largely explained by the fact that the region neither benefited from low CO_2-emissions, as was the case for area two, or by having low N_2O emissions, as was the case for area one.

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Appendix A

Background System

Table A.1: The table shows the background processes associated with the system. Gray values indicate that the value will vary between templates.

Background Process	*Foreground Process*	*Value*	*Unit*
el, low voltage, at grid/ NO	El use	0,1	kWh
diesel, at regional storage/ RER	Tractor & thresher transp.	0,3	kg
heavy fuel oil, at reg. storage/ RER	Tractor & thresher transp.	0,0022	kg
potassium chloride, as K2O / RER	Fullgjodsel	0,034	kg
natural gas, high pressure, at consumer/ RER	Ammonia	27,0	MJ
el, medium voltage, at grid/ NO	Ammonia	0,8	kWh
el, medium voltage, at grid/ NO	Nitric acid	0,0081	kWh
el, medium voltage, at grid/ NO	Steam	0,0009	kWh
el, medium voltage, at grid/ NO	Ammonium nitrate/NO	0,025	kWh
phosphate rock, as P2O5, dry, at plant/ MA	single superphosphate	1,0	kg
sulphuric acid, liquid, at plant/ RER	single superphosphate	1,8	kg
electricity, medium voltage, at grid/ NO	single superphosphate	1,9	kWh
transport, lorry >16t, fleet average/ RER	single superphosphate	4,4	tkm
transport, transoceanic freight ship/ OCE	single superphosphate	24,4	tkm
transport, freight, rail/ RER	single superphosphate	2,9	tkm
chemical plant, organics/ RER	single superphosphate	1,9E-09	unit
limestone, milled, packed, at plant/ CH	Lime	454	kg
shed/ CH	Lime	0,01	m^2
tractor, production/ CH	Lime	0,5	kg
trailer, production/ CH	Lime	3,1	kg
glyphosate, at reg. storehouse/ RER	Pesticide	0,9	kg
herbicides, at reg. storehouse/ RER	Pesticide	0,1	kg
insecticides, at reg. storehouse/ RER	Pesticide	0,0043	kg
growth regluators, at reg. storehouse/ RER	Pesticide	0,0185	kg
fungicides, at reg. storehouse/ RER	Pesticide	0,2	kg
fungicides, at reg. storehouse/ RER	seed	0,01	kg
transport, tractor and trailer/ CH	Related transport	13,4	tkm
transport, passenger car, diesel, fleet avg/ RER	Related transport	1,1	pkm
transport, lorry 3.5-16t, fleet avg/ RER	Related transport	6	tkm
transport, lorry >16t, fleet avg/ RER	Related transport	272,8	tkm
transport, transoceanic freight ship/ OCE	Related transport	748	tkm
tractor, production/ CH	Tractor, new	353,3	kg
tractor, production/ CH	Tractor, old	320	kg
harvester, production/ CH	Thresher	466,7	kg
agricultural machinery, tillage, prod/ CH	Mashinery	1,0	kg

Table A.2: The table shows the background stressors directly associated with the system. Gray values indicate that the value will vary between templates.
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Stressor	*Foreground Process*	*Value*	*Unit*
Glyphosate/ soil/ agricultural	Field em.	0,93	kg
Fluroxypyr/ soil/ agricultural	Field em.	0,07	kg
Trifloxystrobin/ soil/ agricultural	Field em.	0,07	kg
Florasulam/ soil/ agricultural	Field em.	1,70E-03	kg
Trinexapac-ethyl/ soil/ agricultural	Field em.	0,02	kg
Prothioconazol/ soil/ agricultural	Field em.	0,09	kg
Alphacypermethrin	Field em.	4,25E-03	kg
Tribenuron-methyl/ soil/ agricultural	Field em.	0	kg
Chlormequat/ soil/ agricultural	Field em.	0	kg
Pirimicarb/ soil/ agricultural	Field em.	0	kg
Iodosulfuron/ soil/ agricultural	Field em.	0	kg
Carbon dioxide, fossil/ air	Field em.	1102	kg
Dinitrogen monoxide/ air	Field em.	3,21	kg
Nitrogen oxides/ air	Field em.	25	kg
Ammonia/ air	Field em.	2,3	kg
Phosphate/ water/ river	Field em.	3,677	kg
Nitrogen/ water/ river	Field em.	54,1	kg
Occupation, crop, intensive/ resource/ land	Field em.	10000	m^2
Carbon dioxide, fossil/ air	Tractor & thresher transp.	1	kg
Ammonia/ air/ low pop. density	Tractor & thresher transp.	6,41E-06	kg
Benzene/ air/ low pop. density	Tractor & thresher transp.	2,34E-06	kg
Benzo(a)pyrene/ air/ low pop. density	Tractor & thresher transp.	9,63E-09	kg
Cadmium/ air/ low pop. density	Tractor & thresher transp.	3,21E-09	kg
CO, fossil/ air/ low pop. density	Tractor & thresher transp.	1,88E-03	kg
Chromium/ air/ low pop. density	Tractor & thresher transp.	1,60E-08	kg
Copper/ air/ low pop. density	Tractor & thresher transp.	5,45E-07	kg
Dinitrogen monoxide/ air/ low pop. density	Tractor & thresher transp.	3,85E-05	kg
Heat, waste/ air/ low pop. density	Tractor & thresher transp.	14,56	kg
Methane, fossil/ air/ low pop. density	Tractor & thresher transp.	4,14E-05	kg
NMVOC, unspecified origin/ air/ low pop. density	Tractor & thresher transp.	6,87E-04	kg
Nickel/ air/ low pop. density	Tractor & thresher transp.	2,24E-08	kg
PAH, / air/ low pop. density	Tractor & thresher transp.	1,05E-06	kg
Particulates, < 2.5 um/ air/ low pop. density	Tractor & thresher transp.	1,57E-03	kg
Selenium/ air/ low pop. density	Tractor & thresher transp.	3,21E-09	kg
Sulfur dioxide/ air/ low pop. density	Tractor & thresher transp.	3,24E-04	kg
Zinc/ air/ low pop. density	Tractor & thresher transp.	3,21E-07	kg
Cadmium/ soil/ agricultural	Tractor & thresher transp.	5,74E-08	kg
Lead/ soil/ agricultural	Tractor & thresher transp.	2,52E-07	kg
Zinc/ soil/ agricultural	Tractor & thresher transp.	1,54E-04	kg
Nitrogen oxides/ air	Driving at farm	1,7	kg

Table A.3: The table shows the background stressors directly associated with the system. Gray values indicate that the value will vary between templates.

Stressor	*Foreground Process*	*Value*	*Unit*
Carbon dioxide, fossil/ air	Ammonia	1,49	kg
Acetaldehyde/ air	Ammonia	1,26E-06	kg
Acetic acid/ air	Ammonia	8,51E-06	kg
Acetone/ air	Ammonia	1,23E-06	kg
Ammonia/ air	Ammonia	8,24E-08	kg
Arsenic/ air	Ammonia	1,07E-07	kg
Benzene/ air	Ammonia	9,52E-06	kg
Benzo(a)pyrene/ air	Ammonia	4,69E-10	kg
Butane/ air	Ammonia	1,67E-05	kg
Cadmium/ air	Ammonia	2,72E-07	kg
Calcium/ air	Ammonia	6,59E-07	kg
Carbon monoxide, fossil/ air	Ammonia	8,54E-05	kg
Chromium/ air	Ammonia	1,30E-07	kg
Chromium VI/ air	Ammonia	1,32E-09	kg
Cobalt/ air	Ammonia	2,72E-07	kg
Copper/ air	Ammonia	4,04E-07	kg
Dinitrogen monoxide/ air	Ammonia	1,56E-05	kg
Dioxins, as 2,3,7,8-tetrachlorodibenzo-p-dioxin/ air	Ammonia	4,42E-15	kg
Ethanol/ air	Ammonia	2,47E-06	kg
Formaldehyde/ air	Ammonia	6,1E-06	kg
Heat, waste/ air	Ammonia	3,5E+01	MJ
Hydrocarbons, aliphatic, alkanes, unspecified/ air	Ammonia	4,9E-06	kg
Hydrocarbons, aliphatic, unsaturated/ air	Ammonia	2,5E-07	kg
Hydrocarbons, aromatic/ air	Ammonia	1,2E-06	kg
Hydrogen chloride/ air	Ammonia	1,2E-05	kg
Hydrogen fluoride/ air	Ammonia	1,2E-06	kg
Iron/ air	Ammonia	1,5E-06	kg
Lead/ air	Ammonia	4,7E-07	kg
Mercury/ air	Ammonia	2,0E-09	kg
Methane, fossil/ air	Ammonia	1,2E-05	kg
Methanol/ air	Ammonia	4,2E-06	kg
Molybdenum/ air	Ammonia	1,3E-07	kg
Nickel/ air	Ammonia	5,4E-06	kg
Nitrogen oxides/ air	Ammonia	1,0E-03	kg
PAH, polycyclic aromatic hydrocarbons/ air	Ammonia	2,4E-07	kg
Particulates, < 2.5 um/ air	Ammonia	2,93E-04	kg
Particulates, > 10 um/ air	Ammonia	8,24E-05	kg
Particulates, > 2.5 um, and < 10um/ air	Ammonia	4,12E-05	kg
Pentane/ air	Ammonia	2,86E-05	kg
Propane/ air	Ammonia	5,00E-06	kg
Propionic acid/ air	Ammonia	4,76E-07	kg
Selenium/ air	Ammonia	9,89E-08	kg
Sodium/ air	Ammonia	6,18E-06	kg
Sulfur dioxide/ air	Ammonia	1,02E-05	kg
Toluene/ air	Ammonia	5,00E-06	kg
Vanadium/ air	Ammonia	2,15E-05	kg
Zinc/ air	Ammonia	3,30E-07	kg
Water, unspecified natural origin/ resource/ in water	Ammonia	1,12E-03	m^3
Nitrogen/ water/ river	Ammonia	1,02E-04	kg

