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A Review of Environmental Impacts of Cereal Grain Supply Chains

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Abstract

The global reliance upon cereal grains, not only for domestic consumption, but also for export in international markets continues to be critical to many countries' economies. The ecological impacts of the various steps along the supply chain required to get product to the consumer, whether it be fuel, feed, or food, have significant environmental impacts. Ecological assessments have focused historically upon carbon footprints, but by considering other measures of life cycle assessments (LCA), we can come to a better understanding of the environmental significance that some of the most critical crops in our world have. The goal of this study was to compile environmental impact data from published literature and conduct synthesis to determine ecological trends. Published data was compiled and analyzed to determine where critical environmental shortcomings were in the cereal grain industry. Analysis of these data will enable recommendations to be made concerning the weaker spots in supply chains (i.e., more environmentally impactful). In addition, by expanding the geographic locations to an international scale, this study will allow for environmental impacts to be assessed based on various approaches found across the globe. As long as our world continues to place significant emphasis on cereal grains as foundations for societies, we need to better understand the ramifications of these critical crops' ecological impacts and how best to address them.

Keywords: cereals, environmental, grains, life cycle assessment, metrics, supply chains, sustainability

1. Introduction

The Earth is facing ever-growing problems, including increasing population, decreasing resources, and an environmental crisis. By working to improve the last 2 problems, only then can we better support the Earth's increasing population. This means taking measures to improve the sustainability of our natural resources and our essential products, without sacrificing the quantity needed for an increasing population.

One of these essential products is cereal grains, which is the primary focus of this paper. Cereal grains have been a staple crop since the dawn of agriculture, and continue to be staples in modern human diets. The overall diversity of cereal grains allows for food in a variety of populations around the globe. It also creates a market for not only domestic consumption, but also global export. Cereal grains are also used as feed for a majority of livestock, including, beef, dairy, swine, poultry, and other animal species. Another newer use with cereal grains is in the production of biofuels, bioplastics, and other industrial products. With grains' ability to contribute to both food and energy supplies, the importance of making these crops more sustainable and abundant is clear.

The downside to growing crops is that there are many potential environmental pollutants, emissions, and other impacts that arise from cultivating and harvesting these crops. The equipment used to grow, harvest, and transfer the crops, and even the crops themselves all produce carbon dioxide as well as various other environmental emissions. Life cycle assessment (LCA) is a tool that is increasingly being used to quantify environmental impacts. To date, no other studies have comprehensively compiled LCA studies for cereal grains, which is thus the goal for this paper.

2. Methods

For this analysis, the main focus was collecting articles that estimated LCA data for various grains. An LCA, or life cycle assessment, is a specific methodology used to classify various impacts a product has on the environment during its entire supply chain. One such product is cereal grains. The specific metrics used in this analysis included greenhouse gas emissions, global warming potential, water use, land use, acidification potential, abiotic depletion, eutrophication potential, human toxicity potential, non-renewable energy depletion, marine toxicity potential, freshwater toxicity potential, soil toxicity potential, ozone layer depletion potential, and photochemical oxidation. When looking at all fourteen of these metrics together, a more complete picture can be formed regarding the environmental impacts of cereal grains.

While compiling this database, many articles were found that contributed to the creation of this meta-analysis. There were many studies conducted that would take either a single grain or a few grains and compared them based on a single LCA metric. Other studies were also found where a single grain was studied, but many different metrics were analyzed. The difference between those articles and this is the scope of comparisons. While other studies compared a few grains or metrics, this study compares many grains, metrics, supply chain stages, and region of growth and production.

Sustainability is not a one-size fits all solution, so geographic diversity was of importance while compiling this analysis. Instead of focusing on a single country or region, it was decided that looking for studies internationally would bring a better perspective to the study and the environmental crises across the globe. This allows for more trends to form and to draw conclusions of which regions have obtained more efficient crop production when it comes to minimizing pollutants and resource use. If one region has consistently better findings than other regions, further analysis into specific practices or products can be applied to other regions with hopes to improve environmental sustainability.

This analysis gives an overarching idea about how various grains compare when looking at differentiating LCA metrics. During the compilation phase, there were not any articles that were found comparing the number of grains, the number of metrics, or regional areas as this analysis does. This study will be helpful for looking at trends that would be otherwise impossible to see otherwise due to the scope of information presented.

With agriculture being a staple for cultures around the world, numerous studies have been done examining all aspects of crop production. Publications and journals were searched to find articles that focused upon different life cycle assessment (LCA) metrics for various crops. These crops included common ones, such as barley, maize, millet, oats, rice, rye, sorghum, and wheat, as well as less conventional grains, such as amaranth, buckwheat, quinoa, and triticale. Searches also included simple foods made almost exclusively of one grain, such as bread, tortillas, and pasta. Once a database was amassed from the various research articles collected, they were then categorized by the grain type and then again by what they were being used for. These categories included food production, biofuel creation, and animal feed.

Once the articles were categorized accordingly, the process of extracting information from the articles began. The use of an Excel spreadsheet was used to hold the information that was extracted. The data were separated into qualitative information and quantitative information. Qualitative data extracted included the grain that was studied, the region the study took place in, what the crop was being used for, the stage in the supply chain that was being examined, and a description of differences in certain measurements. The quantitative data extracted was the measurements the study found. In total there were 14 different LCA metrics that were found to be the most common. The spreadsheet accommodated all of the data, as well as an addition column beside each metric so that a unit could be associated with each data value.

One element that should be noted was the inclusion of greenhouse gas emissions (GHG) and global warming potential (GWP). Most of the time, these two categories would be combined into one since they are very similar, measuring carbon dioxide release into the atmosphere. The difference arrives in the totality of the measurement. GHG measures only CO_2 emissions, while GWP measures CO_2 emissions as well as other emissions that make up the global warming crisis. For the purpose of comparing all of the studies, it was decided to keep the two categories separate. The biggest reason for this was that there were multiple studies that reported the emissions as GHG only, multiple studies that reported the emissions as GWP only, and a distinct few that reported both separately.

From all the various research articles collected, one main discrepancy was the establishment of Functional Units (FU). The research collected fell into one of three functional units: land, mass, and energy. While efforts could have been made to combine these three groups into a massive comparison, ultimately the data were easier to digest and demonstrated less anomalies if separated by functional unit.

Even with increasing standardization of units, there was still a need for conversion to a single set of units for easier comparison. For the land functional unit, the standard unit was meters squared ($m^{2)}$. The mass functional unit has a standard unit of kilograms (kg), and energy functional unit was measured in joules (J). Units that needed to be converted included tonnes, tons, pounds, acres, hectares, and kilowatt hours. Here are the formulas used to convert into standardized units:

- Tonnes to kg
  - 1 tonne= 1000 kg
- Ton to kg
  - 1 ton= 907.18 kg
- Pounds to kg
  - 1 pound= 0.454 kg
- Acres to m^2
  - 1 acre= 4047 m^2
- Hectares to m^2
  - 1 hectare= 10000 m^2
- Liters to m^3
  - 1 liter= 1000 m^3
- Kilowatt hours to J
  - 1 kilowatt-hour= $3.6x10^6$ J

With the data compiled into uniform units and functional units, the decision was made to compare the data using bar graphs. Each functional unit has its own category of graphs, and these graphs were based on LCAs. Some FUs did not have any data on some LCAs so there were holes in the graphs based on these weaknesses in pre-existing research. The resulting graphs were separated first by grain, then by supply chain stage. Each grain has a color assigned to it in order to easily differentiate between the grains. In addition, there were two shades for each color to denote differences in authorship and supply chain stages. With the mass graphs, supply chain stage is denoted on the x-axis, however the land graphs did not see enough variance from the supply chain stage to warrant an additional comparison on the x-axis. The numerical values were displayed above the data point for easier access as well as the key describing the authorship for the various studies. Units and scales range on each graph, which was why the decision was made to keep the graphs separate based on LCAs and functional units. We were comparing each value to the other values on the same graph so that a trend can be determined based on the findings of the studies collected in each of the various metrics.

3. Results and Discussion

3.1 Land FU

3.1.1 Greenhouse Gas Emissions (GHG)

The studies with the functional unit of land use had measurements in fourteen different metrics, with some studies having data for multiple grains across multiple metrics. The most diverse selection of data was when greenhouse gas emissions were compared. These measurements can be found in Figure 1 with Table 1 giving more information about the studies, including region and farming practices used. The highest measurement was found in oats with 8.50×10^7 kg of CO_2 emitted per FU and the lowest was found in maize with 4.9×10^{-2} of CO_2 emitted per FU. In this selection of data, there were many different studies that consist of multiple entries looking at one specific grain, such as buckwheat, maize, oats, and wheat. Where these studies differed was the agriculture practices that were used as variables to test certain agriculture practices. These variables mainly consisted of the amount of tillage done to the land, and whether a cover crop was used or not. Some anomalies that were present were grains that had studies showing them both near the higher and lower end of the spectrum, such as sorghum. This could be because they were different studies and may have had other factors that impacted the results that were not presented in their respective articles. Some trends that that were present show that for each grain being compared, there were studies that show the grain on the low and as well on the high end of the spectrum.

