Life Cycle Assessment of American Wheat: Analysis of Regional Variations in Production and Transportation

Brendan Gleason O’Donnell

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Life Cycle Assessment (LCA) is a model-based approach to quantify where, and in what form, energy and materials are used in industrial production. The "life cycle" refers to the production of raw materials for fuels, infrastructure and energy conversion equipment, use, maintenance, after life options, and relevant health and social factors. This is sometimes referred to as a “cradle to grave” approach when assessing environmental impacts. Current interest in carbon footprint and environmental impacts of products derived from crops, primarily food and bio-fuels, first requires a detailed life cycle assessment of the agricultural production. American wheat is selected to study the variation in life cycle impacts of an agricultural product that has been aggregated in previous LCAs. All previous studies contain an LCA case study of one species of wheat grown in a specific location. Such a narrow approach is not an accurate representation of the system. This LCA of American wheat differs in the fact that it investigates multiple locations, species, variation in farming practices, fuel use, fertilizer application, and transportation throughout the country in an attempt to be inclusive of the spatial and species variability of wheat production on greenhouse gas emissions. Due to the decentralized nature of American agriculture, an understanding of transportation decisions and resulting impacts are especially important. Results indicate a 101% intra-species and 62% inter-species variation in greenhouse gas emissions of wheat grown in the U.S. However, due to a range of 1440 kg CO₂ eq/ha to -1404 kg CO₂ eq/ha, sequestration of carbon during cultivation is the most sensitive and variable contribution to life cycle greenhouse gas emissions.
TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... iii
LIST OF TABLES .............................................................................................................. iv
ACKNOWLEDGMENTS ...................................................................................................... v

1 Introduction .................................................................................................................. 1
  1.1 Background .............................................................................................................. 1
    1.1.1 Agriculture and LCA ...................................................................................... 2
  1.2 Regional Differences in Agriculture ....................................................................... 5
    1.2.1 Variations in Regional Field Production ......................................................... 6
    1.2.2 Variations in Regional Product Transportation and Modal Systems.............. 9
  1.3 Life Cycle Assessment Methodology ..................................................................... 11
    1.3.1 Goal and Scope Definition ............................................................................. 11
    1.3.2 Inventory Assessment .................................................................................... 12
    1.3.3 Impact Assessment ......................................................................................... 12
    1.3.4 Interpretation and Discussion ......................................................................... 12
    1.3.5 Computational Structure ................................................................................. 12

2 Case Study: American Wheat ........................................................................................ 15
  2.1 Goal and Scope Definition ..................................................................................... 15
    2.1.1 Previous Studies ............................................................................................... 15
    2.1.2 Japanese Perspective ....................................................................................... 20
    2.1.3 Case Study Goal ............................................................................................... 20
    2.1.4 Functional Unit ................................................................................................ 21
    2.1.5 System Boundaries ......................................................................................... 22
    2.1.6 Data Categories ............................................................................................... 23
    2.1.7 Data Quality ..................................................................................................... 23
  2.2 Inventory Analysis ................................................................................................... 25
    2.2.1 System Overview ............................................................................................. 25
    2.2.2 On-Field Chemical Application ...................................................................... 29
    2.2.3 On-Field Equipment Energy Consumption and Emissions ........................... 32
    2.2.4 Yield ................................................................................................................ 33
    2.2.5 Transportation Mode, Distance, and Load Factors ....................................... 34
    2.2.6 Well-to-Point-of-Use Energy and Chemicals Production ............................ 38
    2.2.7 Accounting for System Co-Products ............................................................... 47
    2.2.8 Sequestration ................................................................................................... 47
    2.2.9 Major Assumptions and Limitations ............................................................... 48
  2.3 Impact Assessment ................................................................................................... 50
  2.4 Case Study Results .................................................................................................. 50
    2.4.1 Results By State ............................................................................................... 50
    2.4.2 Results by Species ......................................................................................... 55
2.5 Interpretation and Discussion ................................................................. 56
  2.5.1 Data Quality Analysis ........................................................................ 56
  2.5.2 Regional Differences ......................................................................... 58
  2.5.3 Emissions Contributions .................................................................... 58
  2.5.4 Contribution of Transportation ......................................................... 61
    2.5.4.1 Methods .................................................................................. 61
    2.5.4.2 Results .................................................................................. 64
    2.5.4.3 Rail Spurs ................................................................................ 67
  2.5.5 Comparison with Estimates of Sequestration ...................................... 68
  2.5.6 Comparison with Previous Studies ..................................................... 70

3 Conclusions ................................................................................................. 71
  3.1 LCA Methodology .................................................................................. 72
  3.2 Wheat Production and Transport .............................................................. 73
  3.3 Future Work ......................................................................................... 73

References ..................................................................................................... 75

Appendix A: U.S. Wheat Yield By State and Species .................................... 85
Appendix B: Chemical Application ............................................................... 89
Appendix C: Energy Use ............................................................................... 96
Appendix D: Inventory Results for Wheat Production .................................. 99
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1 – Each stage of an LCA is composed of process information, each with inputs (energy, materials) and outputs (emissions, waste).</td>
<td>1</td>
</tr>
<tr>
<td>Figure 2 – Gross (a) and net (b) energy input of the corn ethanol production.</td>
<td>3</td>
</tr>
<tr>
<td>Figure 3 – Environmental impacts of agriculture.</td>
<td>5</td>
</tr>
<tr>
<td>Figure 4 – Wheat species by production location.</td>
<td>10</td>
</tr>
<tr>
<td>Figure 5 – ISO 14040 LCA framework.</td>
<td>11</td>
</tr>
<tr>
<td>Figure 6 – System boundaries of the study herein include Processes 1. Processes 2 &amp; 3 are currently modeled at AIST.</td>
<td>23</td>
</tr>
<tr>
<td>Figure 7 – Production percentage of hard red winter wheat by state.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 8 – Production percentage of hard red spring wheat by state.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 9 – Production percentage of soft red winter wheat by state.</td>
<td>27</td>
</tr>
<tr>
<td>Figure 10 – Production percentage soft white wheat by state.</td>
<td>27</td>
</tr>
<tr>
<td>Figure 11 – LCA process diagram.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 12 – U.S. wheat bin locations.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 13 – Carbon equivalent emissions for each wheat species.</td>
<td>54</td>
</tr>
<tr>
<td>Figure 14 – Production distribution by species.</td>
<td>55</td>
</tr>
<tr>
<td>Figure 15 – Total life cycle emissions for each wheat species.</td>
<td>56</td>
</tr>
<tr>
<td>Figure 16 – Production contribution analysis.</td>
<td>59</td>
</tr>
<tr>
<td>Figure 17 – Transportation contribution analysis.</td>
<td>60</td>
</tr>
<tr>
<td>Figure 18 – Wheat production in Washington State.</td>
<td>62</td>
</tr>
<tr>
<td>Figure 19 – Rail heads in wheat production counties.</td>
<td>64</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1 – Fertilizer application by state for winter wheat</td>
<td>6</td>
</tr>
<tr>
<td>Table 2 – Example yield for winter wheat by U.S. state</td>
<td>8</td>
</tr>
<tr>
<td>Table 3 – Example yield across wheat species in U.S.</td>
<td>8</td>
</tr>
<tr>
<td>Table 4 – Comparison of previous LCA studies of wheat.</td>
<td>19</td>
</tr>
<tr>
<td>Table 5 – Data Quality Indicators</td>
<td>24</td>
</tr>
<tr>
<td>Table 6 – Chemical application by wheat species, state, and active ingredient.</td>
<td>30</td>
</tr>
<tr>
<td>Table 7 – Energy consumption for 1 ha wheat by American state. Shading indicated states included in system boundary.</td>
<td>33</td>
</tr>
<tr>
<td>Table 8 – Wheat yield in kg/ha for each location and species</td>
<td>34</td>
</tr>
<tr>
<td>Table 9 – Transportation distances for each mode including front haul and back haul</td>
<td>38</td>
</tr>
<tr>
<td>Table 10 – Electricity profile for each wheat production state</td>
<td>40</td>
</tr>
<tr>
<td>Table 11 – Summary of energy use and emissions for front haul transportation modes.</td>
<td>43</td>
</tr>
<tr>
<td>Table 12 – Summary of energy use and emissions for back haul transportation modes</td>
<td>44</td>
</tr>
<tr>
<td>Table 13 – Summary of energy use and emissions for on-site energy production</td>
<td>45</td>
</tr>
<tr>
<td>Table 14 – Summary of Energy Use and Emissions of Agricultural Chemicals</td>
<td>46</td>
</tr>
<tr>
<td>Table 15 – Allocation for wheat and straw by species</td>
<td>47</td>
</tr>
<tr>
<td>Table 16 – Carbon sequestration of wheat cultivation in kg CO₂/ha</td>
<td>48</td>
</tr>
<tr>
<td>Table 17 – Global Warming Potentials (GWP)</td>
<td>50</td>
</tr>
<tr>
<td>Table 18 – Inventory results for hard red winter wheat from Montana. Grey shading indicates the two largest contributors to total greenhouse gas emissions</td>
<td>51</td>
</tr>
<tr>
<td>Table 19 – Life cycle emissions by state for transportation component</td>
<td>52</td>
</tr>
<tr>
<td>Table 20 – Life cycle emissions for each species and state combination</td>
<td>53</td>
</tr>
<tr>
<td>Table 21 – Data quality analysis</td>
<td>57</td>
</tr>
<tr>
<td>Table 22 – Market shares and modal combinations for Walla Walla, Whitman, Lincoln, and Adams County.</td>
<td>63</td>
</tr>
<tr>
<td>Table 23 – Emissions for domestic wheat transport in Washington State</td>
<td>66</td>
</tr>
</tbody>
</table>
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Dr. Cooper, Dr. Goodchild, and Dr. Ozawa have been indispensable to this thesis.
1 Introduction

1.1 Background

Life Cycle Assessment (LCA) is a methodology that can be used to quantify and interpret the environmental impacts of products or processes by examining a broad scope of industrial production at all stages of the system (Figure 1) [1]. LCA studies use a “cradle-to-grave” or “cradle-to-cradle” approach to quantify energy and material use and waste from initial material acquisition, materials processing, manufacturing, use, and end-of-life processes [2]. Each stage of the life cycle is responsible for consuming resources, generating waste, and contributing to emissions to the environment. Thus, LCA provides a protocol to understand the potential impacts of technological choices on resource depletion, contribution to climate change, manufacturing and infrastructure investment, employment, and human health. LCA results can be used to systematically identify opportunities to reduce net environmental impacts by selecting a combination of low-impact industrial processes throughout the life cycle. LCA is a rapidly developing field and as such, the methodologies for conducting LCAs are still evolving and under continuous review [3].

Figure 1 – Each stage of an LCA is composed of process information, each with inputs (energy, materials) and outputs (emissions, waste).
1.1.1 Agriculture and LCA

Within LCA, food and agriculture studies are a growing area of focus [4]. In particular, biofuels processed from field crops, such as ethanol and sunflower oil converted into biodiesel, have been compared to conventional fuels using LCA methodology [5]. Such studies have been well publicized when the use of biofuels are debated. For example, Pimentel published a particularly controversial paper in 2005 claiming a 29% deficient net energy balance for corn ethanol [5]. This prompted several subsequent studies with contrasting results that claim a positive net energy balance for the production of corn based ethanol [6], [7]. Notably, a 2005 study by Kim suggested a 25% positive net energy balance for ethanol production [8]. Figure 2 compares the LCA gross and net energy balance for corn ethanol from six studies [7]. Gross energy indicates the total energy required to make ethanol, where net energy compares the required energy with ethanol’s embodied energy.
Figure 2 – Gross (a) and net (b) energy input of the corn ethanol production.

Eco-labels for consumer food also use agriculturally based LCA models. Eco-labels display life cycle greenhouse gas emissions and other environmental impacts associated with production and transportation directly on food products. They have been proposed both in North America, Europe, and Asia [9], [10], [11]. Tesco and Marks & Spencer's, U.K. retail companies, have already experimented with eco-labels on produce and clothing [12]. David Miliband, the U.K. environmental secretary, has suggested that every product sold should carry both nutrition and eco-labels [10].

Local governments and municipal planners have begun to investigate how food systems and policy produce environmental impacts on a local level. The city of Seattle, WA has evaluated the climate impacts of popular food product [13]. The city,
in cooperation with University of Washington, has constructed an LCA of two representative plates of food – one from a globalized food network and one from a regional network. Based on LCA analysis, the city has concluded that domestic production is almost always preferable.

National governments too are concerned with the environmental impacts of agricultural production. This has prompted Japan to create a governmental Food Study Group (FSG), based out of the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan. Membership includes 36 universities, national research institutes, private research institutes, and private food companies. The main objectives of FSG are: (1) quantification of environmental load with regard to food consumption and production; and (2) development of a sustainability indicator for food consumption and production as an advisory tool for policy and import decisions in Japan.

Thus, LCA is currently a prevalent and well suited methodology for the identification of improvements in the agricultural sector, where initial agricultural processes account for a large percentage of the total impact [14]. However, agricultural systems have been shown to be more dependent on variations in regional production techniques than most product systems [15], [16]. Metals, chemicals, and industrial manufacturing do vary regionally, but not to the degree of crop production [4]. For example, fertilizer and other agro-chemical application, which constitute one of the largest relative contribution to greenhouse gas emissions and toxic emissions, can vary by over 300% by location for the same crop [17].

Despite the resulting need to understand regional differences in LCAs of agricultural systems, LCA methodology is poorly defined with respect to modeling regional heterogeneity in agricultural production and transportation. Thus, an opportunity exists to contribute to the development of LCA protocols by tailoring the methodology to the variation in agricultural production and supply chain.
1.2 Regional Differences in Agriculture

Eutrophication, loss of habitat and biodiversity, changes in land use and disturbance, heavy metal soil release, and greenhouse gas emissions are all directly associated with machinery operation, transportation, and chemical application in agricultural crop production (Figure 3) [18], [19]. Individual species within one class of crop (wheat, corn, soy, etc.) and field location can both influence the magnitude of environmental impact. The variation derives from both at-farm field and production processes and the transportation of crops to point of use (POU), each with their own life cycle processes.

Figure 3 – Environmental impacts of agriculture.
1.2.1 Variations in Regional Field Production

Agricultural practices (including resource use and emissions) vary widely by location and individual species, even for the same crop. Application of chemicals, particularly fertilizer (nitrogen and phosphorus) and petro-chemical insecticides, are highly regionally dependant. Application rates vary due to soil types, available nutrients, precipitation, and temperature [20]. For example, substantial differences can be seen in the quantities of fertilizer for the same species of winter wheat in different U.S. states (Table 1) [17]. The average yearly application for nitrogen, phosphate, potash fertilizer is 1.04E+02, 5.43E+01, 5.68E+01 kg/ha respectively. However, the range for nitrogen fertilizer yearly application is as large as 4.20E+01kg/ha–1.51E+02 kg/ha.