Table A.4: The table shows the background stressors directly associated with the system. Gray values indicate that the value will vary between templates.

Stressor	*Foreground Process*	*Value*	*Unit*
Dinitrogen monoxide/ air	Nitric acid	1,67E-03	kg
Dinitrogen monoxide/ air	Steam	1,85E-04	kg
Ammonia/ air	Nitric acid	4,96E-04	kg
Ammonia/ air	Steam	5,51E-05	kg
Heat, waste/ air	Nitric acid	0,45	MJ
Heat, waste/ air	Steam	5,02E-02	MJ
Nitrogen oxides/ air	Nitric acid	9,32E-04	kg
Nitrogen oxides/ air	Steam	1,04E-04	kg
Water, unspecified/ resource/ in water	Nitric acid	3,96E-04	m^3
Water, unspecified/ resource/ in water	Steam	4,40E-05	m^3
Nitrogen/ water/ river	Nitric acid	2,61E-05	kg
Nitrogen/ water/ river	Steam	2,91E-06	kg
Ammonia/ air	ammonium nitrate	2,00E-04	kg
Heat, waste/ air	ammonium nitrate	-0,84	MJ
Particulates, < 2.5 um/ air	ammonium nitrate	2,00E-04	kg
Particulates, > 10 um/ air	ammonium nitrate	2,00E-04	kg
Particulates, > 2.5 um, and < 10um/ air	ammonium nitrate	1,00E-04	kg
Prothioconazol/ soil/ agricultural	ammonium nitrate	2,58E-04	kg
Heat, waste	single superphosphate, as P2O5	6,67	MJ
Hydrogen fluoride	single superphosphate, as P2O5	1,05E-04	kg
Particulates, < 2.5 um	single superphosphate, as P2O5	6,19E-04	kg
Particulates, > 10 um	single superphosphate, as P2O5	1,24E-03	kg
Particulates, > 2.5 um, and < 10um	single superphosphate, as P2O5	1,24E-03	kg
Arsenic, ion	single superphosphate, as P2O5	4,40E-06	kg
Cadmium, ion	single superphosphate, as P2O5	4,40E-06	kg
Chromium, ion	single superphosphate, as P2O5	2,20E-05	kg
Copper, ion	single superphosphate, as P2O5	2,20E-05	kg
Lead	single superphosphate, as P2O5	1,90E-05	kg
Mercury	single superphosphate, as P2O5	4,20E-06	kg
Nickel, ion	single superphosphate, as P2O5	1,70E-05	kg
Phosphate	single superphosphate, as P2O5	4,42E-03	kg
Zinc, ion	single superphosphate, as P2O5	2,60E-05	kg
Arsenic/ air	Buildings, shed	0,02	kg

Table A.5: The table shows the background stressors directly associated with the system. Gray values indicate that the value will vary between templates.

Stressor	*Foreground Process*	*Value*	*Unit*
Benzo(a)pyrene/ air	Buildings, shed	0,03	kg
Methane, fossil/ air/ unspecified	Buildings, shed	443	kg
Carbon monoxide, fossil/ air/ unspecified	Buildings, shed	797	kg
Carbon dioxide, fossil/ air	Buildings, shed	194174	kg
Cadmium/ air	Buildings, shed	8,01E-03	kg
Chromium/ air	Buildings, shed	2,18E-02	kg
Copper/ air	Buildings, shed	6,81E-02	kg
Dioxins/ air	Buildings, shed	1,04E-06	kg
Benzene, hexachloro-/ air	Buildings, shed	6,89E-06	kg
Mercury/ air	Buildings, shed	5,90E-03	kg
Dinitrogen monoxide/ air	Buildings, shed	1862	kg
Ammonia/ air	Buildings, shed	178	kg
NMVOC, unspecified origin/ air	Buildings, shed	591	kg
Nitrogen oxides/ air	Buildings, shed	326	kg
Nickel/ air	Buildings, shed	0,16	kg
PAH/ air	Buildings, shed	4,55E-02	kg
Polychlorinated biphenyls/ air	Buildings, shed	3,20E-04	kg
Particulates, > 10 um/ air	Buildings, shed	104	kg
Particulates, < 2.5 um/ air	Buildings, shed	91	kg
Lead/ air	Buildings, shed	0,13	kg
Sulfur dioxide/ air	Buildings, shed	345,82	kg
Selenium/ air	Buildings, shed	8,46E-04	kg
Particulates, > 2.5 um, and < 10um/ air	Buildings, shed	132	kg
Zinc/ air	Buildings, shed	0,12	kg
Arsenic/ air	Machinery dryer	0,03	kg
Benzo(a)pyrene/ air	Machinery dryer	0,01	kg
Methane, fossil/ air/ unspecified	Machinery dryer	707	kg
Carbon monoxide, fossil/ air/ unspecified	Machinery dryer	402	kg
Carbon dioxide, fossil/ air	Machinery dryer	255736	kg
Cadmium/ air	Machinery dryer	0,01	kg
Chromium/ air	Machinery dryer	0,13	kg
Copper/ air	Machinery dryer	5,58E-02	kg
Dioxins/ air	Machinery dryer	5,94E-07	kg
Benzene, hexachloro-/ air	Machinery dryer	4,23E-06	kg
Mercury/ air	Machinery dryer	6,62E-03	kg
Dinitrogen monoxide/ air	Machinery dryer	39	kg
Ammonia/ air	Machinery dryer	27	kg
NMVOC, unspecified origin/ air	Machinery dryer	214	kg
Nitrogen oxides/ air	Machinery dryer	463	kg
Nickel/ air	Machinery dryer	7,46E-02	kg
PAH/ air	Machinery dryer	0,23	kg
Polychlorinated biphenyls/ air	Machinery dryer	1,49E-03	kg
Particulates, > 10 um/ air	Machinery dryer	43	kg
Particulates, < 2.5 um/ air	Machinery dryer	29,37	kg
Lead/ air	Machinery dryer	0,34	kg
Sulfur dioxide/ air	Machinery dryer	753	kg
Selenium/ air	Machinery dryer	0,03	kg
Particulates, > 2.5 um, and < 10um/ air	Machinery dryer	59	kg
Zinc/ air	Machinery dryer	0,20	kg

Table A.6: The table shows the background stressors directly associated with the system. Gray values indicate that the value will vary between templates.