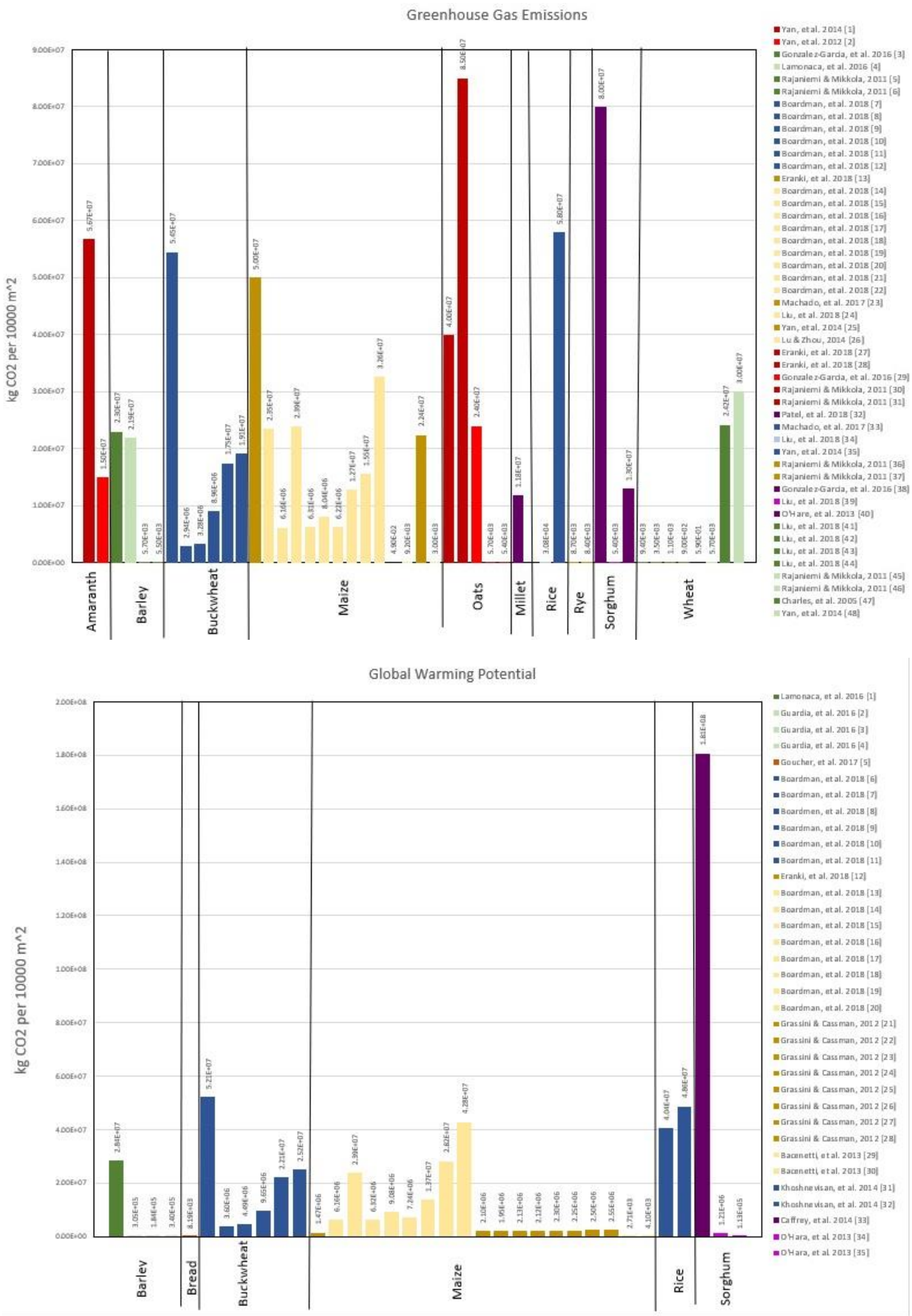


Figure 1. (Top) Greenhouse gas emissions for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 1. (Bottom) Global warming potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 2

3.1.2 Global Warming Potential (GWP)

The measurements for global warming potential metric for land use functional unit is found in Figure 1, with Table 2 giving more information about the studies, including region and farming practices used. The highest measurement was found in sorghum with 1.81 x 10^8 kg CO_2 per FU and the lowest was found in maize with 2.71 x 10^3 kg CO_2 per FU. In this selection of data, every grain with the exception of bread had multiple measurements done comparing different variables. These variables were the amount of tillage, the farming techniques used, irrigation systems, and the grains planted before the measurement crop. There was a high outlier with one sorghum measurement, which was over three times higher than any of the previous measurements in the set. This outlier could be caused by that particular study being done at a much smaller scale than the other studies, so when the measurements were scaled up to match each other, smaller differences were exaggerated. This was most likely the case since the majority of the time this study was included in a dataset, it was consistently the highest.

3.1.3 Water Use (H_2O)

Figure 2 and Table 3 refers to water use for the land based functional unit. The highest recorded value was oats with 2.71 x 10^7 kg of water per FU, and the lowest was barley with 2.50 x 10^7 kg of water per FU. Only two studies were found that measured water use with this particular functional unit, and only three grains were studied. But between the two studies the results were of the grains showed that all three were very similar water usages.

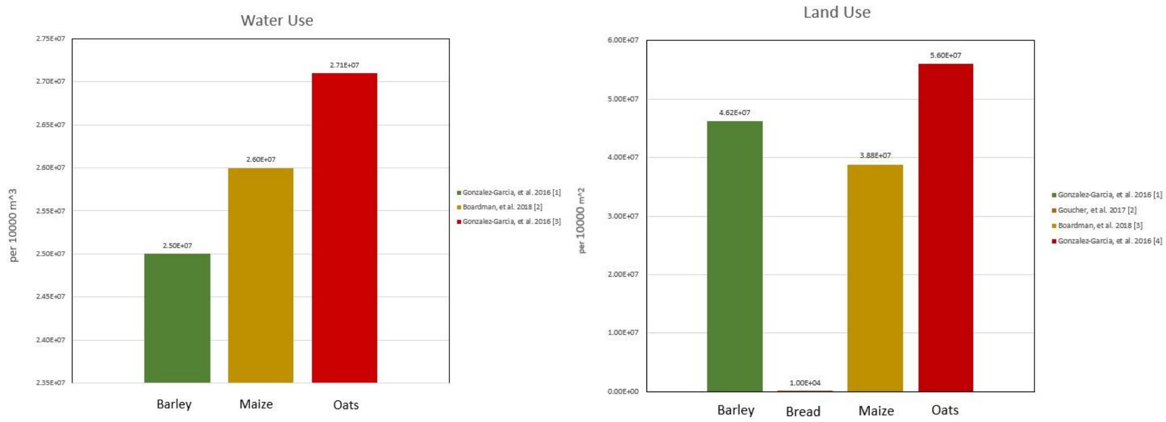


Figure 2. (Top) Water use for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 3. (Bottom) Land use for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 4

3.1.4 Land Use (Land)

Land use was another unique category that focused on the efficiency of farms given the choice to measure land use while also having the functional unit also be land used. The data for these studies are found in Figure 2 as well as additional information in Table 4. The highest measurement was from oats with 5.6 x 10^7 m^3 of land used per FU and the lowest measurement being 1.00 x 10^4 m^3 of land used per FU. The biggest outlier was with bread, and that as mostly due to the fact that multiple plants were produced to make enough grain for a single loaf of bread, bring the overall efficiency down.

3.1.5 Acidification Potential (AP)

Acidification potential is the measurement of various emissions that are released into the atmosphere that lowers the pH of air and water bodies. The measurements are found in Figure 3 and Table 5. The highest value was sorghum with 5.41 x 10^5 kg of emissions per FU and the lowest value was wheat with 1.78 x 10^5 kg of emissions per FU. In this collection of measurements sorghum was a slight outlier, being about twice as much as the next leading value. Since this was the same study that shows sorghum surpassing most other grains in multiple other graphs, this may suggest that there is not as much variance in acidification potential between grains as there were with other metrics.

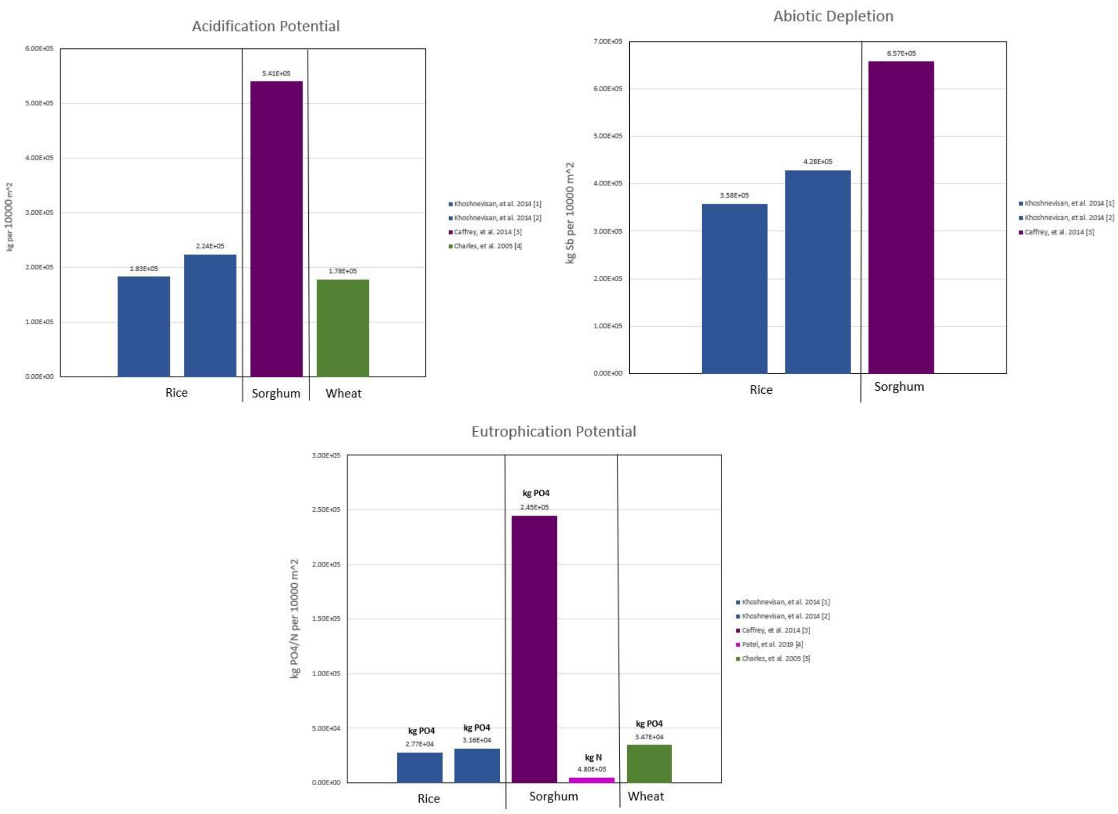


Figure 3. (Top) Acidification Potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 5. (Middle) Abiotic depletion for rice and sorghum using Land Functional Units. Descriptive information about the studies can be found in Table 6. (Bottom) Eutrophication Potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 7

3.1.6 Abiotic Depletion (AD)

Figure 3 and Table 6 refer to the abiotic depletion and the amount of antimony in a given area. The highest value was sorghum with 6.57 x 10^5 kg of Sb/FU while the lowest value was rice with 3.58 x 10^5 kg Sb/ FU. Out of the three measurements taken, two of them were the same study which looked at the different farming techniques. Within this study, it showed that conventional based farming methods have a better abiotic depletion rate than traditional based farming methods.