<table>
<thead>
<tr>
<th>State</th>
<th>Colorado</th>
<th>Montana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>4.20E+01</td>
<td>5.19E+01</td>
</tr>
<tr>
<td>Phosphate</td>
<td>2.47E+01</td>
<td>3.46E+01</td>
</tr>
<tr>
<td>Potash</td>
<td>2.72E+01</td>
<td>1.24E+01</td>
</tr>
<tr>
<td>Idaho</td>
<td></td>
<td>Nebraska</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.51E+02</td>
<td>6.42E+01</td>
</tr>
<tr>
<td>Phosphate</td>
<td>4.45E+01</td>
<td>3.46E+01</td>
</tr>
<tr>
<td>Potash</td>
<td>2.96E+01</td>
<td>2.47E+01</td>
</tr>
<tr>
<td>Illinois</td>
<td></td>
<td>Ohio</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.28E+02</td>
<td>1.11E+02</td>
</tr>
<tr>
<td>Phosphate</td>
<td>1.06E+02</td>
<td>8.40E+01</td>
</tr>
<tr>
<td>Potash</td>
<td>1.46E+02</td>
<td>9.39E+01</td>
</tr>
<tr>
<td>Kansas</td>
<td></td>
<td>Oklahoma</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>9.63E+01</td>
<td>1.11E+02</td>
</tr>
<tr>
<td>Phosphate</td>
<td>4.94E+01</td>
<td>4.45E+01</td>
</tr>
<tr>
<td>Potash</td>
<td>4.20E+01</td>
<td>2.96E+01</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>AVERAGE</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.28E+02</td>
<td>1.04E+02</td>
</tr>
<tr>
<td>Phosphate</td>
<td>6.67E+01</td>
<td>5.43E+01</td>
</tr>
<tr>
<td>Potash</td>
<td>8.40E+01</td>
<td>5.68E+01</td>
</tr>
<tr>
<td>Missouri</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.38E+02</td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td>6.67E+01</td>
<td></td>
</tr>
<tr>
<td>Potash</td>
<td>8.65E+01</td>
<td></td>
</tr>
</tbody>
</table>
Similarly, fuel and energy use and emissions are highly regionally dependant. Soil properties and fertilizer application influence the frequency a field must be tilled [21] and increased tillage results in more machine hours and higher rates of fuel consumption. Regional farm practices, including variations in the classes of farm machinery used and amount of grain drying, also influence energy consumption. Further, different regions use different shares and amounts of gasoline, liquid petroleum gas (LPG), natural gas and electricity [22], which is further complicated from an emissions estimation standpoint by differences in electricity generation technology mixes, for use at the farm and in the production of fuels and other materials. For example, 76% of Idaho’s electricity is generated by hydroelectric, while North Dakota generates 87% of their power using coal [23]. Different energy profiles have vastly different impacts [24].

Crop yield also fluctuate by region and species. Again taking wheat as an example, yields within the same species have been shown to vary by over 400%. Table 2 lists yields of a range of production states for winter wheat [25]. Between species, wheat yields can vary by over 200%. Table 3 lists the yield of the five major species of American wheat [25]. Greater yields require fewer resources used per kg wheat and can result in less impact.
Table 2 – Example yield for winter wheat by U.S. state.

<table>
<thead>
<tr>
<th>U.S. State</th>
<th>Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Mexico</td>
<td>1.69E+03</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1.69E+03</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>2.28E+03</td>
</tr>
<tr>
<td>South Dakota</td>
<td>2.93E+03</td>
</tr>
<tr>
<td>Missouri</td>
<td>3.38E+03</td>
</tr>
<tr>
<td>Indiana</td>
<td>3.58E+03</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>3.64E+03</td>
</tr>
<tr>
<td>Oregon</td>
<td>3.97E+03</td>
</tr>
<tr>
<td>Ohio</td>
<td>4.03E+03</td>
</tr>
<tr>
<td>Idaho</td>
<td>5.85E+03</td>
</tr>
<tr>
<td>Nevada</td>
<td>7.15E+03</td>
</tr>
</tbody>
</table>

Table 3 – Example yield across wheat species in U.S.

<table>
<thead>
<tr>
<th>Wheat Species</th>
<th>Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Red Winter</td>
<td>2.08E+03</td>
</tr>
<tr>
<td>Hard Red Spring</td>
<td>2.08E+03</td>
</tr>
<tr>
<td>Soft Red Winter</td>
<td>4.10E+03</td>
</tr>
<tr>
<td>White</td>
<td>4.03E+03</td>
</tr>
<tr>
<td>Durum</td>
<td>1.89E+03</td>
</tr>
</tbody>
</table>

Further, when the contribution to climate change is of interest, variations in regional field production can be characterized by differences in soil carbon sequestration. Soils are the second largest terrestrial carbon reservoir at 1500 Pg carbon [26], with 10% of atmospheric carbon passing through the plant-soil-atmosphere interface each year [27]. Agricultural lands are generally considered a sink in the global by increasing soil organic carbon (SOC) [28]. The SOC stock is a long term balance between additions of C from organic matter and the atmosphere and its losses through respiration and decomposition pathways [29]. The net carbon left in the soil after each vegetative year is the amount of carbon sequestered from the atmosphere. Therefore, net sequestration is measured by change in total SOC pools [27], [30].
The annual balance in SOC is a function of three main processes: fixation in plant biomass, plant, soil and root respiration, and long-term storage in soils. According to a comprehensive review paper on carbon sequestration by Kuzyakov, roughly half of the total CO₂ absorbed from the atmosphere is fixed by the wheat plant and turned into biomass [30]. However, this fixation into biomass is not a permanent sequestration, as either the end use (alcohol production, animal, or human consumption) or decomposition eventually returns the biomass component of CO₂ to the atmosphere. A third of the total CO₂ absorbed from the atmosphere is respired by roots, soil, and rhizosphere microorganisms and returns directly to the atmosphere during growth [30]. The remaining carbon is permanently incorporated into the soil in clay minerals, organic matter, or resident soil microbes. Therefore, as an estimate, 17% of the total C translocated into the soil remains [30]. This is the annual change in SOC pools due to wheat cultivation and the net sequestration of wheat cultivation.

However, the amount of carbon sequestered as SOC is highly variable and dependant on location and farming practices [31], [27], [32]. The effects of cropland management practices and landscape position on SOC pool depend on temperature, precipitation, soil composition, soil texture, crop management, and landscape morphology [28]. For example, applications of chemicals that change the C available to soil; variations in the amount of tillage that exposes SOC to oxidation from the atmosphere; and variations in the amount of material left on the field to degrade can be assumed to result in variations in sequestration carbon cycling [33]. A review of the extensive literature produced an enormous range of carbon sequestration values. Estimates ranged from 1440 kg CO₂ eq/ha to -1404 kg CO₂ eq/ha based on study and location [34], [35]. A complete review is presented in Section 2.2.8.

1.2.2 Variations in Regional Product Transportation and Modal Systems

The same agricultural product can come from different regions of a country and individual regions can produce different species within a crop category. For example,
in the case of fruit, species of blueberries, strawberries, raspberries are produced in different regions [36]. Again, this is particularly pronounced in the case of wheat. As a specific example, Figure 4 shows regionally cultivated species of U.S. wheat. The path to market, transportation distances, modal contribution (transport by truck, rail, barge, or ocean vessel), and backhaul assumptions (consideration of the return of empty vehicles or vessels as appropriate) thus vary by location [37]. For example, wheat from the Pacific northwest U.S. travels predominantly by barge [38], and rail distances are larger in the central and midwest U.S. [37].

Figure 4 – Wheat species by production location.

Again, LCA provides a framework for modeling the influence of regional differences in field production and product transportation modes on life cycle environmental impacts, as follows.
1.3 Life Cycle Assessment Methodology

LCA provides a protocol to quantify the implications of regional variations on the life cycle impacts of agricultural systems. The LCA methodology is provided by the ISO 14040 standards [39], [40]. The standards define LCA as a method of accounting inputs, outputs and the environmental impacts of a product system throughout its life cycle. The framework includes four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation and discussion (Figure 5).

![Life cycle assessment framework](image)

Figure 5 – ISO 14040 LCA framework.

1.3.1 Goal and Scope Definition

Goal and scope definition outlines the research question to be addressed with LCA methodology [39]. It must include a declaration of the functional unit, important reference flows, assumptions, and the LCA system boundaries. The functional unit defines the magnitude of service or product, duration of service, and the expected level
of quality delivered by the LCA. For the agriculture sector, this is usually a standard quality of delivered product. Reference flows represent the type and quantity of materials and energy necessary per functional unit. The system boundaries define the processes which will be included in the life cycle model. Goal and scope definition can also include important concerns raised in previous research and a discussion of how they will be taken into account.

1.3.2 Inventory Assessment

During this step, an inventory of relevant inputs and outputs is constructed for the life cycle. Examples of common inputs are raw material use, energy and land consumption. The result of inventory analysis is cumulative resource use and emissions for all processes within the system boundaries.

1.3.3 Impact Assessment

The impact assessment estimates the contribution of inventory flows to the environmental impacts of interest. Contributions to global warming, acidification, and smog formation are common impact categories. If applicable, priorities can be set among impacts to facilitate interpretation of the results.

1.3.4 Interpretation and Discussion

The interpretation step is an objective analysis of LCA results. This should include a comparison of results with previously published LCA studies and assessments of the sensitivity of results to key or uncertain modeling parameters, data quality, and assumptions.

1.3.5 Computational Structure

The computational structure of LCA is defined by Heijungs & Suh [41] based on and similar to input-output methods. For the inventory model, the product system is
comprised of “unit processes” (fertilizer application, transportation, etc.) and material and energy flows between processes. Flows between unit processes are called economic flows and flows to or from the environment are called environmental flows. An inventory matrix is prepared by representing each unit process as a vector, and combining all unit process vectors into a matrix. The matrix is then partitioned to group all economic and all environmental flows, forming two matrices: the technology matrix \( A \) and the intervention matrix \( B \), respectively. Solving the inventory problem results in a scaling vector \( s \) which represents the amount of each unit process needed to meet the demand of the overall system \( f \) specified in relation to the functional unit (e.g., 1 kg of wheat):

**Equation 1:** \[ A = sf \]

Where:
- \( s \) = scaling vector for the life cycle system,
- \( A \) = the technology matrix (combining economic flow vectors for all unit processes),
- \( f \) = final demand vector for the life cycle system

The scaling vector is then used to scale the environmental flows in \( B \) to determine the system’s environmental flows:

**Equation 2:** \[ g = Bs \]

Where:
- \( g \) = inventory vector,
- \( B \) = intervention matrix (combining environmental flow vectors for all unit processes)

Finally, the system impacts are estimated based on the environmental flows (emissions and material use) given in the inventory vector \( g \) which represents the combined environmental flows to meet the demand and for the life cycle.
There are, however, several ways that the basic model fails and must be refined. Most commonly, this includes cut-off flows, process alternatives, multifunctionality, and closed-loop recycling [41]. Cut-off economic flows result when a product is included in the system boundaries, but upstream processes are not, and hence cut-off [41]. Infrastructure is a common example of cut-off flows. When truck transport processes are included in LCA studies that truck’s contribution to the construction of the road is often cut-off. Process alternatives result when a choice exists between two alternative processes [41]. For example, electricity can from several different suppliers (coal, wind, hydroelectric). To account for this, alternatives are combined into a single, or aggregate, process [41]. In the case of electricity, a single aggregate process can be created with the correct market share of each mode of generation [42]. Closed loop recycling is the specific case where materials produced by a recycling process are used in another unit process in the LCA [41]. For example, when a car is disassembled the steel is recycled, but the original production process of the car also requires steel. This makes the technology matrix not square. To account for this modification, regression analysis gives an approximation for the demand matrix [41]. Using the approximated demand matrix, the supply matrix can be solved for normally. This also called a pseudoinverse approximation in linear algebra theory [41].

The most pertinent limitation of the basic model for agricultural studies is multifunctional processes. If there are unit processes with more than one product (co-product), the system must be expanded, a representative allocation of impact is made, or all processes are allocated to the main flow (surplus method) [42]. System expansion is the preferred method and includes adding an avoided process for the co-product [41]. Allocation divides the environmental impact of the unit process by relative mass, stochiometric, or economic percentage of each co-product [42]. For example, in agriculture, a co-product like wheat straw is generated in addition to the primary grain crop. An allocation must account for the percentage of each co-product. Generally, the surplus method should be avoided [42].
As follows, a LCA case study is developed based on the computational structure presented by Heijungs & Suh and with the goals of modeling regional differences in agricultural field production and product transportation and documenting model development in a way that facilitates continuing LCA methodological advances.

2 Case Study: American Wheat

This case study investigates the regional variation in field production and product transport for American wheat using LCA and compares results to estimates of carbon sequestration. American wheat is used as a representative agricultural crop due to the fact that it is ranked in the top three for crop production by both volume and value, [43], [44] and is grown in almost all regions of the U.S. [45]. This LCA differs from previous studies in the fact that it investigates multiple locations, species, variation in farming practices, fuel use, fertilizer application, yield, and transportation throughout the country in an attempt to be inclusive of the spatial and species variability of wheat production on greenhouse gas emissions. The case study was sponsored in part by the Research Center for Life Cycle Assessment at AIST in Tsukuba, Japan, whose interest in American wheat stems from the facts that (1) Japan imports most of their wheat from the U.S. [46] and (2) the AIST is able to influence domestic food systems policy [47].

2.1 Goal and Scope Definition

2.1.1 Previous Studies

Several previous LCA studies of wheat exist, but differ widely in motivation, scope, methodology, functional unit, and system boundaries. Studies can be divided into those focusing entirely on wheat production and those using wheat in the production of other products.

Two studies were found in which wheat is used in the production of other products. First, a 2005 study by Lechon at Spain’s Center of Energy, Environment and
Technology Research compared wheat and barley grain as the raw material for domestic conversion for bioethanol production [48]. The functional unit was the production of raw agricultural material for one ton of bioethanol. In the case of Spanish wheat, this equated to the use of 0.85 hectares, and was restricted to wheat produced and processed exclusively within Spain. The system boundaries are the farm gate, but the specific species of wheat species, LCA process information, or transportation distances were not presented at all. It did state that results for allocated for wheat grain and straw, but no allocation percentage was given. The study concluded 154 kg CO₂ equivalents (eq) per tonne of wheat, or 154 g CO₂ eq/kg wheat, were emitted to the air for harvesting, fertilizer application, transportation assuming yield of 3400 kg wheat/ha. This study did include an estimate of sequestration value at 152 g CO₂ eq/kg wheat. The authors stated that the total emissions for wheat would be 1.88 g CO₂ eq/kg if an estimate of net soil sequestration was used.

As part of a larger and more detailed LCA on the Australian grain industry, Narayanaswamy at Curtin University of Technology and Grains Research & Development Corporation investigated the impacts of Western Australian wheat as base ingredient for consumer food products such as bread, beer, and canola cooking oil [49],[14]. This study included agricultural processes in addition to food production, retail packaging, and consumer consumption. The functional unit was defined by the final food product as one loaf of bread, one hectoliter of beer, or one hectoliter canola oil, with emissions of 2.3, 135, 7 kg CO₂ equivalents respectively for each product. The study also reported emissions of 304 g CO₂ equivalents for 1 kg of wheat. However, there was no discussion of wheat species, besides labeling it “Western Australian wheat” [14]. Yield was assumed to be 2.4 tonnes of wheat per hectare, or 2400 kg wheat/hectare. Allocation was included, at 94.7% wheat grain. The study mentioned that transportation processes by truck were included for both transportation of fertilizers and grain product, but no mention of specific truck or distances were included. Carbon sequestration was not included. But, due to its
significance, it was explicitly stated that fertilizer application, particularly nitrogen, altered soil chemistry and increased direct soil NO₂ emissions.