Stressor	*Foreground Process*	*Value*	*Unit*
Arsenic/ air	Buildings, forestry	0,02	kg
Benzo(a)pyrene/ air	Buildings, forestry	0,13	kg
Methane, fossil/ air/ unspecified	Buildings, forestry	532	kg
Carbon monoxide, fossil/ air/ unspecified	Buildings, forestry	4532	kg
Carbon dioxide, fossil/ air/	Buildings, forestry	389118	kg
Cadmium/ air	Buildings, forestry	0,01	kg
Chromium/ air	Buildings, forestry	0,03	kg
Copper/ air	Buildings, forestry	0,05	kg
Dioxins/ air	Buildings, forestry	1,26E-06	kg
Benzene, hexachloro-/ air	Buildings, forestry	1,84E-05	kg
Mercury/ air	Buildings, forestry	4,58E-03	kg
Dinitrogen monoxide/ air	Buildings, forestry	2313	kg
Ammonia/ air	Buildings, forestry	226	kg
NMVOC, unspecified origin/ air	Buildings, forestry	557	kg
Nitrogen oxides/ air	Buildings, forestry	609	kg
Nickel/ air	Buildings, forestry	0,10	kg
PAH/ air	Buildings, forestry	3,00E-02	kg
Polychlorinated biphenyls/ air	Buildings, forestry	3,12E-04	kg
Particulates, > 10 um/ air	Buildings, forestry	436	kg
Particulates, < 2.5 um/ air	Buildings, forestry	428	kg
Lead/ air	Buildings, forestry	0,14	kg
Sulfur dioxide/ air	Buildings, forestry	288	kg
Selenium/ air/	Buildings, forestry	1,81E-03	kg
Particulates, > 2.5 um, and < 10um/ air	Buildings, forestry	459	kg
Zinc/ air	Buildings, forestry	0,36	kg

Appendix B

Variables from Bioforsk

[utf8]inputenc

Table B.1: The table shows the variables used from the bioforsk project that vary with both grain-type and area.

	Unit	*Barley*	*Oat*	*W. Wheat*	*S. Wheat*
Area 1					
Optikas	kg/ha	0	0	-	-
Fertilizer (22.3.10)	kg/ha	440	424	-	-
Tractor and thresher trans.	kg CO_2/ha	212	215	-	-
Area 2					
Optikas	kg/ha	0	0	218	150
Fertilizer (22.3.10)	kg/ha	510	445	444	420
Tractor and thresher trans.	kg CO_2/ha	172	181	191	183
Area 3					
Optikas	kg/ha	0	0	160	110
Fertilizer (22.3.10)	kg/ha	540	520	470	430
Tractor and thresher trans.	kg CO_2/ha	201	204	223	207

Table B.2: The table shows the variables used from the bioforsk project that vary only with area.

	Unit	Area 1	Area 2	Area 3
P run-off	kg/ha	1,2	0,245	2,1
Lime	kg/ha	454	446	417

Table B.3: The table shows the variables used from the bioforsk project that vary only with graintype. The variables in the first section are products required at the farm, while the variables in the second section are stressors emitted to agricultural soils. The bottom section shows variables used to calculate the nitrogen content in crop residues.

	Unit	Barley	Oat	W. Wheat	S. Wheat
Herbicides	kg/ha	0,0717	0,083	0,01	0,0717
Insecticides	kg/ha	0,00425	0,0034	0	0,027
Growth_reg	kg/ha	0,0185	0,375	0	0
Fungicide_pest	kg/ha	0,1625	0	0,2375	0,238
Fungicide_seed	kg/ha	0,01	0	0	0,01
Fluroxypyr	kg/ha	0,07	0,07	0	0,07
Trifloxystrobin	kg/ha	0,075	0	0,075	0,075
Florasulam	kg/ha	0,0017	0	0	0,0017
Trinexapac_ethyl	kg/ha	0,0185	0	0	0
Prothioconazol	kg/ha	0,0875	0	0,1625	0,163
Alphacypermethrin	kg/ha	0,00425	0,0034	0	0,017
Tribenuron_methyl	kg/ha	0	0,013	0	0
Chlormequat	kg/ha	0	0,375	0	0
Pirimicarb	kg/ha	0	0	0	0,01
Iodosulfuron	kg/ha	0	0	0,01	0
Slope	tonnes	0,98	0,91	1,51	1,29
Intercept	tonnes	0,59	0,89	0,52	0,75
N content ab		0,007	0,007	0,006	0,006
ratio ab be		0,22	0.25	0,24	0,28
N content be		0,014	0,008	0,009	0,009

Appendix C

Matlab Codes

C.1 Average Yield

```
 clear all;
clc;

%READING IN DATA;
%yield
tall1=xlsread(’yield_2005_2010.xlsx’,’yield’,’B2:V1015’);
%counties
[tall2,tekst2,begge2]=xlsread(’yield_2005_2010.xlsx’,’county’,’B2:B179’);
%year
ar=xlsread(’kornavlinger_2005_2010.xlsx’,’yield’,’A2:A1015’);
%wheatratios
ratio=xlsread(’kornavlinger_2005_2010.xlsx’,’wheatratio’,’B30:F35’);

%SETTING VARIABLES
da=[tall1(:,18), tall1(:,19),tall1(:,15),tall1(:,14)];
kg_rug_rughvete = tall1(:,8)+tall1(:,9);
kg_bygg =tall1(:,10);
kg_havre=tall1(:,11);
kg_oljev= tall1(:,12);
kg_hvete= tall1(:,7);

%CALCULATING YIELD KG/(HA*YEAR)
avl_rug_rughvete=kg_rug_rughvete ./ tall1(:,17) *10;
avl_bygg= tall1(:,10) ./ tall1(:,18) * 10;
avl_havre= tall1(:,11) ./ tall1(:,19) * 10;
avl_oljev= tall1(:,12) ./ tall1(:,20) * 10;

%extra calculations for wheat:
da_varhvete= tall1(:,14);
da_hosthvete= tall1(:,15);
da_hvete= tall1(:,16);
da_hvete_sjekk = [da_varhvete, da_hosthvete];
sjekk = all(da_hvete_sjekk,2);

%Setting preliminary yield (will only remain for years with only
%either spring or winter wheat being produced)
avl_varhvete = kg_hvete ./ da_varhvete * 10;
avl_hosthvete = kg_hvete ./ da_hosthvete * 10;

kg_varhvete= da_varhvete./da_varhvete.*kg_hvete;
kg_hosthvete= da_hosthvete./da_hosthvete.*kg_hvete;
kg_varhvete(isnan(kg_varhvete))=0;
kg_hosthvete(isnan(kg_hosthvete))=0;

%For years with both spring and winter wheat, the ratio (which is year
```

```
%and area specific) between them is used
 for i = 1:1014
     for j = 1:6
        if (ratio(j,1) == ar(i) &&  tall1(i,1) <= 15 && sjekk(i))
            avl_varhvete(i,1)=(kg_hvete(i)/da_hvete(i))*ratio(j,3)*10;
            avl_hosthvete(i,1)=(kg_hvete(i)/da_hvete(i))*ratio(j,5)*10;
            kg_varhvete(i,1)=kg_hvete(i)*ratio(j,3)/2;
            kg_hosthvete(i,1) = kg_hvete(i)*ratio(j,5)/2;
        end
        if (ratio(j,1) == ar(i) && tall1(i,1) > 15 && sjekk(i))
            avl_varhvete(i,1)=(kg_hvete(i)/da_hvete(i))*ratio(j,2)*10;
            avl_hosthvete(i,1)=(kg_hvete(i)/da_hvete(i))*ratio(j,4)*10;
            kg_varhvete(i,1) = kg_hvete(i)*ratio(j,2)/2;
            kg_hosthvete(i,1) = kg_hvete(i)*ratio(j,4)/2;
        end
     end
 end

tall_avl = [avl_rug_rughvete, avl_bygg, avl_havre, avl_oljev,
            avl_varhvete, avl_hosthvete, kg_rug_rughvete, kg_bygg,
             kg_havre, kg_oljev, kg_varhvete, kg_hosthvete];
tall_avl(isnan(tall_avl))=0;
tall_avl(isinf(tall_avl))=0;

%CALCULATING AVERAGE YIELD (KG) PER HA FOR THE TOWNSHIPS FOR THE
%YEARS WITH AVAILABLE DATA
 j = 1;
 for i = 1:178
     kommune = begge2(i,1);
     summen = zeros(12,1);
     antall = zeros(12,1);
     ant=zeros(4,1);
     sumda=zeros(4,1);

     while(strcmp(begge1(j,1),kommune))
         for k = 1:12
             summen(k) = summen(k) + tall_avl(j,k);
             if(tall_avl(j,k) ~= 0 )
                 antall(k) = antall(k) + 1;
             end
         end
         for m=1:4
             sumda(m)=sumda(m) + da(j,m);
             if(da(j,m) ~= 0 )
                 ant(m) = ant(m) + 1;
             end
         end
         j = j+1;
         if(j == 1015)
             break;
         end
     end
     output_kommune(i,:)=summen./antall;
     da_kommune(i,:)=sumda./ant;
 end

output_kommune(isnan(output_kommune))=0;
da_kommune(isnan(da_kommune))=0;

%CALCULATING AVG YIELD COUNTIES
fylketall = [1;2;3;4;5;6;7;8;11;15;16;17];
l=1;
for i = 1:length(fylketall)
     fylke = fylketall(i);
     summen = zeros(12,1);
     antall = zeros(12,1);
     while(tall1(l,1)==fylke)
         for k = 1:12
             summen(k) = summen(k) + tall_avl(l,k);
             if(tall_avl(l,k) ~= 0 )
                 antall(k) = antall(k) + 1;
             end
         end
         l = l+1;
```

```
        if(l == 1015)
            break;
        end
    end
    output_fylke(i,:)=summen./antall;
end

output_fylke(isnan(output_fylke))=0;