3.1.7 Eutrophication Potential (EP)

For eutrophication potential, there were two different ways that this metric was measured. The most common way was with the amount of phosphate in an area, and the other was the amount of nitrogen in an area. This distinction was apparent in Figure 3 and Table 7. The highest value was sorghum with 2.45 x 10^5 kg PO4/FU and the lowest was 4.80 x 10^3 kg N/ FU, or 2.77 x 10^4 kg PO4/FU. There was a high outlier with sorghum, being over seven times higher than the next largest grain. This could be because it was part of the particular study that has high sorghum measurements in nearly every chart. There were also two rice measurements that were from the same study, which suggest that conventional farming practices were better than traditional farming practices.

3.1.8 Human Toxicity Potential (HTP)

Human toxicity potential was one of the more diverse graphs with the land use functional unit. It has a larger spread of grains than most of the graphs with very diverse values between points, as seen on Figure 4 and Table 8. It was also unique because it has two different ways it was measured, with a majority of the research being done in kg of 1,4 DB and only one study being done in kg of Pb. All of this was shown in Figure 4 and Table 8. The highest value was sorghum with 5.98 x 10^7 kg of 1,4 DB while the lowest was maize with 3.14 x 10^2 kg of 1,4 DB. There are two ranges present in the graph: a low range with maize, oats, and barley, and a middle range with rice and wheat. There was also an outlier with sorghum, which was over 3 times higher than the next highest value. This was not as unreasonable as it was in other graphs since this range as quite a bit bigger than most of the other land use graphs.

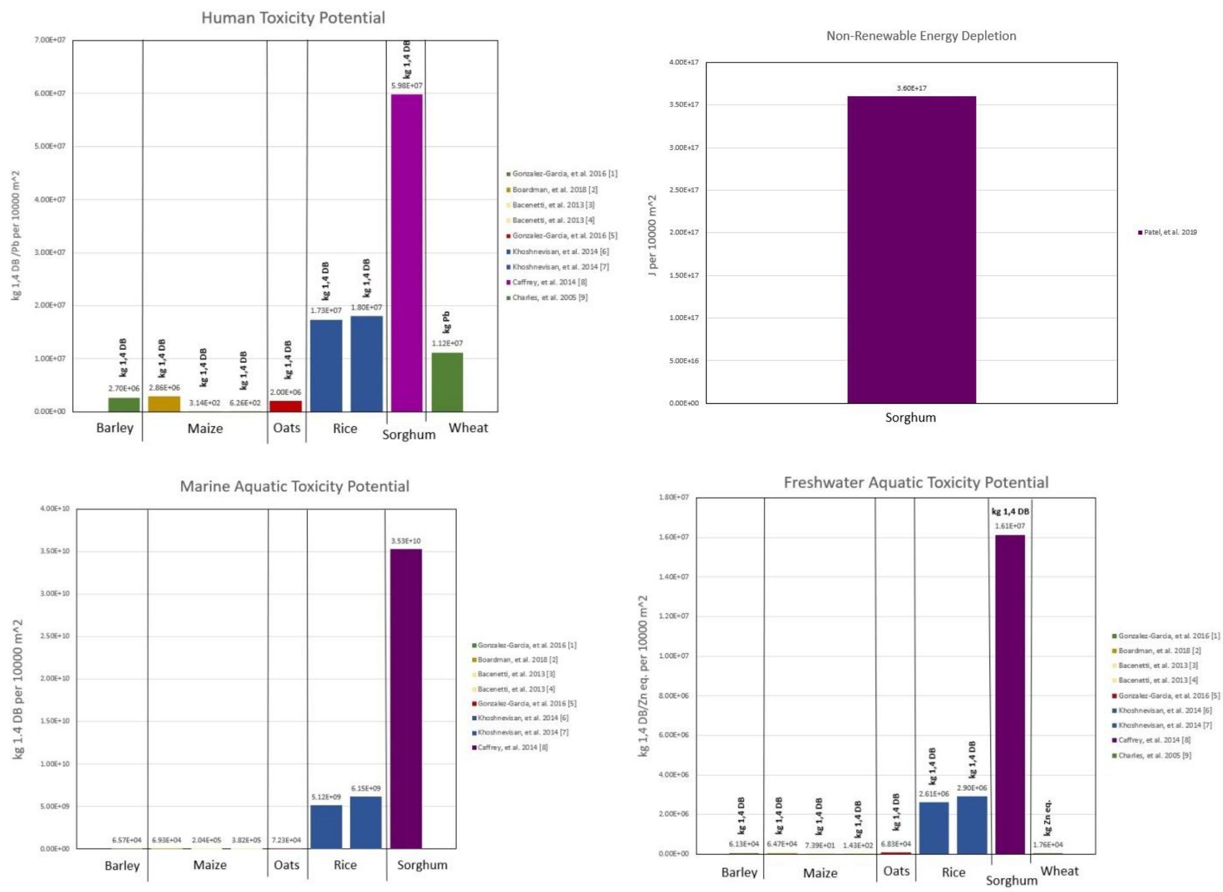


Figure 4. (Top left) Human toxicity potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 8. (Top right) Non-renewable energy depletion for sorghum using Land Functional Units. Descriptive information about the studies can be found in Table 9. (Bottom left) Marine aquatic toxicity potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 10. (Bottom right) Freshwater aquatic toxicity potential for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 11

3.1.9 Non-Renewable Energy Depletion (NRED)

There was only one study that was done to find the nonrenewable energy depletion for any of the grains – this was sorghum, and Figure 4 and Table 9 show the one point of data that was collected. The reason that there was only one point was because it is a very uncommon metric. It is typically only applicable when measuring grains when used as an energy source and there is a separate functional unit dedicated to measuring different aspects of grains when used as a fuel source in terms of energy used. Since there was only one measurement, no trends could be inferred for this metric.

3.1.10 Marine Toxicity Potential (MTP)

When water toxicity is being compared it is usually separated into two separate categories, freshwater toxicity and marine toxicity. Figure 4 and Table 10 shows the marine toxicity we found for a variety of grains. The highest grain was sorghum with 3.53×10^{10} kg 1,4 DB/FU and the lowest value was barley with 3.57×10^{4} kg 1,4 DB/FU. There was a large disparity between the high end of the data for grains such as sorghum and rice being many magnitudes higher than barley, maize, and oats at the low end of the data. The freshwater toxicity measurements were similar to these results, but with much less of a divergence between the ends of the data.

3.1.11 Freshwater Toxicity Potential (FTP)

Freshwater toxicity shows mainly the same story as MTP, as seen in Figure 4 and Table 11. The highest value was sorghum with 1.61 x 10^7 kg 1,4 DB/FU while the lowest value was maize with 73.9 kg 1,4 DB/FU. A difference between these measurements and ones found in the marine toxicity section was that there was a wheat value that was measured in kg of Zinc instead of the 1,4 DB. This section was similar to the marine toxicity in that sorghum and rice were quite a bit higher than the other grains, although not as extreme. With both of these datasets taken into consideration, these data strongly suggest sorghum and rice should be promoted when talking about aquatic toxicity.

3.1.12 Soil Toxicity Potential (STP)

Figure 5 and Table 12 refer to the soil toxicity potential in a given area. The highest value was sorghum with 4.02 x 10^5 kg 1,4 DB per FU while the lowest value was rice with 1.80 x 10^5 kg 1,4 DB per FU. Out of the three measurements taken, two of them were the same study which looked at the different farming techniques. Within this study, it showed that conventional based farming methods have a better soil toxicity rating than traditional based farming methods.