Two studies were found that focused specifically on wheat production. First, a 2003 study by Koga at the Department of Uplands Research in Japan included wheat in a LCA comparison of conventional and reduced tillage cultivation practices [50]. The system boundaries included diesel fuel consumption, fertilizer application, and transportation of agricultural chemicals for winter wheat in the Tokachi crop region of Hokkaido, Japan. The functional unit was 1 hectare of wheat. Emissions for wheat under conventional tillage was 826.2 kg CO₂ ha⁻¹ and 701 kg CO₂ ha⁻¹ for reduced tillage. Assuming a representative yield for Japanese wheat of 5 tonnes/ha [51], this value can be converted to 162 g CO₂/kg wheat for conventional tillage. It’s important to note only CO₂ emissions are included, and not other important greenhouse gases like N₂O. This value only represents production of a single wheat species and does not include life cycle emissions for agricultural chemicals, fuel production or fuel transportation and thus makes this study difficult to compare to those presented above. Transportation for on farm vehicles (tractors) is included, but without lifecycle emissions for the fuel. No estimate of soil carbon sequestration is included.

Second, Version 1.3 of the Swiss Centre for Life Cycle Inventories Ecoinvent LCA database includes wheat production process information as “wheat grains IP (Integrated Production), at farm, process #237” [52] for average production in the Swiss lowlands. For the life cycle, 1 kg wheat is estimated to emit 498 g CO₂ eq/kg wheat [52]. This value includes LCA emissions for all on-farm processes, including infrastructure, land use, and a 92.5% allocation for wheat grain. Infrastructure includes the construction of all on-farm machinery (including hydraulic loader, field sprayer, vacuum tanker) and construction of transportation infrastructure (road and rail). The system boundary is defined as the farm gate, so transportation of fertilizer and chemicals are included, but not the final wheat product to point of use. Direct N₂O emissions to soil are included. Yield is stated at 6420 kg/ha, assuming an average
value over the years 1996-1999. Perhaps the most important aspect of the Ecoinvent data are its estimate of carbon sequestration. 8538 kg CO₂/ha, or 1330 g CO₂ equiv/kg wheat, is sequestered by wheat cultivation, according to a personal communication. This is far larger than any encountered value for sequestration.

Distinctly different included processes, functional units, yields, and location of wheat make direct and robust comparison of previous study results difficult. Important distinctions are summarized in Table 4. However, there are general observations and issues regarding wheat in LCA studies:

- All studies are in agreement that largest sources of greenhouse emissions from production are fertilizer (specifically nitrogen) application and diesel fuel consumption, with differences in emissions results attributed to different fertilizer and fuel requirements to grow wheat in different locations.

- All studies include either a single species of wheat, or include no information about species, class, or location of field. All studies assume that transportation distances and fertilizer applications are the same for all wheat from an individual country.

- No study includes assumptions or a discussion of if wheat production varies within the study scope and how it was addressed in the case study.

- If yield was reported, studies assumed one representative yield. Values ranged from 2400-6420 kg CO₂ eq./ha.

- Estimates of carbon sequestration were highly variable when estimated.
Table 4 – Comparison of previous LCA studies of wheat.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Single Species</th>
<th>Single Location</th>
<th>Assumed Agricultural Yield</th>
<th>Computational remedy for the co-production of wheat straw</th>
<th>Consideration of carbon sequestration</th>
<th>Life Cycle Contribution to Climate Change without consideration of sequestration</th>
<th>Life Cycle Contribution to Climate Change with consideration of sequestration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lechon</td>
<td>Spain</td>
<td>Yes</td>
<td>Yes</td>
<td>3400 kg/ha</td>
<td>Included but the percentages is not specified</td>
<td>Included at 152 g CO₂ eq/kg wheat</td>
<td>154 g CO₂ eq/kg wheat</td>
<td>1.88 g CO₂ eq/kg wheat</td>
</tr>
<tr>
<td>Narayanaswamy</td>
<td>Australia</td>
<td>Yes</td>
<td>Yes</td>
<td>2500 kg/ha</td>
<td>Included, 94.7% of on-field processes allocated to wheat grain</td>
<td>Not included</td>
<td>304 g CO₂ eq/kg wheat</td>
<td></td>
</tr>
<tr>
<td>Koga</td>
<td>Japan</td>
<td>Yes</td>
<td>Yes</td>
<td>5000 kg/ha</td>
<td>Not included</td>
<td>Not included</td>
<td>162 g CO₂ eq/kg wheat</td>
<td></td>
</tr>
<tr>
<td>Ecoinvent</td>
<td>Switzerland</td>
<td>Yes</td>
<td>Yes</td>
<td>6420 kg/ha</td>
<td>Included, 92.5% of on-field processes allocated to wheat grain</td>
<td>Included at 8,538 kg CO₂/ha or 1330 g CO₂ eq/kg wheat</td>
<td>498 g CO₂ eq/kg wheat</td>
<td>-832 g CO₂ eq/kg wheat</td>
</tr>
</tbody>
</table>
2.1.2 Japanese Perspective

This LCA of American wheat includes a Japanese perspective for two reasons: 1) Japan imports most of their wheat from the U.S. [46] and 2) the Food Studies Group at the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan has the resources and governmental influence to report results to influence domestic food systems policy [47].

Japan is highly dependant on foreign imports, and produces little domestically from field-based agriculture, besides rice. For example, Japan imports over three million metric tons of wheat from the U.S. annually, comprising 57% of total wheat consumption [46]. In fact, the U.S. exports over half the wheat produced domestically, with Japan among the top two destinations [37], [53]. An exterior perspective gives an accurate picture of the wheat industry by standardizing the market location and transportation paths.

Japan is increasing concerned with the environmental impact of their largely import-based food system [4], and is interested in selecting wheat based in part on life cycle environmental impact. The Food Studies group at AIST produces an annual report for The Japanese Ministry of Agriculture, Forestry and Fisheries, which will contain the case study results described here.

2.1.3 Case Study Goal

The primary case study goal is to understand the variation in select life cycle greenhouse gas emissions of wheat as a function of wheat species, variation in farming practices (i.e., fuel use, chemical application), crop yield, and the location of the farm and related methodological implications of studying regional variations. The results are intended to inform LCA practitioners on the potential variation of climate change
impact in crop production. Results for the variation in production and transportation will be compared with an estimate of the sequestration potential of wheat fields.

However, this study is not intended to be a comprehensive inventory of every method by which wheat is grown and transported in the U.S. The variation in farming practices and transportation paths to market are as varied as the industry itself. This study is rather intended to be comparative and demonstrate to magnitude that region, species, and transportation influence LCA results for wheat. These goals were kept in mind while designing the study’s motivation and methods. Results should influence the inclusion of region in LCA’s of products and processes that derive from agricultural goods, such as processed food and biofuels, and support transportation decisions.

2.1.4 Functional Unit

The functional unit is defined as 1 kg of dry wheat at the point-of-use (POU) in Yokohama. The ISO standards require a duration and quality of service in addition to magnitude of service [39]. The duration is defined wheat produced and transported during a single season. The quality is defined by four species of dry wheat, as classified by the U.S. Department of Agriculture (USDA) [25], included in the scope: hard red winter, hard red spring, soft red winter, and soft white (both winter and spring varieties). An individual LCA was performed for each wheat species based on yield, energy use, chemical application, and transportation. Durum wheat is also an important USDA wheat species classification, but is excluded from the study scope because Japan imports durum wheat entirely from Canada [54].

The four major classifications of American wheat differ in both their physical properties and production region. Hard red winter and hard red spring varieties tend to have a high gluten content, making it applicable for harder breads, rolls, and bagels [46]. Both varieties are produced in the heartlands and upper plains regions of the
U.S., however, hard red spring usually has higher yields [25]. Soft red winter has a slightly lower gluten content and is produced predominantly in the Midwest region [46]. Soft white wheat is a recent varietal growth predominantly in the northwest. It’s low gluten content is ideal for pastries, cakes, flatbreads, cookies, and crackers [46]. All wheat varieties are used in Japan and applicable to the scope [55].

2.1.5 System Boundaries

This case study of American wheat includes energy production (well-to-POU) and use and fertilizer, herbicide, and insecticide production (well-to-POU) and application during wheat cultivation, as well as wheat transportation from the farm to Japan. Results are compared with a current estimate of wheat field’s carbon sequestration.

In addition, this case study is part of a more comprehensive LCA study on sustainable consumption at AIST, in Tsukuba, Japan which includes the use of wheat in the production of noodles and bread as well as studies of other food sources (Figure 6). Methods and assumptions for production and transportation are presented in further detail in Section 2.2, Inventory Analysis. This LCA follows the guidelines established by ISO14040 series, but maintains the flexibility given by the standards to tailor methodology to study goals [3].
Figure 6 – System boundaries of the study herein include Processes 1. Processes 2 & 3 are currently modeled at AIST.

2.1.6 Data Categories

Emissions tracked are three contributors to climate change: carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O).

2.1.7 Data Quality

Assessing data quality is a difficult but important component to a complete LCA. An analysis of data quality is required in ISO standards [56] and includes an assessment of the time, technology, and geography covered; the precision, completeness, and sources of data; appropriateness of the data; as well as the consistency and reproducibility of the methods being used. Data will be described qualitatively, but will also be evaluated using Data Quality Indicators developed in the Design for Environment Laboratory at the University of Washington listed in Table 5 [57].
<table>
<thead>
<tr>
<th>ISO14040 Data Quality Indicators</th>
<th>Data Quality Scoring Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Time-related coverage</td>
<td>Deviation from intended period:</td>
</tr>
<tr>
<td></td>
<td>(1) Less than 6 years difference to the year of study, (2) Less than 10 years difference, (3) Less than or equal to 15 years difference, (4) Age of data unknown or more than 15 years difference</td>
</tr>
<tr>
<td>(2) Geographical coverage</td>
<td>Deviation from intended area:</td>
</tr>
<tr>
<td></td>
<td>(1) Data from area under study, (2) Average data from larger area in which the area under study is included, (3) Data from area under similar production conditions, (4) Data from unknown area or area with different production conditions</td>
</tr>
<tr>
<td>(3) Technology coverage</td>
<td>Deviation from intended technology:</td>
</tr>
<tr>
<td></td>
<td>(1) Data from enterprises, processes, and materials under study</td>
</tr>
<tr>
<td></td>
<td>(2) Data from processes and materials under study but different enterprises</td>
</tr>
<tr>
<td></td>
<td>(4) Data from processes and materials under study but different or unknown technology</td>
</tr>
<tr>
<td>(4) Precision and uncertainty of the data</td>
<td>(1) Data include a mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps).</td>
</tr>
<tr>
<td></td>
<td>(2) The mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps) can be approximated.</td>
</tr>
<tr>
<td></td>
<td>(4) The mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps) are not available and cannot be approximated.</td>
</tr>
<tr>
<td>(5) Completeness and representativeness of the data</td>
<td>(1) Data are based on site-specific locations reporting primary data as available with the resulting percentages of locations reporting data from the potential number in existence noted.</td>
</tr>
<tr>
<td></td>
<td>(2) Data are based on site-specific locations reporting primary data as available with no information on the resulting percentages of locations reporting data from the potential number in existence.</td>
</tr>
<tr>
<td></td>
<td>(3) Data are estimated or calculated and have received data quality scores of 1 or 2 in the categories of Time-related coverage, Geographical coverage, and Technology coverage.</td>
</tr>
<tr>
<td></td>
<td>(4) Data are estimated or calculated and have received data quality scores of 3 or 4 in the categories of Time-related coverage, Geographical coverage, and Technology coverage.</td>
</tr>
<tr>
<td>(6) Reproducibility of the methods used throughout the LCA</td>
<td>(1) Very high (Data are based on direct measurements using a widely accepted test methods or on sound engineering models representing current technology. Also, the source provides a transparent account of the assumptions made.)</td>
</tr>
<tr>
<td></td>
<td>(2) High (Although the data are based on a generally sound test method or model and the source provides a transparent account of the assumptions made, the data are dated or lack enough detail for adequate validation.)</td>
</tr>
<tr>
<td></td>
<td>(3) Moderate (Data are based on an unproven or new methodology but include a significant amount of background information.)</td>
</tr>
<tr>
<td></td>
<td>(4) Low (Data are based on a generally unacceptable, ill defined, or unpublished method, but the method may provide an order-of-magnitude value)</td>
</tr>
<tr>
<td>(7) Sources of the data and their representativeness</td>
<td>Type of reference</td>
</tr>
<tr>
<td></td>
<td>(1) Data from reviewed source; (2) Data from public written source (not reviewed); (3) Data from closed written source (including review information); (4) Other sources</td>
</tr>
</tbody>
</table>
2.2 Inventory Analysis

2.2.1 System Overview

In order to model wheat production and transport, the life cycle inventory analysis for each species must be representative of areas of the country where each variety of wheat is grown. The USDA compiles yield data for each of the four wheat species included in the study scope at a spatial resolution of one American state [25]. Complete yield data are included in Appendix A. It is assumed that wheat yield varies yearly, so the last two years (2005 and 2006) were averaged by volume in bushels. The top three production states by volume were identified for hard red winter, hard red spring, soft red winter, and soft white and are displayed in Figure 7-10 as percent of total wheat species yield.
Figure 7 – Production percentage of hard red winter wheat by state.

Figure 8 – Production percentage of hard red spring wheat by state.
Figure 9 – Production percentage of soft red winter wheat by state.

Figure 10 – Production percentage soft white wheat by state.
As follows, an individual LCA has been prepared for each species of wheat for the top three production states including chemical use, energy consumption and transportation distances from that state. While it is possible that some wheat comes from other states, the study scope omits states that are not in the top three by volume. Again, this is an attempt to be comparative and demonstrate variability in emissions for agricultural products. Hard red winter wheat is produced in Montana, Oklahoma, and Kansas. Hard red spring is produced in Montana, Minnesota, and North Dakota. Soft red winter is produced in Missouri, Illinois, and Ohio. Soft white is produced in Oregon, Idaho, and Washington. An individual LCA was preformed for each states and species combination.

Given these study regions, wheat is produced from seed in the U.S. almost entirely by conventional agricultural production [16]. The LCA is built around on-field and off-field unit processes. On-field unit processes can be broken down into three major categories: on-field chemical application, equipment electricity and fuel consumption, and sequestration. Chemicals applied to wheat fields are nitrogen fertilizer (N), phosphorous fertilizer (P₂O₅), potassium fertilizer (K₂O), limestone fertilizer (CaCO₃), herbicides (e.g., Atrazine), and insecticides specific to crop type [17]. On-field equipment energy consumption includes electricity, gasoline, liquid petroleum gas (LPG), and natural gas. In addition, atmosphere-plant-soil interactions have the potential to sequester carbon. Off-field processes include transportation, where it is assumed that wheat travels from the field in a truck-rail-barge-ocean vessel modal combination. Given these on-field and off-field processes, unit processes needed to complete the LCA capture well-to-POU energy and chemicals production. Figure 11 gives an overview of included processes, as follows.
2.2.2 On-Field Chemical Application

The USDA maintains a yearly inventory for volume of nitrogen, phosphorus, potassium, and limestone fertilizers, in addition to herbicides and insecticides in its Agricultural Chemical Usage Summary [17]. The USDA tabulates volumes of active ingredients applied for winter, spring, and durum wheat in lbs/acre at the spatial resolution of one American state. Here, it is assumed that the winter or spring variety is applicable to primary species produced in that state, although it is not explicitly stated in the report [17]. For example, it assumed that winter wheat from the state of
Ohio is soft red winter, which is the primary species produced in that state [25]. The complete chemical volumes are listed in Appendix B. Values for each chemical were converted to SI units (kg/ha) assuming 1 lb = 2.20 kg and 1 hectare (ha) = 2.47 acres [58]. An extraction for applicable states is listed in Table 6.