```

C.2 Read Inn Data

```
 clear all;
clc;

%READING IDENTIFICATION
[foo,foo,name_customization]= xlsread(’tabell.xlsx’,’DATA2’,’A6:A220’);
original_name=’LCA_template_’;
[fylkenr,too,fylkenrfoo] = xlsread(’tabell.xlsx’,’DATA2’,’D6:D220’);
[roo,fylkenavn,roo] = xlsread(’tabell.xlsx’,’DATA2’,’E6:E220’);
[roo,kornnavn,roo] = xlsread(’tabell.xlsx’,’DATA2’,’F6:F220’);

%READING INPUT-DATA
Input= xlsread(’tabell.xlsx’,’DATA2’,’G6:U220’);
pesticide_Abf = xlsread(’tabell.xlsx’,’Pesticide’,’D6:G10’);
pesticide_Ff = xlsread(’tabell.xlsx’,’Pesticide’,’D11:G20’);

%READING BASETEMPLATE
[foreground_tall, foreground_navn, basetemplate_foreground]=
   xlsread(’base_template.xlsx’,’Foreground’,’M4:AP32’);
[Abf_tall, Abf_navn, basetemplate_Abf]=
   xlsread(’base_template.xlsx’,’A_bf’,’A5:E39’);
[F_f_tall, F_f_navn, basetemplate_F_f]=
   xlsread(’base_template.xlsx’,’F_f’,’A5:E201’);

%removing NAN
foreground_tall(isnan(foreground_tall))=0;
Abf_tall(isnan(Abf_tall))=0;
F_f_tall(isnan(F_f_tall))=0;

save(’data.mat’);
```

C.3 Template Maker

```

%%%%%%%%%%%%%  TEMPLATEMAKER  %%%%%%%%%%%%%%%

load(’Data.mat’);

%ASSIGNING CONSTANTS
NH3_loss_percent=0.02;
avg_seedbed_prep= 21.8878414 ;
glyphosate = 0.933333333;

for i=1:length(name_customization)

    %ASSIGNING VARIABLENAMES
    grain = Input(i,1);
    yield = Input(i,3);
    MC_grain = Input(i,4);
    N_use_HOLOS = Input(i,5);
    El_use = Input(i,6);
    soil_C_CO2 = Input(i,10);
    soil_N2O_CO2 = Input(i,12);
    gnbn = Input(i,14);
    total_area_farm = Input(i,15);
```

```

   %ASSIGNING GRAIN TYPE SPECIFIC CONSTANTS
   if grain == 5 %Winter Wheat
     slope = 1.51;
     intercept = 0.52;
     n_prop_ab = 0.006;
     ratio_ab_be = 0.24;
     n_prop_be = 0.009;
     seed=230;
     pest_Abf = pesticide_Abf(:,2);
     pest_Ff = pesticide_Ff(:,2);

     %ASSIGNING CONSTANTS THAT VARY WITH GRAIN TYPE AND AREA
     if fylkenr(i) < 4 %Zone 3
         diesel = 223.27;
         kalksalpeter = 160;
         fert = 470;
         phosphate = 2.1*95/31;
         lime=417;
     elseif fylkenr(i) < 6  %Zone 2
         diesel = 191.14;
         kalksalpeter = 218.2;
         fert = 443.9;
         phosphate = 0.245*95/31;
         lime=446;
     elseif fylkenr(i) < 12 %Zone 3
         diesel = 223.27;
         kalksalpeter = 160;
         fert = 470;
         phosphate = 2.1*95/31;
         lime=417;
     else   %Zone 1
         diesel = 227.68;
         kalksalpeter = 140;
         fert = 400;
         phosphate = 1.2*95/31;
         lime=454;
     end

     %REPEATING PROCEDURE FOR THE 3 REMAINING GRAINTYPES
     ...
   end

N_fert = fert*0.216;
N_kalksalpeter= kalksalpeter*0.27;

%NH3 and NOx from volatilization:
N_vol = (N_fert + N_kalksalpeter) * 0.1 ;
NH3_N = N_vol * 0.02;
NH3 = NH3_N / 14 * 17 ;
NOx_N = N_vol * 0.98;
NOx_field = NOx_N / 14 * 46 ;

%N in crop residues:
DM = yield * (1 - 0.15) ;
tot_ab = ((DM/1000) * slope + intercept) *1000;
N_ab = tot_ab * n_prop_ab;
tot_be = tot_ab * ratio_ab_be ;
N_be = tot_be * n_prop_be ;
N_cropresidues = N_ab + N_be; %F_cr

%N-runoff:
soil_C = soil_C_CO2*(12/44);
N_mineralisert = soil_C/10;

N_runoff = (N_fert + N_kalksalpeter + N_mineralisert + N_cropresidues)*0.3;

%N2O emissions
soil_N2O_N_HOLOS = (soil_N2O_CO2/298) * (28/44);

soil_N2O_N_HOLOSfert=(N_use_HOLOS*0.01);
soil_N2O_N_bioforsk = (N_fert + N_kalksalpeter+ N_mineralisert + N_cropresidues)*0.01;

soil_N2O_N = soil_N2O_N_HOLOS-soil_N2O_N_HOLOSfert+soil_N2O_N_bioforsk;
```

```
soil_N2O = soil_N2O_N*(44/28);

%CO2 from added lime:
EF_dolomite = 0.13;
CO2_C_liming = lime * EF_dolomite;
CO2_liming = CO2_C_liming * 44/12;

%CO2 from both mineralization and lime:
CO2_minandlime = soil_C_CO2 + CO2_liming;

%NOx emissions from dieseluse:
NOx_diesel = diesel/2.6391 * avg_seedbed_prep/1000;

%Finding ha required per kg grain produced
haperkg = 1/(yield-seed);

%Infrastructure Requirements:
buildings_shed = 0.4*150000/1000000/8/30/total_area_farm +(0.4*1.6/8/30/total_area_farm);
buildings_forestry = 0.6*150000/1000000/8/30/total_area_farm +(0.6*1.6/8/30/total_area_farm);
machinery_drier = 150000/1000000/8/30/total_area_farm;
tractor_and_tresher = 1/total_area_farm;
machinery = (1360/12+1400/20+1200/20+1700/20+700/12+2700/10+2000/15+200/12)/total_area_farm;

%Assigning new values to foreground:
foreground_tall(1,1) = haperkg;
foreground_tall(2,1) = haperkg;
foreground_tall(3,1) = haperkg;
foreground_tall(4,1) = haperkg;
foreground_tall(10,1) = haperkg;
foreground_tall(21,4) = diesel;
foreground_tall(14,6) = kalksalpeter;
foreground_tall(15,6) = fert;
foreground_tall(22,14) = buildings_shed;
foreground_tall(23,14) = buildings_forestry;
foreground_tall(24,13) = machinery_drier;
foreground_tall(25,12) = tractor_and_tresher;
foreground_tall(26,12) = tractor_and_tresher;
foreground_tall(27,12) = tractor_and_tresher;
foreground_tall(28,13) = machinery;

%Values to abf:
Abf_tall(1,3) = El_use;
Abf_tall(17,3) = lime;
Abf_tall(21,3) = glyphosate;
Abf_tall(22:26,3) = pest_Abf;

%Values to Ff:
F_f_tall(1,3) = glyphosate;
F_f_tall(2:11,3) = pest_Ff;
em = [CO2_minandlime; soil_N2O; NOx_field; NH3; phosphate; N_runoff];
F_f_tall(12:17,3) = em;
F_f_tall(41,3) = NOx_diesel;

eval(['Foreground_' num2str(i) '=foreground_tall']);
eval(['A_bf_' num2str(i) '=Abf_tall']);
eval(['F_f_' num2str(i) '=F_f_tall']);

%Creating temporary template
! copy base_template.xlsx TemplateTmp.xlsx

%Modifying temporary Template
xlswrite ('TemplateTmp.xlsx',foreground_tall, 'Foreground', 'N5');
xlswrite ('TemplateTmp.xlsx',Abf_tall, 'A_bf', 'C5');
xlswrite ('TemplateTmp.xlsx',F_f_tall, 'F_f', 'C5');

%Eliminating Norwegian characters from template filename
x = char(kornnavn(i));
x(x=='å') = 'a' ;
x(x=='æ') = 'a';
x(x=='ø') = 'o';

y = char(fylkenavn(i));
y(y=='å') = 'a';
y(y=='æ') = 'a';
```

```
 y(y=='ø') = 'o';
 y(y=='Å') = 'A';
 y(y=='Æ') = 'A';
 y(y=='Ø') = 'O';

 %Rename Temporary Template and move
 custom_name = [original_name,name_customization{i},'_',x,'_',y,'.xls'];
 eval(['! move TemplateTmp.xlsx ',custom_name]);

end
```