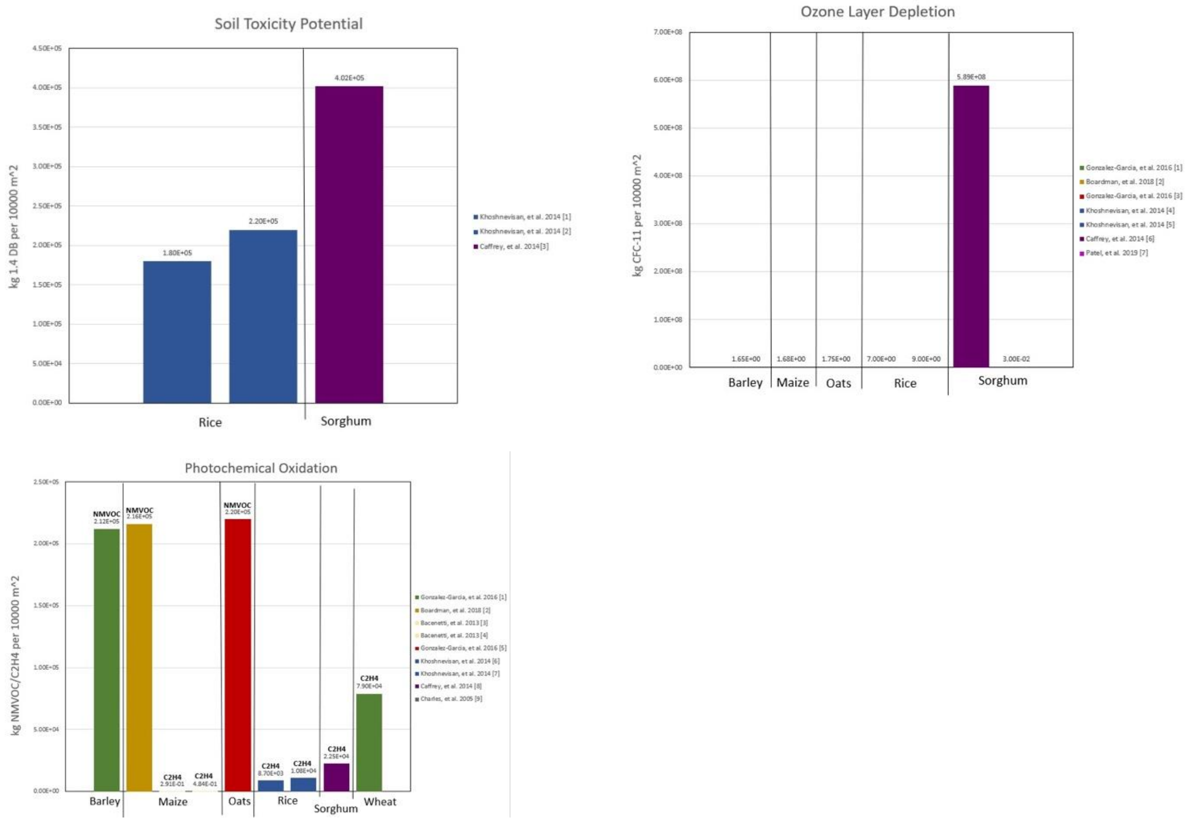


Figure 5. (Top left) Soil toxicity potential for rice and sorghum using Land Functional Units. Descriptive information about the studies can be found in Table 12. (Top right) Ozone layer depletion for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 13. (Bottom left) Photochemical oxidation for various grains using Land Functional Units. Descriptive information about the studies can be found in Table 14

3.1.13 Ozone Layer Depletion Potential (ODP)

Ozone layer depletion was interesting because it had the largest outlier out of all the datasets for the functional unit of land use. It is seen in Figure 5 and Table 13 where only one datapoint was visible because it was so much higher than the rest. This goes to sorghum with 5.89 x 10^8 kg 1,4 DB per FU with the next highest grain being rice with 9 kg 1,4 DB per FU. Along with the graph, nearly every other graph that features this study of sorghum, with some exception, was always at the top of every graph.

3.1.14 Photochemical Oxidation (PO)

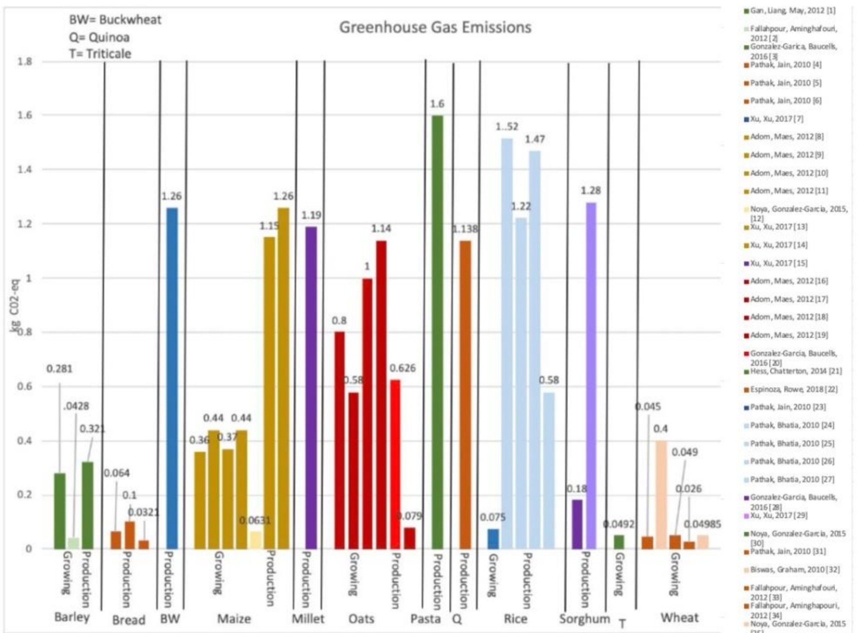
The last dataset for the land use function unit was photochemical oxidation. This dataset was different from the others because one third of the datapoints were measured in kg of Non-Methane Volatile Organic Compound (or NMVOC) while the rest was measured in kg of ethylene. These data are available on Figure 5 and on Table 14.

This highest value was 2.20 x 10^5 kg NMVOC per FU while the lowest value was 0.291 kg C2H4 per FU. There was a large disparity between the NMVOC measurements and the C_2H_4 measurements, with all NMVOC measurements being consistently higher than any C_2H_4 measurements. This could mean that all grains emit more NMVOC's than ethylene, but more studies should be done to test this claim.

3.2 Mass FU

3.2.1 Greenhouse Gas Emissions (GHG)

With the functional unit of land completed, the focus of the study now turns to the mass functional unit. Within the graph (Figure 6) and the supplementary table (Table 15), information about how various cereal grains can affect greenhouse gas emissions can be found. The highest greenhouse gas emission was the production of pasta with 1.6 kg of CO_2 per kg of product. Meanwhile, the lowest emissions came from the growing of wheat with 0.026 kg of CO_2 per FU. There were multiple comparison studies contained within this graph. The first comparison was the production of bread. Differences come from different stages of the overall production process. Namely preparation, processing, and producing. Secondly, the comparison of maize growing practices compares different geographic regions of the United States, taking into account differences in fields, rainfall, and fertilization techniques. The comparison of the growing of oats follows the same comparison as the aforementioned bread. Finally, the production of rice differences follows the same comparison as the first comparison listed in the different stages of the overall production processes. Overall conclusions that may be drawn from this graph was the low greenhouse gas emissions of wheat, bread, and barley as well as the higher greenhouse gas emissions of millet, pasta, and sorghum.



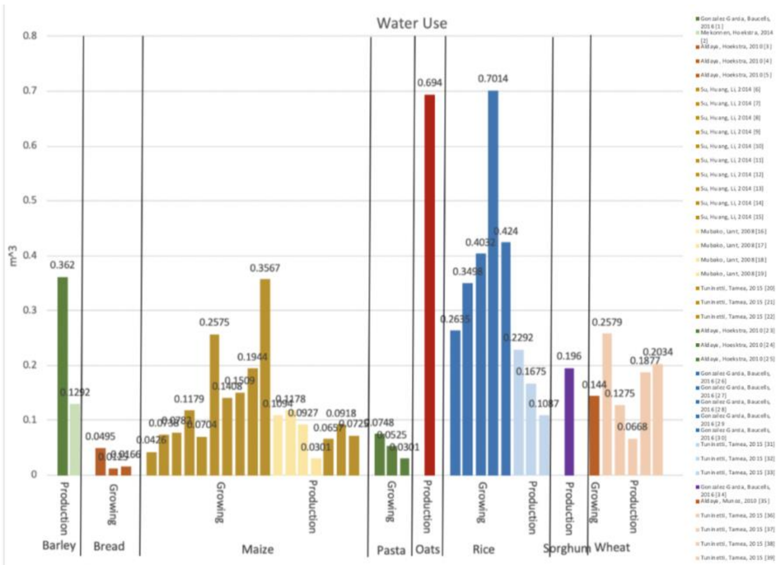


Figure 6. (Top) Greenhouse gas emissions for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 15. (Bottom) Water use for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 16

3.2.2 Water Use (H_2O)

When comparing the graph of Figure 6, and the corresponding table (Table 16), two things become obvious. The water usage of oats and rice were both greater than the rest of the grains compared within the water use graph. Oats has a value of .649 m^3 of water used per FU and rice has 0.701 m^3 per FU. Meanwhile, the production of bread has the lowest values at 0.0125 m^3 and .0166 m^3 per FU. There were multiple comparison studies contained within this graph. The first comparison was the production of bread. The difference in data accommodates for the differences in water usage according to green, blue, and gray water respectively. The rest of the comparisons contained within this graph are attributed to geographic differences and more information can be found in Table 16. One possible outlier was the fourth rice value. These data originate from Uzbekistan and could possibly explain the high-water usage than the other countries in that study. Overall trends demonstrate that maize, bread, and pasta have low water usage, while rice and oats have higher water usage. This follows what previous research has concluded due to both of those crops high water intensity per FU.

3.2.3 Abiotic Depletion (AD)

In Figure 7 and the corresponding Table 17, the abiotic depletion of rice was shown. Due to lack of previously conducted research on abiotic depletion within the mass functional unit, only rice was able to be compared. The differences between the two values can be attributed to the differences in farming practices in Iran. The first value uses consolidated or modern farming practices, while the second value uses traditional farming practices. The higher value of abiotic depletion for traditional farming practices suggests that improvements in farming techniques for rice has reduced abiotic depletion.