### Table 6 – Chemical application by wheat species, state, and active ingredient.

<table>
<thead>
<tr>
<th>Spring Wheat</th>
<th>Pesticides</th>
<th>lb/acre</th>
<th>kg/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho</td>
<td>Nitrogen</td>
<td>1.21E+02</td>
<td>1.36E+02</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>4.10E+01</td>
<td>4.60E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>3.70E+01</td>
<td>4.15E+01</td>
</tr>
<tr>
<td>Minnesota</td>
<td>Nitrogen</td>
<td>1.08E+02</td>
<td>1.21E+02</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>4.90E+01</td>
<td>5.49E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>3.80E+01</td>
<td>4.26E+01</td>
</tr>
<tr>
<td>Montana</td>
<td>Nitrogen</td>
<td>5.70E+01</td>
<td>6.39E+01</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>3.50E+01</td>
<td>3.92E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>2.20E+01</td>
<td>2.47E+01</td>
</tr>
<tr>
<td>North Dakota</td>
<td>Nitrogen</td>
<td>1.14E+02</td>
<td>1.28E+02</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>5.00E+01</td>
<td>5.60E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>2.40E+01</td>
<td>2.69E+01</td>
</tr>
<tr>
<td>Oregon</td>
<td>Nitrogen</td>
<td>5.90E+01</td>
<td>6.61E+01</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>3.40E+01</td>
<td>3.81E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>3.40E+01</td>
<td>3.81E+01</td>
</tr>
<tr>
<td>South Dakota</td>
<td>Nitrogen</td>
<td>9.00E+01</td>
<td>1.01E+02</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>4.90E+01</td>
<td>5.49E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>2.80E+01</td>
<td>3.14E+01</td>
</tr>
<tr>
<td>Washington</td>
<td>Nitrogen</td>
<td>8.60E+01</td>
<td>9.64E+01</td>
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<tr>
<td></td>
<td>Phosphate</td>
<td>2.10E+01</td>
<td>2.35E+01</td>
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<tr>
<td></td>
<td>Potash</td>
<td>4.30E+01</td>
<td>4.82E+01</td>
</tr>
<tr>
<td>Total</td>
<td>Nitrogen</td>
<td>9.80E+01</td>
<td>1.10E+02</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>4.60E+01</td>
<td>5.16E+01</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>2.90E+01</td>
<td>3.25E+01</td>
</tr>
<tr>
<td>Herbicides</td>
<td></td>
<td>5.58E-01</td>
<td>6.30E-01</td>
</tr>
<tr>
<td>Insecticide</td>
<td></td>
<td>4.00E-03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Fungicide</td>
<td></td>
<td>2.20E-02</td>
<td>2.00E-02</td>
</tr>
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Table 6 continued

<table>
<thead>
<tr>
<th>Winter Wheat</th>
<th>Colorado</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>3.80E+01</td>
<td>4.26E+01</td>
</tr>
<tr>
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<td>4.82E+01</td>
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<tr>
<td>Fungicide</td>
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</table>

As described in the literature review, on-farm application of fertilizers and chemicals were among the largest contributors to life cycle greenhouse gas emissions.

### 2.2.3 On-Field Equipment Energy Consumption and Emissions

Similarly, the USDA compiles detailed energy use in the agriculture industry. The Energy Use on Major Field Crops in Surveyed States report tracks fuel consumption for wheat, corn, rice, soybean, sugar beet, and cotton cultivation for each American state [22]. Gasoline (gallons/acre), diesel (gallons/acre), liquid petroleum gas (gallons/acre), electricity (kWh/acre), and natural gas (cubic ft/acre) use are included for all fossil fuel-based farm operations. Farm machinery operations cover all on-farm processes that consume fossil fuels, including tractor and farm truck use, irrigation, and drying of grain [22]. A complete account is included in Appendix C. An extraction for study states and conversion to SI units (assuming 1 gal = 3.79 L, 1 hectare (ha) = 2.47, and 1 ft³ = 0.028 m³) [58] is presented in Table 7. Field practices, and consequently energy use and fossil fuel consumption, vary widely by state. For
example, several states consume no electricity, while Idaho uses over 1.01E+03 kWh/ha wheat. Washington consumes as much as 5.14E+01 L/ha of diesel fuel, while Illinois consumes as little as 1.87E+01 L/ha of diesel fuel. Emissions for each fuel type, including electricity, are quantified in Section 2.2.6 using the Department of Energy Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) LCA Model [59].

Table 7 – Energy consumption for 1 ha wheat by American state. Shading indicated states included in system boundary.

<table>
<thead>
<tr>
<th></th>
<th>Diesel L/ha</th>
<th>Gasoline L/ha</th>
<th>LPG L/ha</th>
<th>Electricity kWh/ha</th>
<th>Natural gas m³/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>4.21E+01</td>
<td>1.31E+01</td>
<td>0.00E+00</td>
<td>2.20E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Georgia</td>
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<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
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<td>4.49E+01</td>
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<td>0.00E+00</td>
<td>1.01E+03</td>
<td>0.00E+00</td>
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<tr>
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<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Kansas</td>
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<td>0.00E+00</td>
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<tr>
<td>Louisiana</td>
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<td>0.00E+00</td>
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<tr>
<td>Minnesota</td>
<td>3.74E+01</td>
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<td>1.90E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
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<td>Mississippi</td>
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<td>0.00E+00</td>
<td>0.00E+00</td>
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<tr>
<td>Missouri</td>
<td>4.12E+01</td>
<td>1.59E+01</td>
<td>0.00E+00</td>
<td>7.20E+00</td>
<td>0.00E+00</td>
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<td>2.69E+01</td>
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<td>Nebraska</td>
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<td>0.00E+00</td>
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<td>1.11E+01</td>
<td>0.00E+00</td>
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<td>2.15E+01</td>
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<td>0.00E+00</td>
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<td>Oklahoma</td>
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<td>5.07E+01</td>
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<td>0.00E+00</td>
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<td>1.22E+01</td>
<td>0.00E+00</td>
<td>4.03E+01</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

2.2.4 Yield

Yield for each state and wheat species combination were extracted from the USDA summary on grain production and are displayed in Table 8 [25]. Complete yield information is included in Appendix A.
Table 8 – Wheat yield in kg/ha for each location and species.

<table>
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<tr>
<th>Species</th>
<th>States</th>
<th>Yield (kg/ha)</th>
</tr>
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<tr>
<td>Hard Red Winter</td>
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<td>2.80E+03</td>
</tr>
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<td></td>
<td>Kansas</td>
<td>2.34E+03</td>
</tr>
<tr>
<td></td>
<td>Oklahoma</td>
<td>1.95E+03</td>
</tr>
<tr>
<td>Hard Red Spring</td>
<td>Montana</td>
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<tr>
<td></td>
<td>Minnesota</td>
<td>3.10E+03</td>
</tr>
<tr>
<td></td>
<td>North Dakota</td>
<td>2.30E+03</td>
</tr>
<tr>
<td>Soft Red Winter</td>
<td>Missouri</td>
<td>3.47E+03</td>
</tr>
<tr>
<td></td>
<td>Illinois</td>
<td>4.05E+03</td>
</tr>
<tr>
<td></td>
<td>Ohio</td>
<td>4.36E+03</td>
</tr>
<tr>
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<tr>
<td></td>
<td>Idaho</td>
<td>5.33E+03</td>
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<tr>
<td></td>
<td>Washington</td>
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</table>

2.2.5 Transportation Mode, Distance, and Load Factors

Transportation modes are generally separated into water, land, or air transport in LCA studies. Intermodal transportation (a combination of one or more modes) is used to transport agricultural bulk freight from field to the POU. Fuel consumption, emissions associated with fuel combustion, cargo spills, noise pollution, and land use from highways, ports, rail development are environmental issues resulting from transportation [60]. The materials acquisition, fuel processing and transport, maintenance of vehicles, and end-of-life processes are also important for an LCA study [61].

A robust model of the wheat supply chain is possible because of a well-documented infrastructure and path to export in the U.S.. Wheat, in addition to corn and soybeans, has been exported from the U.S. for over 100 years [45]. The longevity of the grain
industry gives it an established local infrastructure for moving wheat from the field to market. Wheat is usually grown within a 100km distance from a regional distribution facility in both the northwest and the central plains region [62], [63]. This distance is an upper quartile estimate, so it is unlikely that grain travels longer than 100km by truck [63]. These facilities are often referred to as “grain bins.” In the case of wheat destined for Japan, the wheat continues from local bins by Class I diesel freight train bulk hopper to port of export in Portland, Oregon (Figure 12). Containerized transport of grain currently occupies a small market niche of grain exports (>5%) [64]. This LCA assumes all grain travels solely by covered bulk hopper. From the port, wheat is transported predominantly on Panamax or Handymax bulk ocean vessels to POU in Yokohama, Japan [37], [65]. Currently, Port of Portland is the only port facility that exports large volumes of wheat to Asia, which restricts both the domestic and ocean transportation routes [66]. One exception to the truck-rail-ocean vessel modal combination is in the case of soft white wheat produced in the northwest U.S., where it is assumed that wheat is moved by barge on the Columbia River a distance of 350 km [62].
For this LCA, each species of wheat has three production states with different paths to market in Japan [37]. It was assumed that wheat travels by bulk Class 6 trucks from farms to local bins at a distance of 100km [62]. This estimate is consistent for grain in the northwest and plains [62], [63]. The rail distances for each state bin to Port of Portland was calculated exactly using the Network Analyst extension in ESRI’s ArcGIS software package and the U.S. Department of Transportation GIS database [67]. The ocean distance is assumed to be vessels at a distance of 8,000 km, based on AIST’s LCA database.

In addition to the distances for each mode, transportation methodology developed in the Design for Environment laboratory at the University of Washington requires an accurate representation of backhaul (or return trip) assumptions for each mode [68], [69]. Here, domestic rail, truck, and barge are assumed to have a 100% empty backhaul (i.e., all vehicles and vessels return empty form the destination to the point of origin). Tight capacity, specialized grain containers, and non-existent demand for grain movement back into the American heartland forces all hoppers to currently be
sent back empty [66]. This assumption has been confirmed by Herland Ugles, president of the International Longshore and Warehouse Union Local 19, and Bruce Agnew, Program Director of the Cascadia Transportation Group in personal communications [70], [71].

For ocean transport to Japan, Panamax and Handymax vessels calling from Asia ports return to America ports near capacity [70]. Vessels are carrying predominantly finished bulk goods such as metals, clean paper pulp, minerals, and even specialty grain [72]. There's a slight imbalance in trade for bulk good (20%), with exports from the U.S. still being higher [72]. Because it is unclear from personal communications with Herland Ugles that a consistent backhaul pattern exists for ships used for U.S. grain, it is assumed here that ocean transport of wheat to Japan has 0% empty associated backhaul [70]. This decision was made in an effort to be conservative in backhaul assumptions for ocean transport where a clear pattern is not known. Calculated transportation distances, including backhaul, for each state are listed in Table 9.
Table 9 – Transportation distances for each mode including fronthaul and backhaul.

<table>
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<tr>
<th></th>
<th>Class 6 Truck (km)</th>
<th>Rail (km)</th>
<th>Barge (km)</th>
<th>Bulk Ocean Vessel (km)</th>
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<td>Montana</td>
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<td>Fronthaul</td>
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<tr>
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<td>Backhaul</td>
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<tr>
<td></td>
<td>Backhaul</td>
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<td>3.36E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Ohio</td>
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<td>3.82E+03</td>
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</tr>
<tr>
<td></td>
<td>Backhaul</td>
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<td>0.00E+00</td>
</tr>
<tr>
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<td>Fronthaul</td>
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<td>Backhaul</td>
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<td>3.00E+02</td>
<td>3.50E+02</td>
</tr>
</tbody>
</table>

Load factor assumptions for wheat fronthaul are assumed to be 100% for rail, barge, and truck fronthauls [59]. Domestic backhaul load factors are assumed to be 0%. Ocean fronthaul load factor is modified to 100% based on personal communication with Harold Ugles at the ILWU [70].

2.2.6 Well-to-Point-of-Use Energy and Chemicals Production

Given equipment energy use and emissions, chemical application and emissions, and transportation modes, distances, and load factors for wheat, the Department of Energy Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model version 1.7 was used for LCA process information. GREET estimates life cycle energy consumption (as the total energy, fossil, and petroleum use) and emissions of CO₂ in addition to other greenhouse gas
and particulate emissions. GREET applications to date are primarily assessments of transportations systems (personal and fuel cell vehicles), but what is of value here are the fuel cycle, electricity production, logistics models (transport on land, through inland waters, or by sea), and agricultural equipment and chemicals contained within GREET. In particular, GREET’s analysis of biofuels produces robust, and American-specific process information for all agricultural chemicals used for wheat production and included in the study scope.

There are at least three advantages of using GREET. First, the data and model results are well developed and documented, have been highly peer reviewed, and are widely accepted by LCA practitioners [68]. Combination of GREET emissions with USDA consumption records and robust transportation distances allows a detailed and clear understanding of variation in emissions for wheat export. Second, using only GREET for process information standardizes U.S. emissions data sources. Lastly, the GREET system’s extensive set of fuel cycle parameters are easily modified, allowing exact load factors for transportation, local electricity profiles, and modification if U.S. energy, fertilizer production changes. This allowed an individual electricity mix to be used for wheat produced in that state. Electricity profiles are listed in Table 10.
Table 10 – Electricity profile for each wheat production state.

<table>
<thead>
<tr>
<th>State</th>
<th>Source</th>
<th>Power Generation (Megawatts)</th>
<th>Relative Percentage (%)</th>
</tr>
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<tbody>
<tr>
<td>Idaho</td>
<td>Coal</td>
<td>1.70E+01</td>
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<tr>
<td></td>
<td>Petroleum</td>
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<td></td>
<td>Total</td>
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<td>Other Gas</td>
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<td></td>
<td>Nuclear</td>
<td>1.14E+04</td>
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<td>Hydroelectric</td>
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<td>Natural Gas</td>
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<td>Hydroelectric</td>
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<td>Total</td>
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<td>Power Generation (Megawatts)</td>
<td>Relative Percentage (%)</td>
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<tr>
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<td>Nuclear</td>
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<td><strong>Total</strong></td>
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<td>Coal</td>
<td>1.05E+07</td>
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<td>Petroleum</td>
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<td>Natural Gas</td>
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<tr>
<td><strong>Total</strong></td>
<td>1.02E+08</td>
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Table 11 displays process information for fronthaul study transportation processes. Relevant modes include bulk ocean carriers, transport barge, diesel freight train, medium-heavy truck, with included fuel production processes. On wheat fronthaul, the grain industry is currently operating at capacity [66]. GREET load factors are set at a default of 80% [59] for all modes except rail. However, this was modified here to a 100% load factor to match conditions for wheat. Cargo payloads and mile per gallon estimates were left unmodified from GREET defaults [59].

Table 12 displays process information for backhaul study transportation processes. Again, relevant modes include transport barge, diesel freight train, medium-heavy truck, with included fuel production processes. Again, note that bulk ocean carriers are assumed to have no associated backhaul and are not included. For wheat backhaul, the grain industry has an assumed 100% empty backhaul for barge, rail, and truck due to high demand for grain hoppers in the American plains and Midwest [70]. Therefore, the load factor is 0%, with payload and mile per gallon left unmodified.