C.4 ARDA Robot

```
 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%% ARDA-ROBOT-REPEAT  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% If want "\" in string, type "\\"
%% Pause after "\\", if followed by large letter
%% Make sure computer doesnt enter sleepmode, automatically updates,
%% incoming skypecall ect while running script
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;

% Reading inn variables for making filenames %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[foo,foo,name_customization]= xlsread('tabell.xlsx','DATA2','A6:A220');
[roo,fylkenavn,roo] = xlsread('tabell.xlsx','DATA2','E6:E220');
[roo,kornnavn,roo] = xlsread('tabell.xlsx','DATA2','F6:F220');

% Starting loop %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for j=1:length(name_customization)

    %removing norwegian characters from filename
    x = char(kornnavn(j));
        x(x=='å') = 'a' ;
        x(x=='æ') = 'a';
        x(x=='ø') = 'o';

    y = char(fylkenavn(j));
        y(y=='å') = 'a';
        y(y=='æ') = 'a';
        y(y=='ø') = 'o';
        y(y=='Å') = 'A';
        y(y=='Æ') = 'A';
        y(y=='Ø') = 'O';

custom_name=[name_customization{j},'_',x,'_',y,'.xls'];
pause(1)

% Open arda and write password %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
open('arda15_1_win.exe')
pause(40)
inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','locedni')
pause(0.1)
inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','\SPACE')

% Upload Backgroundatrix%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pause(5)
inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','\DOWN')
pause(0.1)
inputemuu('key_normal','\DOWN')
pause(0.1)
```

```
inputemuu(’key_normal’,’\DOWN’)
pause(0.1)
inputemuu(’key_normal’,’\TAB’)
pause(0.1)
inputemuu(’key_normal’,’\TAB’)
pause(0.5)

inputemuu(’key_normal’,’D:\\’)
pause(0.1)
inputemuu(’key_normal’,’Data\\’)
pause(0.1)
inputemuu(’key_normal’,’Documents\\’)
pause(0.1)
inputemuu(’key_normal’,’Agriculture\\’)
pause(0.1)
inputemuu(’key_normal’,’Ecoinvent_2_2_ReCiPe_H_CustomStressor.mat’)
pause(0.1)
inputemuu(’key_normal’,’\TAB’)
pause(0.1)
inputemuu(’key_normal’,’\SPACE’)
pause(6)

 for i=1:7
     inputemuu(’key_normal’,’\TAB’)
     pause(0.1)
 end

 pause(0.5)
 inputemuu(’key_normal’,’\SPACE’)
 pause(2)

 for i=1:4
     inputemuu(’key_normal’,’\TAB’)
     pause(0.5)
 end

% Upload foreground and demand %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
inputemuu(’key_normal’,’D:\\’)
pause(0.5)
inputemuu(’key_normal’,’Data\\’)
pause(0.5)
inputemuu(’key_normal’,’Documents\\’)
pause(0.5)
inputemuu(’key_normal’,’Agriculture\\’)
pause(0.5)
inputemuu(’key_normal’,’Workfiles\\’)
pause(0.5)
inputemuu(’key_normal’,’LCA_template_’)
pause(0.5)
inputemuu(’key_normal’,custom_name)

pause(2)
inputemuu(’key_normal’,’\TAB’)
pause(0.1)
inputemuu(’key_normal’,’\SPACE’)
pause(15)

% Tabbing down to "manually input indexes" %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 for i=1:17
     inputemuu(’key_normal’,’\TAB’)
     pause(0.1)
 end

 inputemuu(’key_normal’,’\SPACE’)
 pause(5)
 inputemuu(’key_normal’,’\TAB’)
 pause(0.1)

 % Writing indexes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 inputemuu(’key_normal’,’10001, 10002, 10003, 10004, 10005, 10011’)
 pause(1)
 inputemuu(’key_normal’,’\TAB’)
 pause(0.1)
 inputemuu(’key_normal’,’\SPACE’)
```

```
 pause(6)

% Accepting the foreground-processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  inputemuu('key_normal','\TAB')
  pause(0.1)
  inputemuu('key_normal','\TAB')
  pause(0.1)
  inputemuu('key_normal','\SPACE')
  pause(4)


%Tabbing to and pressing ok for "Emissions and Impact Calk" %%%%%%%%%%%%%%%

inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','\TAB')
pause(0.1)
inputemuu('key_normal','\SPACE')


 % Scrolling down %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 pause(30)
 inputemuu('key_normal','\TAB')
 for i=1:10
     inputemuu('key_normal','\PAGEDOWN')
     pause(0.1)
 end

 % Tabbing down and accepting truncation  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 for i=1:32
    inputemuu('key_normal','\TAB')
    pause(0.2)
 end
 inputemuu('key_normal','\SPACE')
 pause(4)

 for i=1:34
     inputemuu('key_normal','\TAB')
     pause(0.05)
 end

 % Writing filename of resultfile %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 pause(2)
 inputemuu('key_normal','LCA_results_')
 pause(0.5)
 inputemuu('key_normal',custom_name)
 pause(0.5)
 inputemuu('key_normal','\TAB')
 pause(0.5)
 inputemuu('key_normal','\TAB')
 pause(0.5)

 % Write location for resultfile %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 inputemuu('key_normal','D:\\')
 pause(0.5)
 inputemuu('key_normal','Data\\')
 pause(0.5)
 inputemuu('key_normal','Documents\\')
 pause(0.5)
 inputemuu('key_normal','Agriculture\\')
 pause(0.5)
 inputemuu('key_normal','results')
 pause(1)

 % Saving as mat-file %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 inputemuu('key_normal','\TAB')
 pause(0.1)
 inputemuu('key_normal','\SPACE')
 pause(10)

 % Closing Arda%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 inputemuu('key_ctrl','w')
```

```
 pause(7)

end
```