3.2.4 Eutrophication Potential (EP)

For the mass FU graphs of the eutrophication potential, see Figure 7. The corresponding tables were also included in the analysis. Current differences in the unit used to conduct eutrophication potential analyses dictated the separation of graphs. For Figure 7, the unit was kg of Nitrogen emissions per FU. The highest value was $2.8x10^{-3}$ kg of N for the growing of wheat. Meanwhile, the lowest value was the growing of barley with $1x10^{-5}$ kg of N. For the first two comparisons within this figure, the differences were differences in regional growing practices. For the last comparison, the difference can be attributed to the differences in production of biofuels. The first point uses straw gasification, while the second point uses straw direct combustion. Outliers within this graph include the low value of barley and one study of wheat. For Figure 7, the unit was kg of PO_4 emissions per FU. The highest value was the growing of barley with $5.62x10^{-4}$ kg of phosphate per FU. The lowest was the growing of rice with $5.2x10^{-5}$ kg of phosphate per FU. Two comparisons take place within this graph. The first comparison can be attributed to the differences in farming practices in Iran. The first value uses consolidated or modern farming practices, while the second value uses traditional farming practices. The second comparison concerns the type of rice grown. The first value reflects conventional rice, while the second value uses long-term organic rice. Overall trends to be noted within this graph was the high value of barley, and the similarity between wheat and rice.

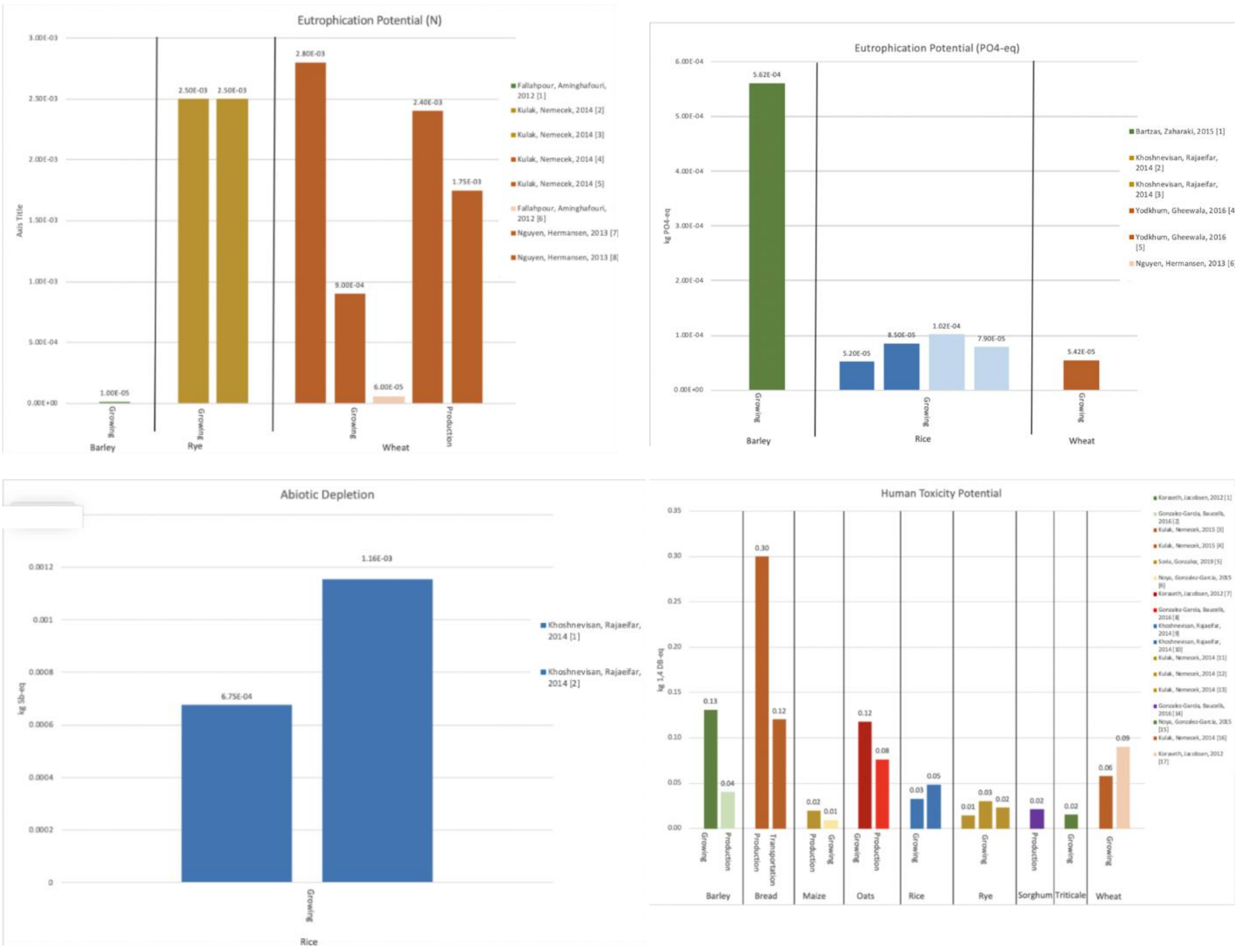


Figure 7. (Top left) Eutrophication Potential of Nitrogen for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 17. (Top right) Eutrophication potential of Phosphate for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 18. (Bottom left) Abiotic depletion for rice using Mass Functional Units. Descriptive information about the studies can be found in Table 19. (bottom right) Human toxicity potential for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 20

3.2.5 Human Toxicity Potential (HTP)

Figure 7 and Table 20 refer to the human toxicity potential of various grains in the mass FU. The highest value was the production of bread at $3x10^{-1}$ kg of 1,4 DB per FU. Meanwhile the lowest value was the growing of maize at $1x10^{-2}$ kg of 1,4 DB per FU. For the comparisons contained within the human toxicity potential graph, the first and last comparison can be attributed to differences in geographic practices. For the comparison of rice growing practices, the comparison was the differences in growing practices in Iran. The first value uses consolidated or modern farming practices, while the second value uses traditional farming practices. Trends to be noted within the graph show that there was not great variance of the human toxicity potential for various grains and their various supply chain stages.

3.2.6 Marine Toxicity Potential (MTP)

The marine toxicity potential graph (Figure 8 and Table 21) details the affect that cereal grains have upon marine health. Measured in kg of 1,4 DB per FU the highest value was the growing of rice with the value of $1.66x10^{-2}$. The lowest value was $4.8x10^{-5}$ for the growing of triticale. Only one comparison takes place on this graph and that comparison was between the growing practices of rice. The first value uses consolidated or modern farming practices, while the second value uses traditional farming practices. One takeaway from this analysis was that the marine toxicity potential for rice was higher than the other grains. This can be attributed to the large water usage for rice in comparison to the other grains found in this graph.

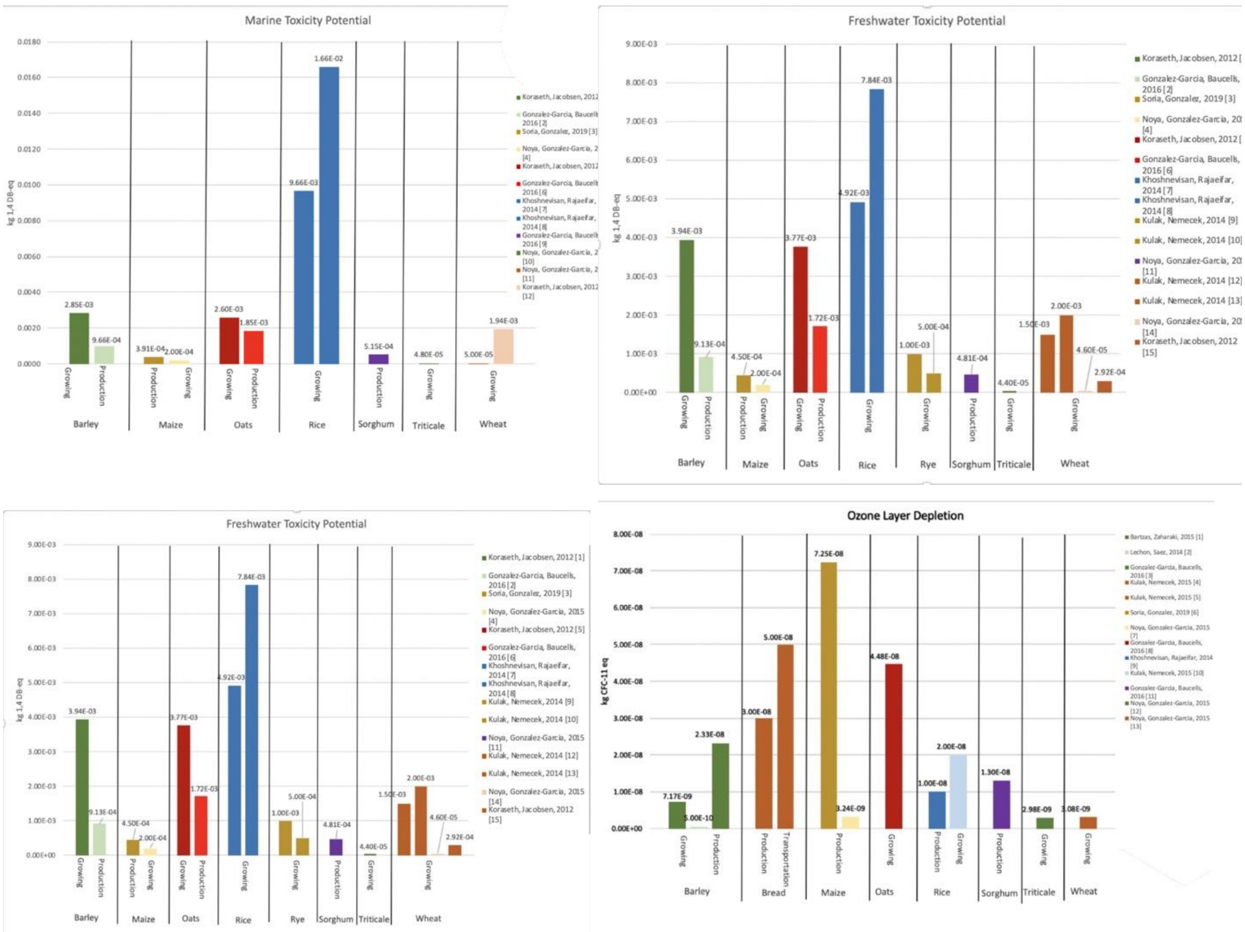


Figure 8. (Top left) Marine toxicity potential for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 21. (Top right) Freshwater toxicity potential for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 22. (Bottom left) Soil toxicity potential for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 23. (Bottom right) Ozone layer depletion for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 24

3.2.7 Freshwater Toxicity Potential (FTP)

When analyzing the graph of the freshwater toxicity potential (Figure 8), and its corresponding table (Table 22), the impact that rice has was clear. Rice has the largest impact with $7.48x10^{-3}$ kg 1,4 DB per FU. Meanwhile, triticale has the lowest with $4.4x10^{-5}$ kg 1,4 DB per FU. The first comparison found was the comparison between growing practices of rice. These two practices were consolidated and traditional farming practices. The other two comparisons were both geographic differences within France. One takeaway from this analysis was that the freshwater toxicity potential for rice was higher than the other grains. This can be attributed to the large water usage for rice in comparison to the other grains found in this graph.