Table 13 displays process information for on-site fuel use and energy production. GREET’s focus on fuel and transportation systems is particularly useful for on-site fuel use. It includes diesel and gasoline combusted specifically in a farming tractor. On-site electricity, natural gas, and LPG consumption and associated fuel production processes are also included. GREET allows a modification of the electricity contribution mix, which was altered to match the generation profile for each wheat producing state. Each state has a different relative contribution of coal, petroleum, natural gas, hydroelectric, and other renewables [23].

Table 14 displays process information for chemical application. Nitrogen, P₂O₅, K₂O, CaCO₃ fertilizer are included in GREET for each gram of active nutrient. Pesticides, insecticides, and herbicides are also included. It is important to note that GREET accounts for the direct emissions of N₂O from fertilized soil [59].
Table 11 – Summary of energy use and emissions for fronthaul transportation modes.

<table>
<thead>
<tr>
<th>Product</th>
<th>Bulk Carriers, 45,000 dwt-100% load</th>
<th>Transport-Barge, average payload 1,500 tons (U.S.), 80% load</th>
<th>Transport by Diesel Freight Train (U.S.), 7.3 mpg, 100% load</th>
<th>Transport by Medium-Heavy Truck-class 6 or 7 (8 ton cargo), 7.3 mpg, 100% load</th>
<th>Residual Oil, at refueling station</th>
<th>Diesel for non-road engines, at fueling station</th>
<th>Conventional and LS Diesel, at fueling station</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECONOMIC FLOWS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product quantity</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product quantity units of measure</td>
<td>kg-km</td>
<td>kg-km</td>
<td>kg-km</td>
<td>kg-km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Oil, at refueling station</td>
<td>BTU</td>
<td>-2.76E-01</td>
<td></td>
<td>1.00E+06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel for non-road engines, at fueling station</td>
<td>BTU</td>
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<td></td>
<td>1.00E+06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional and LS Diesel, at fueling station</td>
<td>BTU</td>
<td>-1.51E+00</td>
<td></td>
<td>1.00E+06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunker fuel</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>ENVIRONMENTAL FLOWS</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>g</td>
<td>6.04E-03</td>
<td>2.34E-02</td>
<td>1.97E-02</td>
<td>1.17E-01</td>
<td>8.36E+03</td>
<td>1.45E+04</td>
</tr>
<tr>
<td>CH4</td>
<td>g</td>
<td>4.09E-08</td>
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<td>9.99E-07</td>
<td>2.31E-06</td>
<td>9.62E+01</td>
<td>1.03E+02</td>
</tr>
<tr>
<td>N2O</td>
<td>g</td>
<td>1.42E-07</td>
<td>5.52E-07</td>
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<td>4.37E-06</td>
<td>1.48E-01</td>
<td>2.41E-01</td>
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</tbody>
</table>
Table 12 – Summary of energy use and emissions for backhaul transportation modes.

<table>
<thead>
<tr>
<th>Product</th>
<th>Transport- Barge, average payload 1,500 tons (U.S.), 0% load</th>
<th>Transport by Diesel Freight Train (U.S.)</th>
<th>Transport by Medium-Heavy Truck- class 6 or 7 (8 ton cargo), 7.3mpg, 0% load</th>
<th>Residual Oil, at refueling station</th>
<th>Diesel for non-road engines, at fueling station</th>
<th>Conventional and LS Diesel, at fueling station</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ECONOMIC FLOWS</strong></td>
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<td>1.00E+00</td>
<td>1.00E+00</td>
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</tr>
<tr>
<td>Product quantity units of measure</td>
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<td>kg-km</td>
<td>kg-km</td>
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<td>Residual Oil, at refueling station</td>
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<td></td>
<td>1.00E+06</td>
<td></td>
</tr>
<tr>
<td>Diesel for non-road engines, at fueling station</td>
<td>BTU</td>
<td>-2.53E-01</td>
<td></td>
<td></td>
<td></td>
<td>1.00E+06</td>
</tr>
<tr>
<td>Conventional and LS Diesel, at fueling station</td>
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<td></td>
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<td>1.00E+06</td>
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<tr>
<td>CO2</td>
<td>g</td>
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<td>g</td>
<td>2.70E-08</td>
<td>5.07E-07</td>
<td>2.97E-06</td>
<td>1.48E-01</td>
<td>2.41E-01</td>
</tr>
</tbody>
</table>
Table 13 – Summary of energy use and emissions for on-site energy production.

| Product | Stationary Grid Electricity, at POU | Natural Gas burned in a Stationary Reciprocating Engine; urban facility, at POU | Diesel Fuel burned in a Farming Tractor; urban farm, at POU | Gasoline burned in a Farming Tractor; urban farm, at POU | Natural Gas as a Stationary Fuel, at POU | Natural Gas for electricity generation, at POU | Diesel, at POU | Gasoline, at POU | LPG, at POU |
|---------|-----------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|----------------|----------------|---------------|
| **ECONOMIC FLOWS** | | | | | | | | | | |
| Product quantity | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 | 1.00E+06 |
| Product quantity units of measure | BTU | BTU | BTU | BTU | BTU | BTU | BTU | BTU | BTU |
| Natural Gas as a Stationary Fuel, at POU | 0.00E+00 | -1.00E+06 | 0.00E+00 | 0.00E+00 | as product quant. | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Natural Gas for electricity generation, at POU | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | as product quant. | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Residual Oil, at POU | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Diesel, at POU | 0.00E+00 | 0.00E+00 | -1.00E+06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Gasoline, at POU | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -1.00E+06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Crude, at POU | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| LPG, at POU | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |

**ENVIRONMENTAL FLOWS**

| CO2 | 2.20E+05 | 5.77E+04 | 7.74E+04 | 7.56E+04 | 5.24E+03 | 5.16E+03 | 1.45E+04 | 1.78E+04 | 1.02E+04 |
| CH4 | 2.96E+02 | 3.69E+02 | 6.30E+01 | 5.19E+00 | 1.96E+02 | 1.75E+02 | 1.03E+02 | 1.07E+02 | 9.83E+01 |
| N2O | 3.12E+00 | 1.50E+00 | 9.20E-01 | 1.10E+00 | 8.55E-02 | 8.32E-02 | 2.41E-01 | 2.91E-01 | 1.76E-01 |
Table 14 – Summary of Energy Use and Emissions of Agricultural Chemicals

<table>
<thead>
<tr>
<th>Fertilizer (per gram of nutrient)</th>
<th>Herbicides: Average for Crop Type</th>
<th>Pesticides: Average for Crop Type</th>
<th>Insecticides: Average for Crop Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Wheat</td>
<td>Wheat</td>
<td>Corn</td>
</tr>
<tr>
<td>Quantity of Fertilizer (grams)</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>Total Emissions: grams per gram</td>
<td>2.60E-03</td>
<td>1.50E-03</td>
<td>7.00E-04</td>
</tr>
<tr>
<td>CH4</td>
<td>1.60E-03</td>
<td>0.00E+00</td>
<td>4.13E-01</td>
</tr>
<tr>
<td>CO2</td>
<td>2.20E+00</td>
<td>7.54E-01</td>
<td>3.56E-01</td>
</tr>
</tbody>
</table>


2.2.7 Accounting for System Co-Products

Grain cultivation in the U.S. produces two products: wheat grain and wheat straw [73]. As indicated by the standards, system expansion is the preferred method for addressing multifunctional processes. However, because there is no mono-functional process to produce wheat straw, allocation of on-field processes and sequestration credits was preformed based on the economic percentage of the two co-products. Each individual wheat species has a slightly different percentage of wheat grain and straw. Table 15 lists the allocation percentages from the USDA’s Characteristics of U.S. Wheat Farming report [73]. According to the report, farms of different value (high, medium, and low) have a different economic percentage of wheat straw vs. wheat grain. Furthermore, each region where wheat is grown has a different distribution of high, medium, and low value farms. An allocation for each species of wheat was calculated by multiplying the disruption of farm value per species by the economic percentage for each value of farm. Note that an allocation was only preformed for the production, and not the transportation of grain.

Table 15 – Allocation for wheat and straw by species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Wheat Grain</th>
<th>Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>96.2%</td>
<td>3.8%</td>
</tr>
<tr>
<td>Hard Red Winter</td>
<td>95.5%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Hard Red Spring</td>
<td>94.7%</td>
<td>5.3%</td>
</tr>
<tr>
<td>Soft Red Winter</td>
<td>95.6%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

2.2.8 Sequestration

A complete agricultural LCA for the quantification of contribution to climate change must correctly address the potential of wheat fields to sequester carbon. A review of carbon sequestration potential for wheat cultivation is presented in Table 16. The range is remarkable, at -1404 kg CO₂ eq./ha to 1440 kg CO₂/ha per year sequestered,
and underscores variability of the range of 152 to 1330 g CO₂ eq/kg wheat presented in Table 4.

Table 16 – Carbon sequestration of wheat cultivation in kg CO₂/ha

<table>
<thead>
<tr>
<th>kg CO₂/ha per year sequestered</th>
<th>Study Method</th>
<th>Cultivation Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1404</td>
<td>Direct Flux Measurement</td>
<td>Conventional</td>
<td>Kessavalou, et al. [34]</td>
</tr>
<tr>
<td>-1548</td>
<td>Direct Flux Measurement</td>
<td>Reduced Tillage</td>
<td>Kessavalou, et al. [34]</td>
</tr>
<tr>
<td>-1764</td>
<td>Direct Flux Measurement</td>
<td>No Tillage</td>
<td>Kessavalou, et al. [34]</td>
</tr>
<tr>
<td>294</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Gregory and Atwell [74]</td>
</tr>
<tr>
<td>750</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Markin &amp; Puckridge [75]</td>
</tr>
<tr>
<td>796</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Keith et al. [76]</td>
</tr>
<tr>
<td>1080</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Martin &amp; Merckx [77]</td>
</tr>
<tr>
<td>1100</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Martin &amp; Merckx [77]</td>
</tr>
<tr>
<td>1140</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Swinnen, et al. [78]</td>
</tr>
<tr>
<td>1250</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Whipps, et al. [79]</td>
</tr>
<tr>
<td>1290</td>
<td>Direct Flux Measurement</td>
<td>Reduced Tillage</td>
<td>Curtin, et al. [28]</td>
</tr>
<tr>
<td>1320</td>
<td>Direct Flux Measurement</td>
<td>Reduced Tillage</td>
<td>Majumder, et al.[80]</td>
</tr>
<tr>
<td>1410</td>
<td>Carbon Tracer</td>
<td>Conventional Tillage</td>
<td>Johnen &amp; Sauerbeck [81]</td>
</tr>
<tr>
<td>1440</td>
<td>Direct Flux Measurement</td>
<td>Reduced Tillage</td>
<td>Purakayastha, et al. [35]</td>
</tr>
</tbody>
</table>

2.2.9 Major Assumptions and Limitations

Assumptions and limitations have been stated in methodological context, but should also be stated explicitly. Significant limitations include exclusions from the system boundary, narrow scope, impacts, and transportation assumptions.

- This LCA is applicable to the current production and transportation conditions in the U.S. for levels of energy use, fertilizer application, and electric generation mix. It represents a single point in time to compare different production locations for the same class of agricultural product. The U.S. agricultural industry as a whole is characterized by extremely volatile market shares, availability, prices, and yield [37]. Both the location of origin and regional energy and chemical field practices for American wheat exported to Japan is annually variable [53]. However, it is assumed that distributed market share of wheat production is consistent with wheat for export to Japan at the
spatial scale of one American state. When data were available for multiple crop years, such as yield, values used for LCA calculation were averaged to account for yearly variation [25].

- The study does not account for every method that wheat can be produced and transported. Results are intended to inform LCA practitioners on the potential variation of environmental impact in crop production and are limited spatially by the available USDA data.

- In the case of multiple modes of transportation in the same location, the most common method was used. For example, wheat from the central U.S. can travel by Columbia River barge or train, but barge is predominantly used for soft white wheat from the northwest [62]. Assumptions for modes, backhauls, and distances are based on current grain infrastructure, USDA data, and communication with grain experts [65], [70]. Shifts in port of export, increase in the use of containerized grain, or increase in bulk hopper capacity could change the modeled transportation processes.

- Process information for chemicals application, fuel use, and transportation are much better understood that sequestration of wheat fields. However, a comparison with applicable SOC data are presented in the discussion.

- Farm, infrastructure, and equipment construction have not been included.

- Impact analysis is limited to greenhouse gas emissions only. Ideally, all impact categories should be included (as eutrophication, loss of habitat and biodiversity, changes in land use and disturbance, heavy metal soil release as noted in Section 1.2), but only greenhouse gases were quantified here. This is consistent with the ISO standards to tailor impact assessment to primary study goals [3].
2.3 Impact Assessment

Impact assessment includes contribution to global warming from emissions of CO₂, CH₄, and N₂O and carbon sequestration. The IPCC Fourth Assessment developed the global warming potentials (GWPs) used to calculate the contribution of each emission type to global warming relative to the contribution of emissions of CO₂ [82]. For example, the most recent report equates 1 unit of CO₂ to 25 units of CH₄ in terms of climate forcing (Table 17). In the impact assessment, the life cycle emissions and sequestration of each gas estimated in the inventory analysis is multiplied by the respective GWP and summed to obtain an estimate of the life cycle total.

Table 17 – Global Warming Potentials (GWPs)

<table>
<thead>
<tr>
<th>Emission</th>
<th>CO₂ Equivalent (100 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>25</td>
</tr>
<tr>
<td>N₂O</td>
<td>298</td>
</tr>
</tbody>
</table>

2.4 Case Study Results

2.4.1 Results By State

Case study results for wheat production were calculated for each wheat species from the top three production states as described above. This combines USDA crop production usage with LCA emissions from the GREET database. Table 18 presents an example for Hard Red Winter wheat from Montana. The initial data sources from the USDA report production inputs per hectare. For example, nitrogen fertilizer is kg/ha and diesel use is L/ha. Since the functional unit for the LCA is 1 kg dry wheat, inputs must be converted using each state’s wheat yield (assuming conversion factors of 2.47 ha per acre and 25.43 kg per bushel dry wheat [83] and varied in the interpretation Section 2.4.5). Here, for clear presentation, emissions for each
economic flow include their associated processes and are referred to as intensity. This process was repeated for each species and state combination in Appendix D.

Table 18 – Inventory results for hard red winter wheat from Montana. Grey shading indicates the two largest contributors to total greenhouse gas emissions.