C.5 Result Management

```
clear all;
%Reading inn variables for making filenames%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[foo,foo,name_customization]= xlsread('tabell.xlsx','DATA2','A6:A220');
[roo,fylkenavn,roo] = xlsread('tabell.xlsx','DATA2','E6:E220');
[roo,kornnavn,roo] = xlsread('tabell.xlsx','DATA2','F6:F220');
farm_kg_produced1 =xlsread('tabell.xlsx','DATA2','Z6:Z220');

farm_kg_produced=repmat(farm_kg_produced1,1,18);
kg_produced_farm_barley=farm_kg_produced1(1:70);
kg_produced_farm_oat=farm_kg_produced1(71:131);
kg_produced_farm_springwh=farm_kg_produced1(132:181);
kg_produced_farm_winterwh=farm_kg_produced1(182:215);

%making empty matrices
emp=zeros(215,6);
agricultural_land_occupation = emp;
climate_change = emp;
fossil_depletion = emp;
freshwater_ecotoxicity = emp;
freshwater_eutrophication = emp;
human_toxicity = emp;
ionising_radiation = emp;
marine_ecotoxicity = emp;
marine_eutrophication = emp;
metal_depletion = emp;
natural_land_transformation = emp;
ozone_depletion = emp;
particulate_matter_formation = emp;
photochemical_oxidant_formation = emp;
terrestrial_acidification = emp;
terrestrial_ecotoxicity = emp;
urban_land_occupation = emp;
water_depletion = emp;

d_all = zeros(18,215);
d_f_all = zeros(18,215);

for j=1:length(name_customization)
      x = char(kornnavn(j));
        x(x=='å') = 'a' ;
        x(x=='æ') = 'a';
        x(x=='ø') = 'o';
      y = char(fylkenavn(j));
        y(y=='å') = 'a';
        y(y=='æ') = 'a';
        y(y=='ø') = 'o';
        y(y=='Å') = 'A';
        y(y=='Æ') = 'A';
        y(y=='Ø') = 'O';

custom_name=['LCA_results_',name_customization{j},'_'
    ,x,'_',y,'_kommuneyield.xls.mat'];

%importing resultfile j
a = importdata(custom_name);

%Collecting all data in D_pro_f-categories in resultfile j
agricultural_land_occupation(j,:)= full(a.D_pro_f(1,1:6));
climate_change(j,:) = full(a.D_pro_f(2,1:6));
fossil_depletion(j,:) = full(a.D_pro_f(3,1:6));
freshwater_ecotoxicity(j,:) = full(a.D_pro_f(4,1:6));
freshwater_eutrophication(j,:) = full(a.D_pro_f(5,1:6));
human_toxicity(j,:) = full(a.D_pro_f(6,1:6));
ionising_radiation(j,:) = full(a.D_pro_f(7,1:6));
```

```
marine_ecotoxicity(j,:) = full(a.D_pro_f(8,1:6));
marine_eutrophication(j,:) = full(a.D_pro_f(9,1:6));
metal_depletion(j,:) = full(a.D_pro_f(10,1:6));
natural_land_transformation(j,:) = full(a.D_pro_f(11,1:6));
ozone_depletion(j,:) = full(a.D_pro_f(12,1:6));
particulate_matter_formation(j,:) = full(a.D_pro_f(13,1:6));
photochemical_oxidant_formation(j,:) = full(a.D_pro_f(14,1:6));
terrestrial_acidification(j,:) = full(a.D_pro_f(15,1:6));
terrestrial_ecotoxicity(j,:) = full(a.D_pro_f(16,1:6));
urban_land_occupation(j,:) = full(a.D_pro_f(17,1:6));
water_depletion(j,:) = full(a.D_pro_f(18,1:6));

%Collecting d
 d_all(:,j) = full(a.d(1:18,1));
 d_f_all(:,j)=full(a.d_f(1:18,1));

end

d_all=d_all’;
d_f_all=d_f_all’;

%finding the d considering kg produced at farm:
d_farm_kg_produced=d_all.*farm_kg_produced;

%Arranging d_all into individual graintype matrices:
d_all_barley=d_all(1:70,:);
d_all_oat=d_all(71:131,:);
d_all_springwh=d_all(132:181,:);
d_all_winterwh=d_all(182:215,:);

%Arranging d_farm_kg_produced into individual graintype matrices:
d_kg_produced_barley=d_farm_kg_produced(1:70,:);
d_kg_produced_oat=d_farm_kg_produced(71:131,:);
d_kg_produced_springwh=d_farm_kg_produced(132:181,:);
d_kg_produced_winterwh=d_farm_kg_produced(182:215,:);

%Rearranging d_all to have graintype in individual columns:

  d_graintype_together=zeros(70,72);
  for j=1:18

   emp=zeros(70,1);
x_barley=emp;
x_oat=emp;
x_springwh=emp;
x_winterwh=emp;
x_barley=d_all(1:70,j);
x_oat(1:61,:)=d_all(71:131,j);
x_springwh(1:50,:)=d_all(132:181,j);
x_winterwh(1:34,:)=d_all(182:215,j);
x=[x_barley x_oat x_springwh x_winterwh]
d_graintype_together(:,(j+(3*j)-3):(j+(3*j)))=x;
  end

 d_graintype_farm_kg_produced=zeros(70,72);

  for j=1:18
   emp=zeros(70,1);
y_barley=emp;
y_oat=emp;
y_springwh=emp;
y_winterwh=emp;
y_barley=d_farm_kg_produced(1:70,j);
y_oat(1:61,:)=d_farm_kg_produced(71:131,j);
y_springwh(1:50,:)=d_farm_kg_produced(132:181,j);
y_winterwh(1:34,:)=d_farm_kg_produced(182:215,j);
y=[y_barley y_oat y_springwh y_winterwh]
d_graintype_farm_kg_produced(:,(j+(3*j)-3):(j+(3*j)))=y;
  end

[tall1, tekst1, begge1]  = xlsread(’tabell.xlsx’,’DATA2’,’C6:C220’);
[tall2, tekst2, begge2] = xlsread(’tabell.xlsx’,’ikke ror’,’AQ3:AQ49’);

%FINDING TOTAL KG and IMPACT ON COUNTYLEVEL FROM THE FARMS WE HAVE DATA FOR
```

```
dtot_farmsincounty=zeros(47,18);
kgtot_farmsincounty=zeros(47);

 for i=1:47
   kommune = begge2(i,1);
   antall = zeros(18,1);
   j = 1;
  while(j<216)
     if(strcmp(begge1(j,1),kommune))
        kgtot_farmsincounty(i)=kgtot_farmsincounty(i) +
          farm_kg_produced1(j);
        for k = 1:18
           dtot_farmsincounty(i,k) = dtot_farmsincounty(i,k) +
             d_farm_kg_produced(j,k);
        end
    end
    j=j+1;
  end
 end

 sum_impact_all_farms=sum(d_farm_kg_produced);
 sum_impact_all_farms_test=sum(dtot_farmsincounty);
 sum_kg_all_farms=sum(kgtot_farmsincounty);

 farm_kg_produced_grain=zeros(70,4);
 farm_kg_produced_grain(1:70,1)=farm_kg_produced1(1:70,1);
 farm_kg_produced_grain(1:61,2)=farm_kg_produced1(71:131,1);
 farm_kg_produced_grain(1:50,3)=farm_kg_produced1(132:181,1);
 farm_kg_produced_grain(1:34,4)=farm_kg_produced1(182:215,1);

 %FINDING TOT KG AND IMPACT OF EACH GRAINTYPE IN EACH FYLKE
[tall1, tekst1, begge1]  = xlsread(’tabell.xlsx’,’DATA2’,’E6:E220’);
[tall2, tekst2, begge2] = xlsread(’tabell.xlsx’,’ikke ror’,’AT3:AT11’);

%BARLEY (template 1 to 70)
dtot_barley_fylke=zeros(9,18);
kgtot_barley_fylke=zeros(9);
 for i=1:9
     fylke = begge2(i,1);
     j = 1;
    while(j<71)
        if(strcmp(begge1(j,1),fylke))
            kgtot_barley_fylke(i)=kgtot_barley_fylke(i)
              + farm_kg_produced1(j);
            for k = 1:18
               dtot_barley_fylke(i,k) = dtot_barley_fylke(i,k)
                 + d_farm_kg_produced(j,k);
            end
        end
        j=j+1;
    end
 end

 %OAT (template 71-131)
dtot_oat_fylke=zeros(9,18);
kgtot_oat_fylke=zeros(9);
 for i=1:9
     fylke = begge2(i,1);
     j = 71;
    while(j<132)
        if(strcmp(begge1(j,1),fylke))
            kgtot_oat_fylke(i)=kgtot_oat_fylke(i) + farm_kg_produced1(j);
            for k = 1:18
               dtot_oat_fylke(i,k) = dtot_oat_fylke(i,k)
                 + d_farm_kg_produced(j,k);
            end
        end
        j=j+1;
    end
 end

  %SPRING WHEAT (template 132-181)
dtot_springwh_fylke=zeros(9,18);
kgtot_springwh_fylke=zeros(9);
```

```
 for i=1:9
     fylke = begge2(i,1);
     j = 132;
    while(j<182)
        if(strcmp(begge1(j,1),fylke))
            kgtot_springwh_fylke(i)=kgtot_springwh_fylke(i)
                + farm_kg_produced1(j);
            for k = 1:18
               dtot_springwh_fylke(i,k) = dtot_springwh_fylke(i,k)
               + d_farm_kg_produced(j,k);
            end
        end
        j=j+1;
    end
 end

 %WINTER WHEAT (template 182-215)
dtot_winterwh_fylke=zeros(9,18);
kgtot_winterwh_fylke=zeros(9);
 for i=1:9
     fylke = begge2(i,1);
     j = 182;
    while(j<216)
        if(strcmp(begge1(j,1),fylke))
            kgtot_winterwh_fylke(i)=kgtot_winterwh_fylke(i)
            + farm_kg_produced1(j);
            for k = 1:18
               dtot_winterwh_fylke(i,k) = dtot_winterwh_fylke(i,k)
               + d_farm_kg_produced(j,k);
            end
        end
        j=j+1;
    end
 end

  %FINDING VALUES FOR THE 3 ZONES
 dtot_barley_zone=zeros(3,18);
dtot_barley_zone(1,:)= dtot_barley_fylke(8,:)+dtot_barley_fylke(9,:);
dtot_barley_zone(2,:)= dtot_barley_fylke(3,:)+dtot_barley_fylke(4,:);
dtot_barley_zone(3,:)= dtot_barley_fylke(1,:)+dtot_barley_fylke(2,:)
    +dtot_barley_fylke(5,:)+dtot_barley_fylke(6,:)+dtot_barley_fylke(7,:);
kgtot_barley_zone=zeros(3);
kgtot_barley_zone(1)=kgtot_barley_fylke(8)+kgtot_barley_fylke(9);
kgtot_barley_zone(2)=kgtot_barley_fylke(3)+kgtot_barley_fylke(4);
kgtot_barley_zone(3)=kgtot_barley_fylke(1)+kgtot_barley_fylke(2)
    +kgtot_barley_fylke(5)+kgtot_barley_fylke(6)+kgtot_barley_fylke(7);

dtot_oat_zone=zeros(3,18);
dtot_oat_zone(1,:)= dtot_oat_fylke(8,:)+dtot_oat_fylke(9,:);
dtot_oat_zone(2,:)= dtot_oat_fylke(3,:)+dtot_oat_fylke(4,:);
dtot_oat_zone(3,:)= dtot_oat_fylke(1,:)+dtot_oat_fylke(2,:)
    +dtot_oat_fylke(5,:)+dtot_oat_fylke(6,:)+dtot_oat_fylke(7,:);
kgtot_oat_zone=zeros(3);
kgtot_oat_zone(1)=kgtot_oat_fylke(8)+kgtot_oat_fylke(9);
kgtot_oat_zone(2)=kgtot_oat_fylke(3)+kgtot_oat_fylke(4);
kgtot_oat_zone(3)=kgtot_oat_fylke(1)+kgtot_oat_fylke(2)
    +kgtot_oat_fylke(5)+kgtot_oat_fylke(6)+kgtot_oat_fylke(7);

dtot_springwh_zone=zeros(3,18);
dtot_springwh_zone(1,:)= dtot_springwh_fylke(8,:)+dtot_springwh_fylke(9,:);
dtot_springwh_zone(2,:)= dtot_springwh_fylke(3,:)+dtot_springwh_fylke(4,:);
dtot_springwh_zone(3,:)= dtot_springwh_fylke(1,:)+dtot_springwh_fylke(2,:)
    +dtot_springwh_fylke(5,:)+dtot_springwh_fylke(6,:)+dtot_springwh_fylke(7,:);
kgtot_springwh_zone=zeros(3);
kgtot_springwh_zone(1)=kgtot_springwh_fylke(8)+kgtot_springwh_fylke(9);
kgtot_springwh_zone(2)=kgtot_springwh_fylke(3)+kgtot_springwh_fylke(4);
kgtot_springwh_zone(3)=kgtot_springwh_fylke(1)+kgtot_springwh_fylke(2)
    +kgtot_springwh_fylke(5)+kgtot_springwh_fylke(6)+kgtot_springwh_fylke(7);

dtot_winterwh_zone=zeros(3,18);
dtot_winterwh_zone(1,:)= dtot_winterwh_fylke(8,:)+dtot_winterwh_fylke(9,:);
dtot_winterwh_zone(2,:)= dtot_winterwh_fylke(3,:)+dtot_winterwh_fylke(4,:);
dtot_winterwh_zone(3,:)= dtot_winterwh_fylke(1,:)+dtot_winterwh_fylke(2,:)
    +dtot_winterwh_fylke(5,:)+dtot_winterwh_fylke(6,:)+dtot_winterwh_fylke(7,:);
```

```
kgtot_winterwh_zone=zeros(3);
kgtot_winterwh_zone(1)=kgtot_winterwh_fylke(8)+kgtot_winterwh_fylke(9);
kgtot_winterwh_zone(2)=kgtot_winterwh_fylke(3)+kgtot_winterwh_fylke(4);
kgtot_winterwh_zone(3)=kgtot_winterwh_fylke(1)+kgtot_winterwh_fylke(2)
    +kgtot_winterwh_fylke(5)+kgtot_winterwh_fylke(6)+kgtot_winterwh_fylke(7);

%SAVING THE WORKSPACE
save(’results_management_kommuneyield’)