3.2.8 Soil Toxicity Potential (STP)

The soil toxicity potential is analyzed in Figure 8 and Table 23. The largest value was the growing of oats with $6.4x10^{-4}$ kg 1,4 DB per FU. The smallest was the production of maize with $9x10^{-5}$ kg 1,4 DB per FU. Three comparisons are found on this graph. The first comparison found was the comparison between growing practices of rice. These two practices were consolidated and traditional farming practices in Iran. The second comparison were various geographic differences. The final comparison was between the years 2010 and 2012, thus accounting for differences in rainfall and soil productivity. Overall, the graph does not display a large difference between any particular grain and the toxicity of the soil, however oats and rice have a larger value than the other grains found in this analysis.

3.2.9 Ozone Layer Depletion Potential (ODP)

Within the ozone layer depletion graph and table (Figure 8 and Table 24), the affect that the various cereal grains have upon the ozone layer was measured in kg of CFC-11 emitted during the supply chain stages. The highest value was the production of maize with 7.25×10^{-8} kg of CFC-11 per FU. Meanwhile the lowest was the growing of bread at 5×10^{-10} kg of CFC-11 per FU. Possible outliers within this graph include a value of bread growing and maize production. These outliers could be attributed to different regional practices or methods of collecting data between studies. Overall trends show that the growing of grains has less impact than the production of grains upon the ozone layer.

3.2.10 Photochemical Oxidation (PO)

Concluding the mass functional unit, analysis was conducted of the photochemical oxidation measured in kg of NMVOC per FU (Figure 9 and Table 25). The highest value was the production of oats with 5.75×10^{-3} kg of NMVOC per FU. The lowest value was the growing of maize with 1.30×10^{-4} kg of NMVOC per FU. Overall, the production of grains has a higher impact on photochemical oxidation than the growing of said grains.

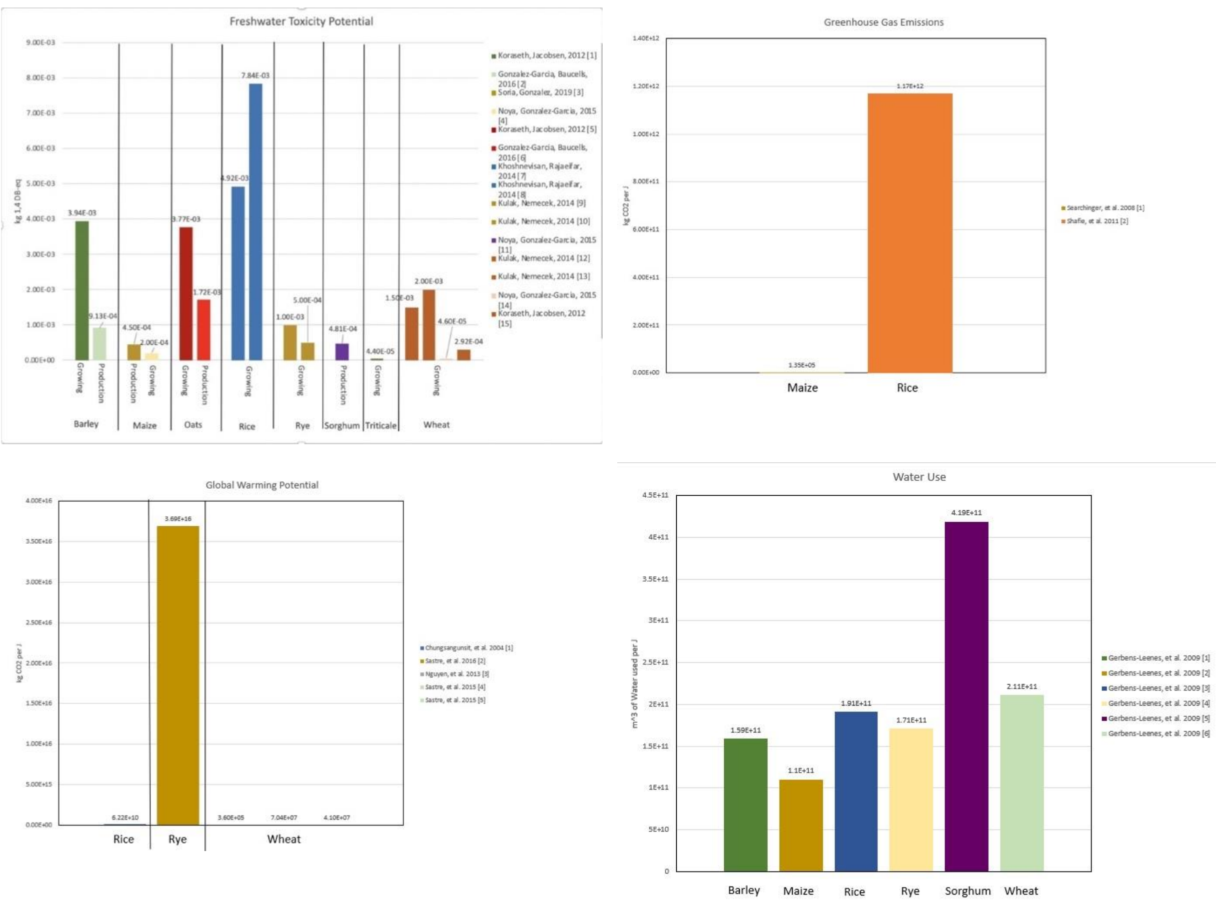


Figure 9. (Top left) Photochemical oxidization for various grains using Mass Functional Units. Descriptive information about the studies can be found in Table 25. (Top right) Greenhouse gas emission for maize and rice for Energy Functional Units. Descriptive information about the studies can be found in Table 26. (Bottom left) Global warming potential for various grains using Energy Functional Units. Descriptive information about the studies can be found in Table 27. (Bottom right) Water use for various grains using Energy Functional Units. Descriptive information about the studies can be found in Table 28

3.3 Energy FU

3.3.1 Greenhouse Gas Emissions (GHG)

The final functional unit was the energy functional unit, measured in Joules. There has not been extensive research conducted on the effect that various grains have upon LCAs in terms of biofuels. There was some literature though, which has been analyzed in the following figures and tables. For greenhouse gas emissions, there were two data points (Figure 9 and Table 26). Rice has the highest emissions at 1.17x10^{12} kg of CO_2/J of energy produced. The lowest point was maize with 1.55x10^{5} kg of CO_2/J of energy. Overall trends suggest that rice causes a greater greenhouse gas impact than maize.

3.3.2 Global Warming Potential (GWP)

In a similar vein to greenhouse gas emissions, the global warming potential has been measured for rice, rye and wheat (Figure 9 and Table 27). The largest impact was rye with 3.69x10^{16} kg of CO_2. The smallest impact was wheat with 4.10x10^{7} kg of CO_2. There was one comparison conducted between wheat. The difference between the data points can be attributed to confidence intervals in the original study. One possible outlier was the large impact of rye which could be caused by geographic differences or insufficient data being collected to accurately compare and draw conclusions.

3.3.3 Water Use (H_2O)

The water usage needed for biofuels was estimated for barley, maize, rice, rye, sorghum and wheat (Figure 9 and Table 28). The highest value was 4.19x10^{11} m^{3} of water used for sorghum. The lowest value was maize with a value of 1.1x10^{11} m^{3} of water used. A possible outlier was sorghum, however insufficient data was collected to determine possible outliers. Overall, the water usage graph demonstrates the general consistency of water usage for use in biofuels.

3.3.4 Acidification Potential (AP)

The acidification potential data (Figure 10 and Table 29) have been quantified for rice, rye, and wheat in units of SO_2. Rye has the largest value at 5.22x10^{14} kg of SO_2 and wheat has the smallest value at 3.24x10^{3} kg of SO_2/J. A possible outlier was rye, however insufficient data was collected to determine outliers. Overall, the acidification graph details the similarity between rice and wheat in terms of acidification potential.