<table>
<thead>
<tr>
<th>MONTANA – Hard Red Winter</th>
<th>43</th>
<th>Bushel s/acre</th>
<th>Process</th>
<th>Input (normalized to yield)</th>
<th>Unit</th>
<th>Intensity</th>
<th>Unit</th>
<th>Process Reference</th>
<th>CO2 Emission (gCO2 eq./kg Wheat)</th>
<th>Relative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen fertilizer (N)</td>
<td>5.27E+01 kg/ha</td>
<td>1.88E+02 kg/fertilizer/kg wheat</td>
<td>2.94E+00 kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>5.54E+01</td>
<td>39.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorus fertilizer (P2O5)</td>
<td>3.36E+01 kg/ha</td>
<td>1.20E+02 kg/kg wheat</td>
<td>6.70E-01 kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>8.06E+00</td>
<td>5.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potassium Fertilizer (K2O)</td>
<td>1.12E+01 kg/ha</td>
<td>4.01E-03 kg/kg wheat</td>
<td>9.90E-01 kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>3.97E+00</td>
<td>2.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>4.48E+01 kg/ha</td>
<td>1.60E-02 kg/kg wheat</td>
<td>6.10E-01 kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>9.78E+00</td>
<td>6.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herbicides</td>
<td>2.80E-01 kg/ha</td>
<td>1.00E-04 kg/kg wheat</td>
<td>2.08E+01 kg CO2/kg herbicide</td>
<td>GREET 1.7</td>
<td>2.08E+00</td>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insecticides</td>
<td>2.01E-02 kg/ha</td>
<td>7.18E-06 kg/kg wheat</td>
<td>2.43E+01 kg CO2/kg insecticides</td>
<td>GREET 1.7</td>
<td>1.74E-01</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (Farm machinery)</td>
<td>3.19E+01 L/ha</td>
<td>1.14E-02 L/kg wheat</td>
<td>3.35E+01 kg CO2/L consumed</td>
<td>GREET 1.7</td>
<td>3.82E+01</td>
<td>26.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (Custom operation)</td>
<td>7.79E+00 L/ha</td>
<td>2.79E-03 L/kg wheat</td>
<td>3.35E+00 kg CO2/L consumed</td>
<td>GREET 1.7</td>
<td>9.34E+00</td>
<td>6.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>2.69E+01 kWh/ha</td>
<td>9.63E-03 kWh/kg wheat</td>
<td>5.34E-01 kg CO2/kWh</td>
<td>GREET 1.7 (assuming local mix)</td>
<td>5.15E+00</td>
<td>3.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>9.37E+00 L/ha</td>
<td>3.35E-03 L/kg wheat</td>
<td>2.97E+00 kg CO2/L consumed</td>
<td>GREET 1.7</td>
<td>9.96E+00</td>
<td>7.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP Gas</td>
<td>0.00E+00 L/ha</td>
<td>0.00E+00 L/kg wheat</td>
<td>2.84E+00 kg CO2/L consumed</td>
<td>GREET 1.7</td>
<td>0.00E+00</td>
<td>0.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.00E+00 m3/ha</td>
<td>0.00E+00 m3/kg wheat</td>
<td>2.35E+00 kg CO2/m3 consumed</td>
<td>GREET 1.7</td>
<td>0.00E+00</td>
<td>0.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAW TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.42E+02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALLOCATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.36E+02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Inventory results for the transportation component are displayed in Table 19. This combines fronthaul and backhauls distances from in Table 9 with LCA emissions from the GREET database in Table 11 and Table 12. Distances are multiplied by life cycle emissions from GREET, resulting in total transportation emissions by state. Again, in GREET each economic flow for transportation (Class 6 Truck, Bulk Ocean Vessel) has only one associated process for the fuel production. Therefore, emissions for the two are combined for clear presentation in Table 19.

Table 19 – Life cycle emissions by state for transportation component.

<table>
<thead>
<tr>
<th>Emissions (gCO2 eq/km)</th>
<th>FRONTHAUL</th>
<th>BACKHAUL</th>
<th>TOTAL (gCO2 eq/kg wheat)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class 6 Truck (km)</td>
<td>Rail (km)</td>
<td>Barge (km)</td>
</tr>
<tr>
<td>Oregon</td>
<td>1.00E+02</td>
<td>3.00E+02</td>
<td>3.50E+02</td>
</tr>
<tr>
<td>Washington</td>
<td>1.00E+02</td>
<td>3.00E+02</td>
<td>3.50E+02</td>
</tr>
<tr>
<td>Idaho</td>
<td>1.00E+02</td>
<td>6.00E+02</td>
<td>3.50E+02</td>
</tr>
<tr>
<td>Montana</td>
<td>1.00E+02</td>
<td>1.35E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>North Dakota</td>
<td>1.00E+02</td>
<td>2.08E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Minnesota</td>
<td>1.00E+02</td>
<td>2.75E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Kansas</td>
<td>1.00E+02</td>
<td>2.86E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Missouri</td>
<td>1.00E+02</td>
<td>2.86E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Illinois</td>
<td>1.00E+02</td>
<td>3.36E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>1.00E+02</td>
<td>3.43E+03</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Ohio</td>
<td>1.00E+02</td>
<td>3.82E+03</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

Total inventory results for each species in each of the top three production states were combined to form Table 20. Note that an economic allocation was performed on wheat production values as listed in Table 15 for each species of wheat to account for
wheat straw co-production. Total life cycle emissions are the result of both production and transportation to POU in Japan. Production ranged from a maximum of 272 g CO₂ eq/kg wheat for hard red spring produced in North Dakota to a minimum of 136 g CO₂ eq/kg wheat for hard red winter wheat from Montana. Transportation varied from 104 g CO₂ eq/kg for wheat delivered from Oregon and Washington, to 223 g CO₂ eq/kg for wheat from Oklahoma. Intra-species variation for total greenhouse gas emissions was as large as 101% for hard red winter and as little as 7% for soft white.

Table 20 – Life cycle emissions for each species and state combination.

<table>
<thead>
<tr>
<th>Hard Red Winter</th>
<th>Production (kgCO₂ eq/ha)</th>
<th>Production (gCO₂ eq/kg wheat)</th>
<th>Transportation (gCO₂ eq/kg wheat)</th>
<th>Total (gCO₂ eq/kg wheat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montana</td>
<td>379</td>
<td>136</td>
<td>134</td>
<td>269</td>
</tr>
<tr>
<td>Kansas</td>
<td>587</td>
<td>251</td>
<td>199</td>
<td>450</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>617</td>
<td>316</td>
<td>223</td>
<td>540</td>
</tr>
<tr>
<td><strong>Hard Red Spring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>625</td>
<td>202</td>
<td>194</td>
<td>395</td>
</tr>
<tr>
<td>Montana</td>
<td>430</td>
<td>233</td>
<td>134</td>
<td>367</td>
</tr>
<tr>
<td>North Dakota</td>
<td>625</td>
<td>272</td>
<td>165</td>
<td>437</td>
</tr>
<tr>
<td><strong>Soft Red Winter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohio</td>
<td>635</td>
<td>146</td>
<td>240</td>
<td>386</td>
</tr>
<tr>
<td>Illinois</td>
<td>730</td>
<td>180</td>
<td>145</td>
<td>326</td>
</tr>
<tr>
<td>Missouri</td>
<td>758</td>
<td>219</td>
<td>199</td>
<td>417</td>
</tr>
<tr>
<td><strong>White</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idaho</td>
<td>811</td>
<td>152</td>
<td>117</td>
<td>269</td>
</tr>
<tr>
<td>Washington</td>
<td>608</td>
<td>160</td>
<td>104</td>
<td>264</td>
</tr>
<tr>
<td>Oregon</td>
<td>626</td>
<td>178</td>
<td>104</td>
<td>283</td>
</tr>
</tbody>
</table>

Results for carbon equivalent emissions in each state are displayed spatially using GIS in Figure 13.
Figure 13 – Carbon equivalent emissions for each wheat species.
2.4.2 Results by Species

Total emissions for each of the four species were derived by the relative percentage in each of the top three production states following Design for Environment methodology [84]. Figure 14 contains the relative production percentage of the top three states for each wheat species. These were calculated based on total average yield for each species for the 2005 and 2006 crop production years [25].

![Production distribution by species.](image)

Total emissions for each species were calculated by summing each state’s production percentage multiplied by the total carbon equivalent emissions for wheat produced in that state. For example, hard winter is produced 63%, 20%, and 17% in Kansas, Oklahoma, and Montana, respectively. Emissions are 450, 540, 269 g CO₂ eq/kg wheat for Kansas, Oklahoma, and Montana, respectively. Therefore, total life cycle emissions for hard red winter wheat is \(0.63 \times 450 + 0.20 \times 540 + 0.17 \times 269 = 437\) g CO₂ eq/kg wheat. This process was repeated for all species. Results are listed in Figure 15. Hard red winter wheat has the highest total emissions with 437 g CO₂ eq/kg wheat. Soft white winter has the lowest total emissions with 269 g CO₂ eq/kg wheat.
Overall, there is a 62% inter-species variation across the four main species of wheat grown in the U.S and transported to Yokohama, Japan.

![Bar chart showing total life cycle emissions for each wheat species.](image)

Figure 15 – Total life cycle emissions for each wheat species.

### 2.5 Interpretation and Discussion

#### 2.5.1 Data Quality Analysis

The Design for Environment Lab’s data quality scoring method presented in Table 5 was applied to the wheat LCA in Table 21. All data comes from peer-reviewed databases, so in general, data quality is good. No scores 3 or below were assigned to any data source.
Table 21 – Data quality analysis.

<table>
<thead>
<tr>
<th>ISO14040 Data Quality Indicators</th>
<th>USDA State Specific Yield Data</th>
<th>USDA Chemical Application</th>
<th>USDA Energy Consumption</th>
<th>GREET Database</th>
<th>Network Analyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Time-related coverage</td>
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<td>1</td>
<td>2</td>
<td>1</td>
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<tr>
<td>(2) Geographical coverage</td>
<td>2</td>
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<td>2</td>
<td>1</td>
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<tr>
<td>(3) Technology coverage</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(4) Precision and uncertainty of the data</td>
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<td>2</td>
<td>2</td>
<td>1</td>
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</tr>
<tr>
<td>(5) Completeness and representativeness of the data</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(6) Reproducibility of the methods used throughout the LCA</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(7) Sources of the data and their representativeness</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
</tr>
</tbody>
</table>

The energy and transportation data from GREET and USDOT Spatial Analyst data are U.S. specific, have been peer reviewed, extensively used, and of very good quality. However, there are some concerns that should be addressed with the USDA data sources for energy, yield, and fertilizer application. Data quality scores of 2 were assigned based on representativeness and geographic coverage of the data. All three USDA sources report data at the spatial resolution of one American state. This resolution is consistent with the study goals, but assumes farmers in a state all use the same farming practices. This assumption is not always true, especially in the case of organic and reduced tillage systems [50]. However, data at the resolution of an
American state is assumed to be sufficient to address differences in location and species understanding these assumptions.

### 2.5.2 Regional Differences

Results demonstrate the variability in emissions within a previously aggregated production category. All previous studies assess wheat as an aggregated product and report one value for greenhouse gas emissions associated with wheat. However, results show that greenhouse gas emission for different wheat species and production locations are not the same, and modeling them as such using LCA methodologies is insufficient. LCA results indicate that different species of wheat can have a 62% variation in emissions, while intra-species variation can be over 101%.

It is important to understand that results demonstrate need for information and detail when modeling agricultural production, products that derive from initial agricultural products, or any other industry when regional production varies so drastically. The variability in systems like the agricultural sector make an inventory of every species and farm location difficult. However, since the goal is comparison, there is a need to understand regional differences using the LCA methodology. This includes differences in production practices and logistics considerations (distances, backhauls, load factors, etc.).

### 2.5.3 Emissions Contributions

Nitrogen fertilizer and diesel combustion were the two largest contributors to production emissions in most locations and species, which is in agreement with previous LCA studies of wheat [50], [15], [49]. A comparison of relative contributions to production emissions for each states and species are presented in Figure 16. Soft red winter wheat had higher phosphorus application, which was also a
significant contributor in those states. The variation in total species emissions was predominantly due to variations in the two top contributors. Generally, the harder wheat is (higher gluten content), the larger the fertilizer application. Harder wheat is also predominantly grown in the central, north plains regions of the U.S. where transportation distances are also greater.

Ocean vessel and rail were the two largest contributors to transportation emissions for most wheat locations. A comparison of relative contributions to transportation emissions for each state and species are presented in Figure 17. International ocean travel accounted for as much as 53% of total transportation greenhouse gas emission for soft white wheat from Oregon and Washington and as little as 23% for hard red winter wheat from Oklahoma. Rail accounted for as much as 68% (88% of the domestic component) of total transportation greenhouse gas emission for hard red
winter wheat from Oklahoma and as little as 12% (25% of the domestic component) for soft white wheat from the northwest.

Figure 17 – Transportation contribution analysis.

More than raw emission values, the relatively small contribution of truck emission is particularly surprising. Truck emissions range from 9-21% of the total transportation component. For a variety of reasons (low price, high volume, high price sensitivity), truck distances are lower for commercial grains than in other industries [16], [62]. In fact, according to the U.S. Department of Transportation’s Commodity Flow Survey, grain products have some of the lowest share-weighted truck distances of any economic good [85]. Low utilization of trucks in the grain supply chain highlights several key assumptions in the LCA study design. This includes the assumption of a single path to market and 100km truck distance, both of which were used to streamline the study and allow robust comparison between state and species combinations for wheat production. However, good data availability for Washington State made a
supplemental transportation analysis possible to test these assumptions and highlight logistics concerns in supply chains of agricultural products.

2.5.4 Contribution of Transportation

For the case study of American wheat, a truck-rail-ship modal combination was assumed for the transportation component of the LCA. However, there are certainly other modal combinations taken by American wheat, such as truck-barge-ship, rail-barge-ship, truck-rail-ship and rail-ship [62],[65]. To compare contribution of different modes, an addition LCA was performed using more specific transportation distances and modal combinations.

White wheat from Washington State was used as an example for two reasons.

- Washington States serves as a good example because it utilizes a combination of all domestic modes (barge, rail, truck).
- It is the only state we found that had detailed data for modal combinations and distances at a county level resolution [62]. Data are provided from the Strategic Freight Transportation Association’s report on the Dynamics of Wheat and Barley Shipments on Haul Roads to and from Grain Warehouses in Washington State.

2.5.4.1 Methods

The transportation study was constructed to compare the assumed truck-rail-ship modal combination used in the wheat case study with an LCA that included all modal combinations using Washington State as a case study. The primary motivation was to understand if a more detailed knowledge of the supply chain should be modeled. In
addition, it was used to investigate the limited use of trucks in the transportation of agricultural goods.

In Washington State, the Strategic Freight Transportation Analysis (SFTA) database has accumulated percentages of white wheat for export traveling by different modal combinations from the top four production counties: Adams, Lincoln, Walla Walla, and Whitman [62]. There are other wheat producing counties, but these four account for 81% of wheat produced in the state [62], [86]. Other counties are excluded from the system boundary. Figure 18 displays wheat producing counties in the southeast region within the scope of the transportation LCA.

Figure 18 – Wheat production in Washington State.
The SFTA’s detailed inventory gives the total volume of wheat traveling by truck-bare, rail-barge, and rail modal combinations to Port of Portland at a country resolution [62]. For example, Whitman County is the largest producer of white wheat in Washington State, with a 47% relative market share. Within Whitman County, 44% of wheat travels by truck-barge, 3% by rail-barge, and 53% by rail only to Port of Portland. Complete market shares by both county and modal combination are listed in Table 22.

<table>
<thead>
<tr>
<th></th>
<th>Percentage of Washington Wheat by County</th>
<th>County Modal Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Truck-Barge</td>
</tr>
<tr>
<td>Whitman</td>
<td>47%</td>
<td>44%</td>
</tr>
<tr>
<td>Walla Walla</td>
<td>22%</td>
<td>87%</td>
</tr>
<tr>
<td>Lincoln</td>
<td>17%</td>
<td>42%</td>
</tr>
<tr>
<td>Adams</td>
<td>13%</td>
<td>75%</td>
</tr>
</tbody>
</table>

Distances traveled for each modal combination from each county were calculated using Spatial Analyst (Figure 19) and the National Transportation Atlas Database [67]. Table 23 contains distances for each modal component from each of the four counties. The distances were combined with emissions values from the GREET database for each mode as detailed in Section 2.2.6 [59]. The transportation assumptions, backhaul percentages, and load factors are consistent with the case study of American wheat and detailed in Section 2.2.5 [69].
Figure 19 – Rail heads in wheat production counties.