```

```
%Result_analysis, only the case of barley:
clear all
load(’results_management_kommuneyield’)

%SUMMARY STATISTICS; UNWEIGHTED
mean_barley=mean(d_all_barley);
median_barley=median(d_all_barley);
max_barley=max(d_all_barley);
min_barley=min(d_all_barley);
std_barley=std(d_all_barley);

%SUMMARY STATISTICS; WEIGHTED
for i=1:18
    weightedmean_barley(:,i)=wmean(d_all_barley(:,i),kg_prod_farm_barley);
    weightedmedian_barley(:,i)=weightedMedian(d_all_barley(:,i),
        kg_prod_farm_barley);
    weightedvar_barley(:,i)=var(d_all_barley(:,i),kg_prod_farm_barley);
    weightedstd_barley(:,i)=sqrt(weightedvar_barley(:,i));
end

fore_wmean_cc=zeros(4,6);
fore_wmean_freshwecotox=zeros(4,6);
fore_wmean_humantox=zeros(4,6);
fore_wmean_marinetox=zeros(4,6);
fore_wmean_terrtox=zeros(4,6);
fore_wmean_fresheutrop=zeros(4,6);
fore_wmean_marineeutrop=zeros(4,6);
fore_wmean_photochem=zeros(4,6);
fore_wmean_terracid=zeros(4,6);

for i=1:6
 %Finding Weighted mean broken down of foregroundprocesses
 fwmean_cc(1,i)=wmean(climate_change(1:70,i), kg_produced_farm_barley);
 fwmean_freshwecotox(1,i)=wmean(f_ecotox(1:70,i), kg_prod_farm_barley);
 fwmean_humantox(1,i)=wmean(h_toxicity(1:70,i), kg_prod_farm_barley);
 fwmean_marinetox(1,i)=wmean(m_ecotoxicity(1:70,i), kg_prod_farm_barley);
 fwmean_terrtox(1,i)=wmean(t_ecotoxicity(1:70,i), kg_prod_farm_barley);
 fwmean_fresheutrop(1,i)=wmean(f_eutr(1:70,i), kg_prod_farm_barley);
 fwmean_marineeutrop(1,i)=wmean(m_eutr(1:70,i), kg_prod_farm_barley);
 fwmean_photochem(1,i)=wmean(p_o_formatation(1:70,i), kg_prod_farm_barley);
 fwmean_terracid(1,i)=wmean(t_acidification(1:70,i), kg_prod_farm_barley);
end

% Making summarymatrixes:
summary_barley=[mean_barley; weightedmean_barley; median_barley;
    weightedmedian_barley; max_barley; min_barley;
    std_barley; weightedstd_barley];

for i=1:18
    summary_all_graintypes(:,i+4*(i-1))=summary_barley(:,i);
    summary_all_graintypes(:,i+1+4*(i-1))=summary_oat(:,i);
    summary_all_graintypes(:,i+2+4*(i-1))=summary_winterwh(:,i);
    summary_all_graintypes(:,i+3+4*(i-1))=summary_springwh(:,i);
end

a=kgtot_barley_fylke(:,1);
kgtot_barley_f =repmat(a,1,18);

%Weighted Average on fylkesnivå
waverage_barley_fylke=dtot_barley_fylke./kgtot_barley_f;

for j=1:length(d_all_barley)
wmean_barley_curve(j)=wmean(d_all_barley(1:j,2),kg_prod_farm_barley(1:j,1));
```

```
end

%FINDING DATA FOR KOMMUNE BROKEN DOWN ON GRAIN:
[tall1, tekst1, begge1]  = xlsread(’tabell.xlsx’,’DATA2’,’C6:C220’);
[tall2, tekst2, begge2] = xlsread(’tabell.xlsx’,’ikke ror’,’AQ3:AQ49’);
daa= xlsread(’tabell.xlsx’,’DATA2’,’H6:H220’);
haa=daa./10
n2o_kg=xlsread(’Results_managed_ky_n2o plusse.xls’,’N2O’,’E6:E220’);
n2o=n2o_kg.*haa;
co2_kg=xlsread(’Results_managed_ky_n2o plusse.xls’,’CO2’,’D2:D216’);
co2=co2_kg.*haa;
dtot_farmsincounty_barley=zeros(47,18);
n2o_county_barley=zeros(47,1);
co2_county_barley=zeros(47,1);
kgtot_farmsincounty_barley=zeros(47);
hatot_farmsincounty_barley=zeros(47);

 for i=1:47
     kommune = begge2(i,1);
     antall = zeros(18,1);
     j = 1;
    while(j<71)
        if(strcmp(begge1(j,1),kommune))
            kgtot_farmsincounty_barley(i)=kgtot_farmsincounty_barley(i)
             + farm_kg_produced1(j);
            hatot_farmsincounty_barley(i)=hatot_farmsincounty_barley(i)
             + haa(j);
            n2o_county_barley(i)=n2o_county_barley(i) + n2o(j);
             co2_county_barley(i)=co2_county_barley(i) + co2(j);
            for k = 1:18
               dtot_farmsincounty_barley(i,k) =
                dtot_farmsincounty_barley(i,k) + d_farm_kg_produced(j,k);
            end
        end
        j=j+1;
    end
 end

%Example of making cummulative distributionplot:
set(0,’DefaultAxesColorOrder’,[0 1 1;1 0 0;1 0 1;0 0 1;0 1 0;0 0 0])
ecdf(terrestrial_acidification(1:70,2),’frequency’,kg_produced_farm_barley);
hold all
ecdf(terrestrial_acidification(1:70,3),’frequency’,kg_produced_farm_barley);
hold all
ecdf(terrestrial_acidification(1:70,4),’frequency’,kg_produced_farm_barley);
hold all
ecdf(terrestrial_acidification(1:70,5),’frequency’,kg_produced_farm_barley);
hold all
ecdf(terrestrial_acidification(1:70,6),’frequency’,kg_produced_farm_barley);
hold all
ecdf(d_all(1:70,15),’frequency’,kg_produced_farm_barley);
xlabel(’kg SO2 Eq’);
title(’Barley’)

%Example of running statistical tests:
%anova and kruskalwallis on regions:
barley_area_stat=xlsread(’Results_managed_ky_n2o plusse.xls’,
    ’finner soneCC’,’N3:P41’);
toogtre=barley_area_stat(:,2:3);
enogtre=xlsread(’Results_managed_ky_n2o plusse.xls’,
    ’finner soneCC’,’AI3:AJ41’);
[p,d,stat]=anova1(enogtre)
[krus,s,statkrus]=kruskalwallis(enogtre)

%anova and kruskalwallis between grainspecies
grain_stat=xlsread(’Results_managed_ky_n2o plusse.xls’,
    ’finner soneCC’,’AB3:AE72’);
[p,d,stat]=anovan(grain_stat)
[krus,s,statkrus]=kruskalwallis(grain_stat)

c = multcompare(stat)
k=multcompare(statkrus)
```