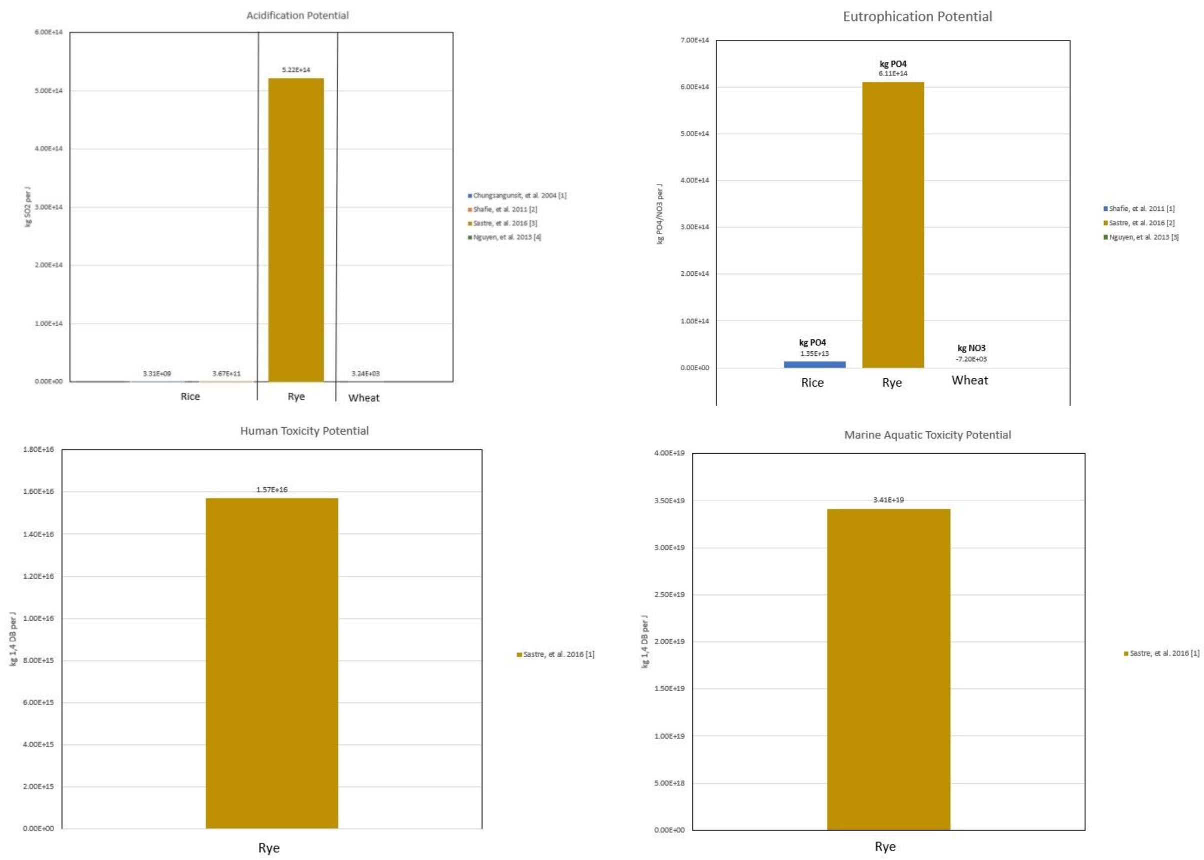


Figure 10. (Top left) Acidification Potential for various grains using Energy Functional Units. Descriptive information about the studies can be found in Table 29. (Top right) Eutrophication Potential for various grains using Energy Functional Units. Descriptive information about the studies can be found in Table 30. (Bottom left) Human toxicity potential for rye using Energy Functional Units. Descriptive information about the studies can be

found in Table 1. (Bottom right) Marine aquatic toxicity potential for rye using Energy Functional Units. Descriptive information about the studies can be found in Table 32

3.3.5 Eutrophication Potential (EP)

Eutrophication potential (Figure 10 and Table 30) shows the impact that rice, rye, and wheat have upon phosphate emissions. Rye has the highest value at 6.11x10^{14} kg PO. Meanwhile, rice has 1.35x10^{11}kg of PO_4/FU. One thing to note was that the wheat values mentioned in the graph were the data for the amount of nitrate absorbed, so it has a negative LCA measurement.

3.3.6 HTP/ MTP/ FTP/ STP/ ODP

Due to lack of previous research using energy as a FU, the graph and tables of human toxicity potential, marine toxicity potential, freshwater toxicity potential, soil toxicity potential, and ozone layer depletion potential only have one data point per graph (Figures 10 and 11 and Tables 31-35). These graphs all display the values for rye in each corresponding LCA. No comparisons or conclusions can be drawn due to the limited scope of the research.

3.3.7 Photochemical Oxidation (PO)

The final environmental impact was photochemical oxidation and can be found in Figure 11 and Table 36. This graph compares rice and rye. Rye has the largest value with 1.87x10^{13} kg of C_2H_4/J and rice has the smallest with 1.22x10^9 kg of C_2H_4/J. Possible outliers could be either point, however insufficient data has been collected to make that determination. Based on the presumption that the data were accurate, rice has a significantly lower impact on photochemical oxidation than rice.

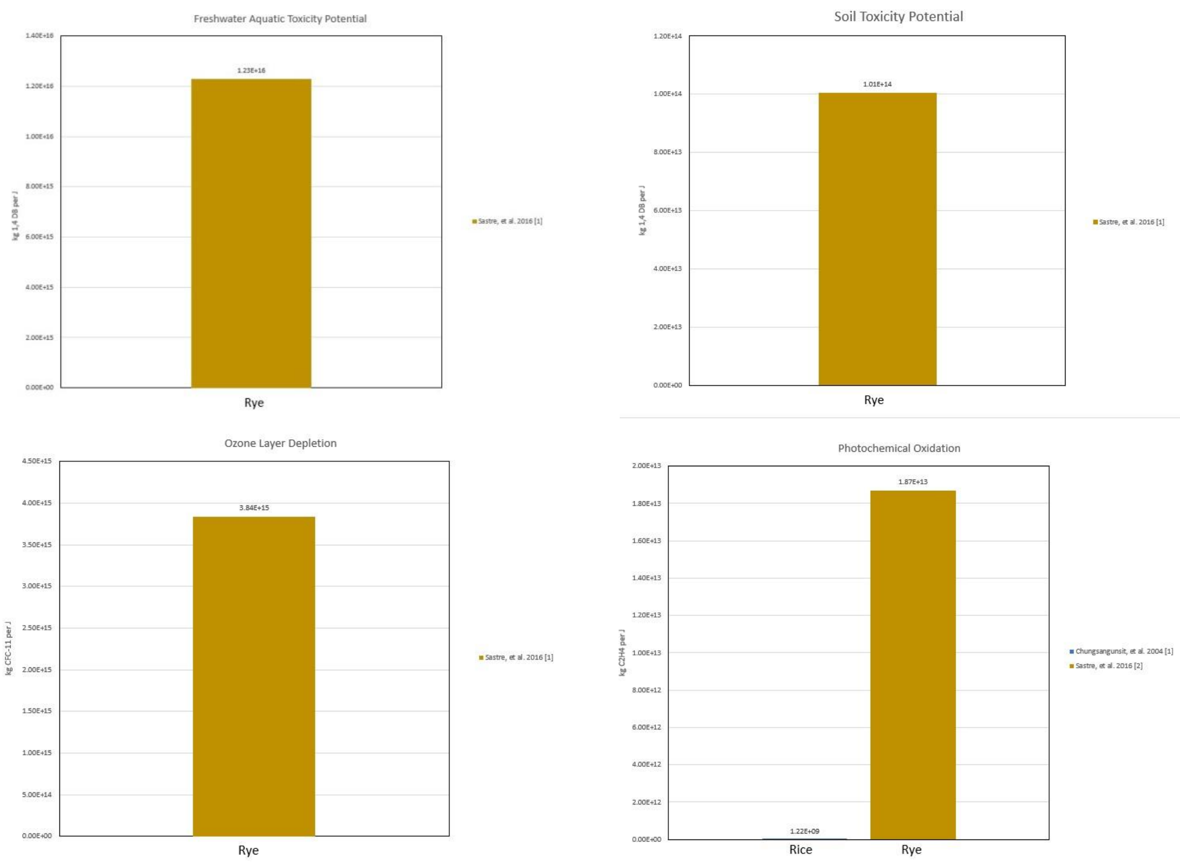


Figure 11. (Top left) Freshwater aquatic toxicity potential of rye using Energy Functional Units. Descriptive information about the studies can be found in Table 33. (Top right) Soil toxicity potential for rye using Energy Functional Units. Descriptive information about the studies can be found in Table 34. (Bottom left) Ozone layer depletion for rye using Energy Functional Units. Descriptive information about the studies can be found in Table 35. (Bottom right) Photochemical oxidation for rice and rye using Energy Functional Units. Descriptive information about the studies can be found in Table 36

One of the most notable differences when comparing the graphs was that there were many graphs where sorghum was many magnitudes higher than the rest of the grains. Once this trend was noted, further analysis of the paper done by Caffery et al. revealed that their study was done using sweet sorghum instead of grain sorghum. The biggest difference between the two was that grain sorghum was harvested by collecting the grains, like nearly every other comparison that was done in this meta-analysis, while sweet sorghum was harvested for the entire stalks and is predominantly used for syrup. This accounts for the massive disparity in many of the charts that measure sweet sorghum.

4. Implications

This review identifies and discusses specific areas for agricultural improvements throughout cereal grain supply chains. While some environmental aspects may not be applicable to all production, due to geographic differences, by further examining various agricultural practices around the globe, these practices can be studied and tested in varying agricultural regions. For example, considering the land functional unit and the freshwater toxicity potential for wheat, there was a substantial difference in environmental impacts. The first data set originates from France and the other from Italy. While these two regions may not differ substantially environmentally, the higher values from France should indicate the potential for alterations of agricultural practices based on the results of this paper. For a more severe geographic difference, once again considering the land functional unit for the eutrophication potential of wheat, there was an apparent difference between wheat grown in France and wheat grown in Iran. While geographical differences play a role here, future studies could be conducted to see if any of the practices used in France could be applied with positive environmental impacts in Iran. There were several more examples of this throughout the study where geographic differences can be applied to work on general improvements.

Another implication of this research is general improvements needed during specific stages of supply chains. Overall, the growing stage performed significantly worse than either the transportation or processing stages of the supply chain. This is something that almost all crops in almost all regions need to work to improve on, and future research needs to be conducted in order to determine what steps need to be taken to minimize the difference between these stages.