The methods for calculating total CO₂ equivalent emissions that account for each county’s modal combination and distances were very similar to calculating emissions for each species of wheat using its top three production states in the case study of American wheat (Section 2.4.2). Total emissions for each county were calculated by summing each modal relative percentage (by weight) multiplied by the total carbon equivalent emissions for that modal combination. The total emissions for each county were multiplied by that county’s relative percent of total Washington white wheat production. Results were representative of each county’s relative percentage of market share.

2.5.4.2 Results

Results for the domestic transportation of wheat in Washington State in carbon dioxide equivalent emissions are listed in Table 23. The transportation of 1kg of wheat emitted a range of 34.1 to 56.2 g-CO₂eq./kg wheat based on the county of origin
in Washington State. When distributed by market share, the total value is 45.3 g-CO$_2$eq./kg wheat. To compare the detailed study of Washington transportation with the larger case study of American wheat, the ocean ship component of the transportation must be removed from the transportation results presented in Table 20. This yields a result of 51.1 g-CO$_2$ eq./kg wheat for the domestic transportation of white wheat from the original case study of American wheat. This is within the range of the more detailed case transportation case study from Washington State.
Table 23 – Emissions for domestic wheat transport in Washington State.

<table>
<thead>
<tr>
<th>County</th>
<th>Modal Choice</th>
<th>Distance (km)</th>
<th>(g-CO2/kg Wheat)</th>
<th>(g-CO2/kg Wheat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adams</td>
<td>Truck-Barge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>2.68E+02</td>
<td>3.78E+01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barge</td>
<td>7.00E+02</td>
<td>1.80E+01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Train Barge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Train</td>
<td>2.68E+02</td>
<td>6.20E+00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barge</td>
<td>7.00E+02</td>
<td>1.80E+01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Train</td>
<td>8.96E+02</td>
<td>2.09E+01</td>
<td>4.71E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>County Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lincoln</td>
<td>Truck-Barge</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Truck</td>
<td>5.40E+02</td>
<td>7.61E+01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barge</td>
<td>7.00E+02</td>
<td>1.80E+01</td>
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</tr>
<tr>
<td></td>
<td>Train Barge</td>
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</tr>
<tr>
<td></td>
<td>Train</td>
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<td>1.26E+01</td>
<td></td>
</tr>
<tr>
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<td>7.00E+02</td>
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<td>Train</td>
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<td>County Total</td>
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</tr>
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<td>Walla Walla</td>
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<tr>
<td></td>
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<td>1.80E+01</td>
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</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Train Barge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Train</td>
<td>1.28E+02</td>
<td>3.00E+00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barge</td>
<td>7.00E+02</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>County Total</td>
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<td></td>
</tr>
<tr>
<td>Whitman</td>
<td>Truck-Barge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck</td>
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<td></td>
<td>Train Barge</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Train</td>
<td>3.94E+02</td>
<td>9.20E+00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barge</td>
<td>7.00E+02</td>
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<tr>
<td></td>
<td>Train</td>
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<td>County Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WASHINGTON TOTAL 4.53E+01
Detailed inventory of Washington State wheat accounting for each county’s modal combination was very close to the single origin truck-rail combination used to model wheat from other states. 51.1 g-CO₂ eq./kg wheat was within the range of the more detailed inventory. This can be explained by similar emissions for train and barge, and the limited use of trucks in Washington State. Trucks contribute an order of magnitude greater LCA emissions than an equivalent trip mileage on rail or barge. In addition, production counties are closer together in Washington State than in central and upper plains production states [63]. Fields are located quite close to storage facilities, making truck distances minimal when compared to other goods. Therefore, modeling agricultural transportation using a truck-rail combination for each state gave a good value for greenhouse emissions provided accurate distances, backhaul percentages, and knowledge of wheat production location within the state.

2.5.4.3 Rail Spurs

The transportation case study confirms the unique use of modes in the agricultural sector. According to results, trucks contribute a small component of transportation emissions for Washington wheat. This is confirmed by a review of the U.S. Bureau of Transportation Statistics’ Commodity Flow Survey. The report ranks wheat in the bottom 10% of goods by total truck miles [85]. All other cereal grains, corn, and soybeans had similarly low truck utilization [85].

The utilization of rail directly from storage bins is the primary cause of low truck utilization in the wheat industry [62]. Specifically, the use of short line rail infrastructure, often known as rail spurs, is a function of age of agriculture production in the U.S. [87]. Short lines connect local grain bins with the neighboring Class I main lines. Companies operating on short lines tend to be privately held and general serve a small, low density market [88].
As a result, short line railroads have been particularly important in Washington State for the export of agricultural and timber goods and provide at critical service to remote shippers in the state [62]. However, small railroad companies are hurt by maintenance costs and low capital investment in infrastructure, making it difficult to offer competitive rates to Class 1 railway service. The economic viability of short lines in Washington State is currently in jeopardy. There are increasing calls for the State government to step in and rescue these failing short line railroads to maintain service options for agricultural communities.

This decision to support private infrastructure is a difficult investment for the State. The Washington State Transportation Commissions’ Statewide Rail Capacity and Needs Study outlines the benefits that short line railroads offer [88]. Besides economic factors, emissions reduction and fuel efficiency are cited as benefits. However, the report fails to specify or quantify emissions results. Therefore, results of this transportation case study of wheat specifically address the magnitude of emissions reduction from short line railroads. Most short line railroads in Washington State are 50-100 miles (80 -160km) in length [88]. Using rail over truck over these distances results in a 7-10 g-CO₂ eq./kg wheat decrease in life cycle greenhouse gas emissions. In the case of wheat, at least a 15% decrease in domestic transportation emissions. Given the complex social and economic factors, it is difficult to recommend a public investment in short line rail infrastructure. However, the reduction in greenhouse emissions is another piece of a complicated decision.

2.5.5 Comparison with Estimates of Sequestration

Case study results of wheat have a maximum range of 891-1570 kg CO₂ eq/ha between locations and species for transportation and production, when results were converted to a per hectare unit. As mentioned, nitrogen fertilizer was the single largest contributor to greenhouse gas emissions at 30% of the total production and transportation.
However, when compared to the large body of research investigating modification in soil organic carbon (SOC), it is clear that sequestration remains the most important and variable component in wheat LCA studies. Studies of wheat’s potential to sequester carbon have little censuses, as shown in Table 16. In addition, the magnitude of variance is substantial, with studies reporting up to 1440 kg CO₂ eq/ha sequestered, down to 1404 kg CO₂ eq/ha emitted for conventional tillage wheat cultivation. The variability and disagreement in sequestration studies cannot be understated. In fact, the variation of production and transportation LCA almost fits within the variation of sequestration.

Previous studies have demonstrated the potential magnitude of wheat cultivation on carbon sequestration. Studies have also been quick to point out the important of local soil, terrain, climate, duration since conversion to wheat field and cultivation methods [32], [89], [34], [31]. This demonstrated variability and lack of consensus of carbon sequestration based on these factors is clear. However, data similar to the spatial and species resolution of fertilizer and fuel use data are currently available for sequestration, making a robust estimate of state or individual species wheat impossible.

Further complicating matters is the evolving nature of carbon sequestration from wheat fields over time. Current research indicates that SOC pools decreased drastically in initial conversion from native prairie grasslands into conventional tillage wheat production [33]. As dormant soil carbon was exposed to the atmosphere from primary tillage, SOC rapidly oxidized [90]. While the rate of loss varied by location and climate, an average of 56% of SOC was lost from this initial oxidation [35]. Since fields have only been monitored for 10 or 20 years for sequestration and carbon fluxes, it currently debated how much current sequestration is restoring the initial depletion. Rates of SOC are generally high directly after disturbance, and decrease with time [31]. It’s unclear if an equilibrium exists under any crop system or location [35].
Therefore, counting raw sequestration rates measured over short time periods in LCA studies is slightly disingenuous to the concept of carbon mitigation.

Even with the complications in sequestration research and history, it is clearly of utmost importance for a robust LCA of agricultural production. The variation in sequestration further highlights the need for regional and species specific data for wheat cultivation.

2.5.6 Comparison with Previous Studies

Direct comparison of results with previous studies is difficult due to the importance and variation in sequestration estimates, or their total exclusion. However, study results for wheat production can be compared with previous LCAs of wheat that excluded sequestration. From Table 4, Lechon, Koga, Narayanaswamy reported results of 154 g CO₂ eq/kg wheat, 162 g CO₂/kg wheat, 304 g CO₂ eq/kg wheat respectively. This range fits within the range of 136 g CO₂/kg - 316 g CO₂/kg of production based on different U.S. state and species combinations. This shows agreement with past studies, but also reinforces the inaccuracy of a single value for wheat production emissions.

Direct comparison of values from the EcoInvent database is also challenging given sequestration assumptions. EcoInvent’s estimate of 8538 kg CO₂/ha sequestered is well outside the range encountered in a review of the sequestration research [52]. Furthermore, this value derives from a single personal communication, which is not acceptable given the volume of literature and importance of sequestration in agricultural LCA studies [91]. This estimate would be assigned several values of 4 on the Design for Environment Laboratory’s data quality ranking for completeness and data sourcing. The range of LCA greenhouse gas emissions from wheat production presented in Table 20 is 379-811 kg CO₂/ha. This is dwarfed by the variation in sequestration data presented in Table 16 at 1440 kg CO₂ eq/ha to 1404 kg CO₂ eq/ha
emitted. Therefore, Ecoinvent’s estimate for such an important process makes its greenhouse emissions for wheat inaccurate.

3 Conclusions

The LCA results presented here compare well with similar studies and highlight sensitivities to regional production differences, transport assumptions, and sequestration considerations. The Agriculture Organization of the United Nations best presents the problem of sequestration when they report a 180 – 1080 kg CO₂/ha per year sequestration potential in prairie agriculture cultivation [90]. While this estimate is most likely realistic approximation of the state-of-the-art research, it does little to promote accurate LCA modeling of agricultural production. The fact is that the true potential for terrestrial soil carbon sequestration is not known because of a lack of a reliable model and fundamental understanding of the SOC dynamics at the molecular, landscape, regional and global scales [92], [93]. A better understanding of sequestration is essential.

The lack of understanding produces somewhat inconclusive results for a robust LCA of wheat production. However, the primary case study conclusion remains the importance of regional modeling in greenhouse gas emissions of a major agricultural crop. This is demonstrated by the variability in production and transportation life cycle emissions and variability in the published literature for sequestration. This reinforces the need for better data availability and consensus on sequestration. Several other conclusions and suggestions of future work came from the LCA. They are separated into suggestions to improve LCA methodology, wheat production and transport, and further work.
3.1 LCA Methodology

- LCA results demonstrate a high degree of variation in greenhouse gas emissions for both species and farm location of American wheat. Wheat is characteristic of many agricultural products, in that the top contributors to LCA emissions (fuel and fertilizer application) vary by location, farming practices, and species. Results are not intended to be a robust methodology for all agricultural products. However, results suggest that subsequent LCAs of products based on agricultural raw materials should at least address region in their methodology. Therefore, agricultural LCAs should not include an average value for nitrogen fertilizers or on-farm diesel consumption applied to agricultural products.

- Agricultural LCAs must include an estimate, or more accurately, a range, of sequestration potential. Exclusion or poor use of sources for magnitude of carbon sequestration has been demonstrated to produce incorrect results in LCA studies.

- Study results demonstrate that the life cycle emissions from a detailed transportation study are quite close to the assumed truck-rail-barge-ship combination. Therefore, in agricultural LCA studies, it is sufficient to model a single path to market, assuming correct distance information, particularly for truck utilization.

- Biofuels are a particularly high profile application of LCA methodology. Two high profile studies by Fargione [94] and Searchinger [95] on land use and biofuels production use GREET data. The studies address regional land use in biofuels production. Regional variation in fertilizers and energy use should also be included in future biofuels studies.
3.2 Wheat Production and Transport

- Due to the longevity of the grain industry and supporting rail infrastructure, truck distances in the grain industry are both currently and historically low. Agricultural rail spurs that feed major Class I main lines allow storage facilities such low truck utilization. As rail track ages, there is increased pressure for state governments to step in and support spur maintenance. There are certainly many economic and rural development concerns with funding rail spurs. However, trucks have an order of magnitude greater life cycle emissions than either rail or barge and supporting rail spurs would maintain low truck distances. Results would be different if short line railroad infrastructure was not maintained.

- Nitrogen fertilizer application and on farm diesel fuel consumption were the largest life cycle production emission contributors. This is not a study of soil science or agricultural methods. Therefore, it is difficult to suggest reduced tillage agriculture as a way to decrease greenhouse gas emissions. However, since reduced tillage primarily addresses fertilizer application and fuel use, these methods for reducing greenhouse gas emissions associated with production would agree with study results. Reduced tillage has also been show to have higher rates of carbon sequestration.

3.3 Future Work

- The LCA community would benefit from a regional knowledge of other large crops, dairy farms, and meat products. Future studies would show if there’s similar regional variation in other agricultural product classes to the variation demonstrated for American wheat.
• The results of this study support the need for dynamic modeling in LCA. The case study of American wheat modeled current wheat production. Ideally, a dynamic LCA methodology would include trends in agricultural supply chain. If a shift in modal utilization occurs, particularly trucks, this should be modeled against currently reliance on short distance rail spurs. Similarly, shipping grain in containers is currently economically viable only for specialized grains. If this changes, future work should include container movement and disposal in LCA studies.

• However, above all, consensus is needed for sequestration potential of agricultural fields. A robust estimate will allow for more accurate agricultural LCA studies and data at a similar resolution to energy and fertilizers use currently collected by the USDA.
References


Appendix A: U.S. Wheat Yield By State and Species

Data for wheat yield by state and species was extracted from the U.S. Department of Agriculture’s 2006 Small Grains Summary [25]. Significant figures are unmodified.

Spring Wheat

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<tr>
<th>STATE</th>
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<th>Hard White 1,000 Bushels</th>
<th>Soft White 1,000 Bushels</th>
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<td>1211</td>
<td>1087</td>
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### Winter Wheat

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**Average Percent**

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|       | 268342 | 234462 | 251402 |
Appendix B: Chemical Application

Extraction from Agricultural Chemical Usage Summary [17]. Significant figures are unmodified.

The agricultural chemical use estimates in this report refer to on-farm use of commercial fertilizers and pesticides on targeted crops for the 2004 crop year. Targeted crops included durum wheat, peanuts, soybeans, other spring wheat, and winter wheat. Farm and ranch operators were enumerated late in the growing season after the farm operator had indicated that planned applications were completed. The chemical use data were not summarized for geographical areas other than those States published in this report.