Appendix D

Results

Table D.1: The table shows the results for the impactcategories agricultural land occupation (ALO), Climate change (CC), fossil depletion (FD), freshwater ecotoxicity (FET), freshwater eutrophication (FE), human toxicity (HT), ionizing radiation (IR), marine ecotoxicity (MET), marine eutrophication (ME), metal depletion (MD).

Impact	*Unit*	*Cereal*	*W. Mean*	*W. StD*	*Max*	*Min*
ALO	$m^2 a$	Barley	2,83	0,24	3,68	2,29
		Oat	2,78	0,36	4,36	2,29
		W. Wheat	2,25	0,29	3,23	1,90
		S. Wheat	2,62	0,32	3,75	2,15
CC	kg CO_2 -Eq	Barley	0,93	0,20	1,80	0,52
		Oat	0,98	0,19	1,62	0,47
		W. Wheat	0,92	0,14	1,73	0,73
		S. Wheat	0,99	0,22	1,79	0,56
FD	kg oil-Eq	Barley	0,11	0,02	0,24	0,09
		Oat	0,11	0,03	0,23	0,08
		W. Wheat	0,09	0,02	0,19	0,08
		S. Wheat	0,11	0,03	0,26	0,08
FET	kg 1,4DCB-Eq	Barley	0,0029	0,0010	0,0091	0,0018
		Oat	0,0039	0,0011	0,0092	0,0026
		W. Wheat	0,0019	0,0006	0,0056	0,0013
		S. Wheat	0,0026	0,0013	0,0096	0,0014
FE	kg P-Eq	Barley	5,36E-04	2,12E-04	1,06E-03	1,69E-04
		Oat	6,70E-04	1,77E-04	1,00E-03	1,68E-04
		W. Wheat	5,63E-04	1,02E-04	9,21E-04	1,81E-04
		S. Wheat	6,08E-04	1,97E-04	1,02E-03	1,49E-04
HT	kg 1,4DCB-Eq	Barley	0,14	0,05	0,44	0,08
		Oat	0,13	0,05	0,37	0,08
		W. Wheat	0,09	0,03	0,26	0,06
		S. Wheat	0,12	0,06	0,44	0,07
IR	kg U235-Eq	Barley	0,060	0,026	0,208	0,031
		Oat	0,059	0,026	0,192	0,029
		W. Wheat	0,039	0,016	0,129	0,024
		S. Wheat	0,054	0,033	0,236	0,026
MET	kg 1,4DCB-Eq	Barley	2,79E-03	1,08E-03	9,43E-03	1,56E-03
		Oat	2,76E-03	1,08E-03	8,26E-03	1,51E-03
		W. Wheat	1,88E-03	6,75E-04	5,69E-03	1,19E-03
		S. Wheat	2,50E-03	1,35E-03	9,99E-03	1,28E-03
ME	kg N-Eq	Barley	0,015	0,002	0,022	0,011
		Oat	0,015	0,002	0,019	0,010
		W. Wheat	0,016	0,002	0,023	0,014
		S. Wheat	0,016	0,002	0,022	0,012
MD	kg Fe-Eq	Barley	0,068	0,034	0,280	0,029
		Oat	0,065	0,033	0,242	0,027
		W. Wheat	0,043	0,020	0,158	0,022
		S. Wheat	0,062	0,043	0,302	0,024

Table D.2: The table shows the results for the impact categories natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POF), terrestrial acidification (TA), terrestrial ecotoxicity (TET), urban land occupation (ULO) and water depletion (WD).

Impact	*Unit*	*Cereal*	*W. Mean*	*W. StD*	*Max*	*Min*
NLT	m^2	Barley	9,27E-05	1,54E-05	1,73E-04	7,14E-05
		Oat	9,15E-05	1,88E-05	1,62E-04	6,84E-05
		W. Wheat	7,64E-05	1,36E-05	1,48E-04	6,42E-05
		S. Wheat	8,71E-05	2,06E-05	1,84E-04	6,66E-05
OD	kg CFC11-Eq	Barley	3,82E-08	6,24E-09	7,23E-08	2,98E-08
		Oat	3,78E-08	7,76E-09	6,69E-08	2,80E-08
		W. Wheat	3,17E-08	5,58E-09	6,11E-08	2,67E-08
		S. Wheat	3,63E-08	8,53E-09	7,62E-08	2,78E-08
PMF	kg PM10-Eq	Barley	0,0032	0,0003	0,0050	0,0028
		Oat	0,0032	0,0005	0,0046	0,0025
		W. Wheat	0,0032	0,0004	0,0050	0,0027
		S. Wheat	0,0033	0,0005	0,0050	0,0027
POF	kg NMVOC	Barley	0,0117	0,0011	0,0173	0,0100
		Oat	0,0117	0,0016	0,0159	0,0091
		W. Wheat	0,0120	0,0016	0,0182	0,0101
		S. Wheat	0,0122	0,0016	0,0178	0,0100
TA	kg SO_2-Eq	Barley	0,0080	0,0008	0,0118	0,0068
		Oat	0,0079	0,0011	0,0108	0,0061
		W. Wheat	0,0079	0,0011	0,0120	0,0066
		S. Wheat	0,0080	0,0011	0,0118	0,0066
TET	kg 1,4DCB-Eq	Barley	7,18E-05	8,90E-06	1,21E-04	6,07E-05
		Oat	8,73E-05	1,36E-05	1,28E-04	6,97E-05
		W. Wheat	5,64E-05	9,16E-06	1,00E-04	4,73E-05
		S. Wheat	6,80E-05	1,19E-05	1,14E-04	5,50E-05
ULO	m^2a	Barley	2,86E-03	4,51E-04	5,37E-03	2,33E-03
		Oat	2,81E-03	5,60E-04	4,92E-03	2,13E-03
		W. Wheat	2,11E-03	3,82E-04	4,13E-03	1,76E-03
		S. Wheat	2,48E-03	5,95E-04	5,29E-03	1,88E-03
WD	m^3	Barley	8,14E-04	2,55E-04	2,26E-03	5,29E-04
		Oat	7,95E-04	2,66E-04	2,10E-03	4,91E-04
		W. Wheat	5,56E-04	1,66E-04	1,50E-03	3,90E-04
		S. Wheat	7,14E-04	3,26E-04	2,49E-03	4,17E-04