The data were compiled from two surveys, the Agricultural Resources Management Survey (ARMS) and Conservation Effects Assessment Project (CEAP). Data collection occurred primarily during the months of September to December of 2004. This report excludes pesticides used for seed treatments and post harvest applications to the commodity. The table below shows the number of States surveyed, the number of summarized reports for each State, and the percent of the Program States’ acres planted to that commodity compared with the U.S. total.
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Appendix C: Energy Use

Estimates of State-average fuel consumption from surveys of crop producers during 1997 to 2002 are presented here and extracted from the U.S. Department of Agriculture’s *Energy Use on Major Field Crops in Surveyed States* [22]. Significant figures are unmodified.
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<th>New York</th>
<th>North Carolina</th>
<th>North Dakota</th>
<th>Ohio</th>
<th>Pennsylvania</th>
<th>Texas</th>
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Appendix D: Inventory Results for Wheat Production

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<th>Input (normalized to yield)</th>
<th>Unit</th>
<th>YIELD</th>
<th>Unit</th>
<th>Process Reference</th>
<th>CO2 Emission (gCO2 eq/kg Wheat)</th>
<th>Relative %</th>
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<tr>
<td>Nitrogen fertilizer (N)</td>
<td>5.27E+01</td>
<td>kg/ha</td>
<td>1.88E-02</td>
<td>kg fertilizer/kg Wheat</td>
<td>2.94E+00</td>
<td>kg CO2/kg fertilizer GREET 1.7 5.54E+01</td>
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<td>3.36E+01</td>
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<td>1.20E-02</td>
<td>kg/kg Wheat</td>
<td>6.70E-01</td>
<td>kg CO2/kg fertilizer GREET 1.7 8.06E+00</td>
<td>5.7%</td>
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<tr>
<td>Potassium Fertilizer (K2O)</td>
<td>1.12E+01</td>
<td>kg/ha</td>
<td>4.01E-03</td>
<td>kg/kg Wheat</td>
<td>9.90E-01</td>
<td>kg CO2/kg fertilizer GREET 1.7 3.97E+00</td>
<td>2.8%</td>
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<tr>
<td>Limestone</td>
<td>4.48E+01</td>
<td>kg/ha</td>
<td>1.60E-02</td>
<td>kg/kg Wheat</td>
<td>6.10E-01</td>
<td>kg CO2/kg fertilizer GREET 1.7 9.78E+00</td>
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<tr>
<td>Herbicides</td>
<td>2.80E-01</td>
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<td>2.08E+01</td>
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<td>kg CO2/L consumed GREET 1.7 9.34E+00</td>
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<td>kg CO2/kWh GREET 1.7 (assuming local mix) 5.15E+00</td>
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<td>9.37E+00</td>
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<td>kg CO2/L consumed GREET 1.7 9.96E+00</td>
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<td>L/kg Wheat</td>
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<td>kg/kg Wheat</td>
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<td>kg CO2/kg fertilizer</td>
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<tr>
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<tr>
<td>Herbicides</td>
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<td>1.19E-04</td>
<td>kg/kg Wheat</td>
<td>2.08E+01</td>
<td>kg CO2/kg herbicide</td>
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<td>1.84E-02</td>
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<td>kg CO2/L consumed</td>
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<td>Diesel (Custom operation)</td>
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<td>L/ha</td>
<td>3.33E-03</td>
<td>L/kg Wheat</td>
<td>3.35E+00</td>
<td>kg CO2/L consumed</td>
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<td>8.36E-01</td>
<td>kg CO2/kWh</td>
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<td>L/ha</td>
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<td>L/kg Wheat</td>
<td>2.97E+00</td>
<td>kg CO2/L consumed</td>
<td>GREET 1.7</td>
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<tr>
<td>LP Gas</td>
<td>8.43E+00</td>
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<td>kg CO2/L consumed</td>
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<td>kg CO2/m3 consumed</td>
<td>GREET 1.7</td>
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**RAW TOTAL** 2.63E+02
**ALLOCATION** 95.5%
**TOTAL** 2.51E+02
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<th>Unit</th>
<th>Intensity</th>
<th>Unit</th>
<th>Process Reference</th>
<th>CO2 Emission (g-CO2/kg Wheat)</th>
<th>%</th>
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<tbody>
<tr>
<td>Nitrogen fertilizer (N)</td>
<td>1.12E+02</td>
<td>kg/ha</td>
<td>5.75E-02</td>
<td>kg/ha Wheat</td>
<td>2.94E+00</td>
<td>kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>1.69E+02</td>
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<td>kg/ha</td>
<td>2.24E-02</td>
<td>kg/ha Wheat</td>
<td>6.70E-01</td>
<td>kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>1.50E+01</td>
<td>4.5%</td>
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<td>kg/ha</td>
<td>1.49E-02</td>
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<td>kg CO2/kg fertilizer</td>
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<td>2.80E-01</td>
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<td>1.43E-04</td>
<td>kg/ha Wheat</td>
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<td>kg CO2/kg herbicide</td>
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<td>2.80E-01</td>
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<td>0.00E+00</td>
<td>kWh/kg Wheat</td>
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</tr>
<tr>
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<td>0.00E+00</td>
<td>L/kg Wheat</td>
<td>2.84E+00</td>
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<td>Unit</td>
<td>Intensity Unit</td>
<td>Unit</td>
<td>Process Reference</td>
<td>%</td>
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<td>GREET 1.7</td>
<td>1.33E+01 5.4%</td>
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<tr>
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<td>4.48E+01</td>
<td>kg/ha</td>
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<td>GREET 1.7</td>
<td>1.48E+01 6.0%</td>
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<td>Herbicides</td>
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<tr>
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<td>L/kg Wheat</td>
<td>GREET 1.7</td>
<td>0.00E+00 0.0%</td>
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<td>m3/kg Wheat</td>
<td>GREET 1.7</td>
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**TOTAL** 2.33E+02
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<th>Unit</th>
<th>Input</th>
<th>Intensity</th>
<th>Unit</th>
<th>Process Reference</th>
<th>CO2 Emission (g- CO2/kg Wheat)</th>
<th>%</th>
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<tbody>
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<td>Nitrogen fertilizer (N)</td>
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<td>kg/ha</td>
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<td>5.49E+01</td>
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<td>1.77E-02</td>
<td>kg/ha</td>
<td>6.70E-01</td>
<td>GREET 1.7</td>
<td>1.19E+01</td>
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<td>Potassium Fertilizer (K2O)</td>
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<td>kg/ha</td>
<td>9.90E-01</td>
<td>GREET 1.7</td>
<td>1.36E+01</td>
<td>6.4%</td>
</tr>
<tr>
<td>Limestone</td>
<td>4.48E+01</td>
<td>kg/ha</td>
<td>1.45E-02</td>
<td>kg/ha</td>
<td>6.10E-01</td>
<td>GREET 1.7</td>
<td>8.82E+00</td>
<td>4.1%</td>
</tr>
<tr>
<td>Herbicides</td>
<td>6.25E-01</td>
<td>kg/ha</td>
<td>2.02E-04</td>
<td>kg/ha</td>
<td>2.08E+01</td>
<td>GREET 1.7</td>
<td>4.20E+00</td>
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<tr>
<td>Insecticides</td>
<td>4.25E-03</td>
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<td>1.37E-06</td>
<td>kg/ha</td>
<td>2.43E+01</td>
<td>GREET 1.7</td>
<td>3.33E-02</td>
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<td>Diesel (Farm machinery)</td>
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<td>L/kg/ha</td>
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<td>GREET 1.7</td>
<td>8.43E+00</td>
<td>4.0%</td>
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<tr>
<td>Electricity</td>
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<td>0.00E+00</td>
<td>kWh/kg/Wh</td>
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<td>8.43E+00</td>
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<tr>
<td>Gasoline</td>
<td>9.37E+00</td>
<td>L/ha</td>
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<td>L/kg/Wh</td>
<td>2.97E+00</td>
<td>GREET 1.7</td>
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<td>4.2%</td>
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<tr>
<td>LP Gas</td>
<td>1.87E+00</td>
<td>L/ha</td>
<td>6.05E-04</td>
<td>L/kg/Wh</td>
<td>2.84E+00</td>
<td>GREET 1.7</td>
<td>1.72E+00</td>
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<tr>
<td>Natural Gas</td>
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<td>m3/ha</td>
<td>0.00E+00</td>
<td>m3/kg/Wh</td>
<td>2.35E+00</td>
<td>GREET 1.7</td>
<td>0.00E+00</td>
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RAW TOTAL: 2.13E+02
ALLOCATION: 94.7%
TOTAL: 2.02E+02
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<td>Phosphorous fertilizer (P2O5)</td>
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<td>Potassium Fertilizer (K2O)</td>
<td>2.69E+01 kg/ha</td>
</tr>
<tr>
<td>Limestone</td>
<td>4.48E+01 kg/ha</td>
</tr>
<tr>
<td>Herbicides</td>
<td>6.25E-01 kg/ha</td>
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<tr>
<td>Insecticides</td>
<td>4.25E-03 kg/ha</td>
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<td>Electricity</td>
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<td>Gasoline</td>
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<tr>
<td>LP Gas</td>
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<tr>
<td>Natural Gas</td>
<td>0.00E+00 m3/ha</td>
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<td>RAW TOTAL</td>
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<tr>
<td>Process</td>
<td>Input</td>
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**RAW TOTAL**: 2.29E+02  
**ALLOCATION**: 95.6%  
**TOTAL**: 2.19E+02
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<th>Input</th>
<th>Unit</th>
<th>Intensity</th>
<th>Unit</th>
<th>Process</th>
<th>Reference</th>
<th>CO₂ Emission (g·CO₂/kg Wheat)</th>
<th>%</th>
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<tr>
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<td>kg CO₂/kg fertilizer</td>
<td>GREET 1.7</td>
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<td>Potassium Fertilizer (K₂O)</td>
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<td>kg/ha</td>
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<td>2.08E+01</td>
<td>kg CO₂/kg herbicide</td>
<td>GREET 1.7</td>
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<td>Insecticides</td>
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<td>5.55E-06</td>
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<td>2.43E+01</td>
<td>kg CO₂/kg insecticides</td>
<td>GREET 1.7</td>
<td>1.35E-01</td>
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<td>Diesel (Farm machinery)</td>
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<td>4.62E-03</td>
<td>L/kg Wheat</td>
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<td>kg CO₂/L consumed</td>
<td>GREET 1.7</td>
<td>1.55E+01</td>
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<td>1.92E-03</td>
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<td>kg CO₂/L consumed</td>
<td>GREET 1.7</td>
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<td>0.00E+00</td>
<td>kWh/ha</td>
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<td>0.0%</td>
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<td>GREET 1.7</td>
<td>1.17E+01</td>
<td>6.2%</td>
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</tr>
<tr>
<td>LP Gas</td>
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<td>L/ha</td>
<td>0.00E+00</td>
<td>L/kg Wheat</td>
<td>2.84E+00</td>
<td>kg CO₂/L consumed</td>
<td>GREET 1.7</td>
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<td>Natural Gas</td>
<td>0.00E+00</td>
<td>m³/ha</td>
<td>0.00E+00</td>
<td>m³/kg Wheat</td>
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<td>Process Reference</td>
<td>CO2 Emission (g-CO2/kg Wheat)</td>
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<td>Herbicides</td>
<td>2.80E-01</td>
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<td>6.42E-05</td>
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<td>kg CO2/kg herbicide</td>
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<td>2.84E+00</td>
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<td>kg CO2/m3 consumed</td>
<td>GREET 1.7</td>
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<tr>
<td>Nitrogen fertilizer (N)</td>
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<td>kg CO2/kg fertilizer</td>
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<td>GREET 1.7</td>
<td>9.73E+00</td>
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<tr>
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<td>kg/ha</td>
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<td>kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
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<td>7.2%</td>
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<td>6.10E-01</td>
<td>kg CO2/kg fertilizer</td>
<td>GREET 1.7</td>
<td>7.79E+00</td>
<td>4.2%</td>
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<tr>
<td>Herbicides</td>
<td>2.80E-01</td>
<td>kg/ha</td>
<td>7.98E-05 kg/k grain</td>
<td>2.08E+01</td>
<td>kg CO2/kg herbicide</td>
<td>GREET 1.7</td>
<td>1.66E+00</td>
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<td>7.44E+00</td>
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<td>1.44E-02 kWh/k grain</td>
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<td>kg CO2/kWh</td>
<td>GREET 1.7 (assuming local mix)</td>
<td>3.78E+00</td>
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<td>6.67E-03 L/kg grain</td>
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<td>kg CO2/L consumed</td>
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<td>1.98E+01</td>
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<td>LP Gas</td>
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<td>0.00E+00 L/kg grain</td>
<td>2.84E+00</td>
<td>kg CO2/L consumed</td>
<td>GREET 1.7</td>
<td>0.00E+00</td>
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<td>kg CO2/m³ consumed</td>
<td>GREET 1.7</td>
<td>0.00E+00</td>
<td>0.0%</td>
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**TOTAL** 1.78E+02
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<th>Input</th>
<th>Intensity</th>
<th>Unit</th>
<th>Process Reference</th>
<th>CO2 Emission (g- CO2/kg Wheat)</th>
<th>%</th>
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<tr>
<td>Nitrogen fertilizer (N)</td>
<td>1.43E+02</td>
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<td>2.68E-02</td>
<td>kg/ha</td>
<td>kg/fertilizer/kg Wheat</td>
<td>GREET 1.7</td>
<td>7.88E+01</td>
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<tr>
<td>Phosphorous fertilizer (P2O5)</td>
<td>4.54E+01</td>
<td>kg/ha</td>
<td>8.52E-03</td>
<td>kg/ha</td>
<td>kg/ha</td>
<td>GREET 1.7</td>
<td>5.71E+00</td>
<td>3.6%</td>
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<tr>
<td>Potassium Fertilizer (K2O)</td>
<td>3.53E+01</td>
<td>kg/ha</td>
<td>6.62E-03</td>
<td>kg/ha</td>
<td>kg/ha</td>
<td>GREET 1.7</td>
<td>6.56E+00</td>
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<tr>
<td>Limestone</td>
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<td>kg/ha</td>
<td>8.41E-03</td>
<td>kg/ha</td>
<td>kg/ha</td>
<td>GREET 1.7</td>
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<tr>
<td>Herbicides</td>
<td>2.80E-01</td>
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<td>5.25E-05</td>
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<td>kg/ha</td>
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<td>kg/ha</td>
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<td>Diesel (Farm machinery)</td>
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<td>L/ha</td>
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<td>L/ha</td>
<td>GREET 1.7</td>
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<tr>
<td>LP Gas</td>
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<td>L/ha</td>
<td>0.00E+00</td>
<td>L/ha</td>
<td>L/ha</td>
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<td>m3/ha</td>
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**TOTAL** 1.52E+02
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<th>Unit</th>
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<th>CO2 Emission (g·CO2/kg Wheat)</th>
<th>%</th>
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<tr>
<td>Nitrogen fertilizer (N)</td>
<td>1.00E+02</td>
<td>kg/ha</td>
<td>2.64E-02 kg fertilizer/kg Wheat</td>
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<td>Herbicides</td>
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<td>kg CO2/kg herbicide</td>
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<td>1.53E+00</td>
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<td>Insecticides</td>
<td>2.25E-02</td>
<td>kg/ha</td>
<td>5.91E-06 kg/kg Wheat</td>
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<td>kg CO2/kg insecticides</td>
<td>GREET 1.7</td>
<td>1.44E-01</td>
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<td>Diesel (Farm machinery)</td>
<td>5.15E+01</td>
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<td>1.36E-02 L/kg Wheat</td>
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<td>kg CO2/L consumed</td>
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<td>9.52E+00</td>
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<td>LP Gas</td>
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<td>kg CO2/L consumed</td>
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<td>0.00E+00</td>
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