5. Conclusions

The biggest aspect found during the analysis of the articles was that there was no one grain that was primarily better than another in terms of environmental performance. A particular grain can do well for some environmental parameters, and in another it can do poorly. Each grain has its own specific strengths and weaknesses that account for the emissions that they release to the environment. For best practices going forward, these data suggest that we should continue growing a variety of grains so that we don’t create an excess of one particular pollutant. Another suggestion is that we determine which emissions we want to minimize and which ones we can give more leeway to. Currently, lower emissions such as ozone and greenhouse gasses have a high priority, and we can work towards growing fewer crops that have these emissions or making those grain supply chains less environmentally impactful.

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Appendix

Table 1. Descriptive information for the studies in Fig. 1

Authors	Geographical Region	Summary
Yan, et al. 2014	China	Conventional farming practices used over the whole course of production.
Yan, et al. 2012	China	Based on surveys from 10 different farms.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Lamonaca, et al. 2016	Italy	No tillage used on soil; a cover crop was used. Based on a 2014 farm.
Rajaniemi & Mikkola, 2011	Finland	Conventional farming practices used.
Rajaniemi & Mikkola, 2011	Finland	Reduced tillage on the soil.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop was used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2014 farm.
Eranki, et al. 2018	USA	Biological farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop used. Based on a 2012 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2012 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2012 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop was used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2014 farm.
Machado, et al. 2017	Brazil	Conventional farming practices used.
Liu, et al. 2018	China	Conventional farming practices used.
Yan, et al. 2014	China	Average taken from 123 farms.
Lu & Zhou, 2014	China	Local biofuels created from grains in local farms.
Eranki, et al. 2018	USA Midwest	Biological farming practices used.
Eranki, et al. 2018	USA Midwest	Conventional farming practices used.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Rajaniemi & Mikkola, 2011	Finland	Conventional farming practices used.
Rajaniemi & Mikkola, 2011	Finland	Reduced tillage on the soil.
Patel, et al. 2018	USA	Conventional farming practices used.
Machado, et al. 2017	Brazil	Conventional farming practices used.
Liu, et al. 2018	China	Conventional farming practices used.
Yan, et al. 2014	China	Average taken from 123 farms.

Rajaniemi & Mikkola, 2011	Finland	Conventional farming practices used.
Rajaniemi & Mikkola, 2011	Finland	Reduced tillage on the soil.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Liu, et al. 2018	China	Conventional farming practices used.
O'Hare, et al. 2013	Australia	Conventional farming practices used to make Sorghum for animal feed.
Liu, et al. 2018	China	Conventional farming practices used in China.
Liu, et al. 2018	UK	Conventional farming practices used in the UK.
Liu, et al. 2018	Denmark	Conventional farming practices used in Denmark.
Liu, et al. 2018	Australia	Conventional farming practices used in Australia.
Rajaniemi & Mikkola, 2011	Finland	Conventional farming practices used.
Rajaniemi & Mikkola, 2011	Finland	Reduced tillage on the soil.
Charles, et al. 2005	No Region Listed	Good agricultural practices, as stated by Swiss regulations.
Yan, et al. 2014	China	Average taken from 123 farms.

Table 2. Descriptive information for studies in Fig. 1

Authors	Geographical Region	Summary
Lamonaca, et al. 2016	Italy	No tillage used on soil; a cover crop was used. Based on a 2014 farm.
Guardia, et al. 2016	Iran	To tillage used on soil.
Guardia, et al. 2016	Iran	Minimum tillage used on the soil.
Guardia, et al. 2016	Iran	Conventional tillage used on the soil.
Goucher, et al. 2017	UK	Farming, Processing, and Transportation measurements used in making an 800g loaf of bread.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop was used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2014 farm.
Eranki, et al. 2018	US Midwest	Conventional farming practices used.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop used. Based on a 2012 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2012 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2012 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	No tillage used on soil; a cover crop was used. Based on a 2013 farm.
Boardman, et al. 2018	USA	Tillage used on soil; no cover crop used. Based on a 2014 farm.
Boardman, et al. 2018	USA	Tillage used on soil; a cover crop used. Based on a 2014 farm.
Grassini & Cassman, 2012	US Midwest	Pivot Irrigation and conventional tilling used. Maize planted after soybeans.
Grassini & Cassman, 2012	US Midwest	Pivot irrigation and reduced tillage used. Maize planted after soybeans.
Grassini & Cassman, 2012	US Midwest	Pivot irrigation and conventional tilling used. Maize planted after maize.
Grassini & Cassman, 2012	US Midwest	Pivot irrigation and reduced tillage used. Maize planted after maize.
Grassini & Cassman, 2012	US Midwest	Surface irrigation and conventional tilling used. Maize planted after soybeans.
Grassini & Cassman, 2012	US Midwest	Surface irrigation and reduced tilling used. Maize planted after soybeans.
Grassini & Cassman, 2012	US Midwest	Surface irrigation and conventional tilling used. Maize planted after maize.
Grassini & Cassman, 2012	US Midwest	Surface irrigation and reduced tilling used. Maize planted after maize.
Bacenetti, et al. 2013	Italy	Methane potential from Maize 700.
Bacenetti, et al. 2013	Italy	Methane potential from a combination of maize 500 and wheat.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffery, et al. 2014	USA	Conventional farming practices used.
O'Hare, et al. 2013	Australia	Sorghum used to make ethanol.
O'Hare, et al. 2013	Australia	Sorghum used as a biomass.

Table 3. Descriptive information for studies in Fig. 2

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boarman, et al. 2018	USA	Conventional farming practices used.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.

Table 4. Descriptive information for studies in Fig. 2

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Goucher, et al. 2017	UK	Farming, Processing, and Transportation measurements used in making an 800g loaf of bread.
Boardman, et al. 2018	USA	Conventional farming practices used.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.

Table 5. Descriptive information for studies in Fig. 3

Authors	Geographical Region	Summary
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Charles, et al. 2005	No Region Listed	Good agricultural practices used, based on Swiss regulations.

Table 6. Descriptive information for studies in Fig. 3

Authors	Geographical Region	Summary
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.

Table 7. Descriptive information for studies in Fig. 3

Authors	Geographical Region	Summary
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Patel, et al. 2019	India	Conventional farming practices used.
Charles, et al. 2005	No Region Listed	Good agricultural practices used, based on Swiss regulations.

Table 8. Descriptive information for studies in Fig. 4

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
Bacenetti, et al. 2013	Italy	Methane potential from Maize 700.
Bacenetti, et al. 2013	Italy	Methane potential from a combination of Maize 500 and wheat.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Charles, et al. 2005	No Region Listed	Good agricultural practices used, based on Swiss regulations.

Table 9. Descriptive information for studies in Fig. 4

Author	Geographical Region	Summary
Patel, et al. 2019	India	Conventional farming practices used.

Table 10. Descriptive information for studies in Fig. 4

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
Bacenetti, et al. 2013	Italy	Methane potential from Maize 700.
Bacenetti, et al. 2013	Italy	Methane potential from a combination of Maize 500 and wheat.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.

Table 11. Descriptive information for studies in Fig. 4

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
Bacenetti, et al. 2013	Italy	Methane potential from Maize 700.
Bacenetti, et al. 2013	Italy	Methane potential from a combination of Maize 500 and wheat.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Charles, et al. 2005	No Region Listed	Good agricultural practices used, based on Swiss regulations.

Table 12. Descriptive information for studies in Fig. 5

Authors	Geographical Region	Summary
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffery, et al. 2014	USA	Conventional farming practices used.

Table 13. Descriptive information for studies in Fig. 5

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
González-García, et al. 2016	No Region Listed	Conventional farming practices uses.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Patel, et al. 2019	India	Conventional farming practices used.

Table 14. Descriptive information for studies in Fig. 5

Authors	Geographical Region	Summary
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Boardman, et al. 2018	USA	Conventional farming practices used.
Bacenetti, et al. 2013	Italy	Methane potential from Maize 700.
Bacenetti, et al. 2013	Italy	Methane potential from a combination of Maize 500 and wheat.
González-García, et al. 2016	No Region Listed	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Conventional farming practices used.
Khoshnevisan, et al. 2014	Iran	Traditional farming practices used.
Caffrey, et al. 2014	USA	Conventional farming practices used.
Charles, et al. 2005	No Region Listed	Good agricultural practices used, based on Swiss regulations.

Table 15. Descriptive information for studies in Figure 6

Authors	Geographical Region	Summary
Gan, et al. 2012	Canada	Located in Indian Head, Saskatchewan, Canada; Urea fertilization
Fallahpour, et al. 2012	Iran	Irrigated; Fertilizer Rates (140-160 kn N/ha)
González-García, et al. 2016	USA	Fertilized with 170 kg of cattle slurry/ ha
Pathak, et al. 2010	India	Conventional preparation practices
Pathak, et al. 2010	India	Conventional processing practices
Pathak, et al. 2010	India	Conventional producing practice
Xu, et al. 2017	China	Medium-scale mill and crusher were used to produce product
Adom, et al. 2012	NE USA	Conventional USA growing practices
Adom, et al. 2012	S USA	Conventional USA growing practices
Adom, et al. 2012	Midwest USA	Conventional USA growing practices
Adom, et al. 2012	Rockies USA	Conventional USA growing practices
Noya, et al. 2015	Italy	Conventional growing practices
Xu, et al. 2017	China	Medium-scale mill and crusher were used to produce product/ Per kg of crushed grain
Xu, et al. 2017	China	Medium-scale mill and crusher were used to produce product/ Per kg of flour
Xu, et al. 2017	China	Medium-scale mill and crusher were used to produce product
Adom, et al. 2012	NE USA	Conventional USA growing practices
Adom, et al. 2012	Midwest USA	Conventional USA growing practices
Adom, et al. 2012	Rockies USA	Conventional USA growing practices
Adom, et al. 2012	Pacific Coast	Conventional USA growing practices
González-García, et al. 2016	USA	Fertilized with 170 kg of cattle slurry/ ha
González-García, et al. 2016	Finland	Conventional production practices
Hess, et al. 2014	Italy	Produced in integrated process plants having an average productivity of 1,000 tons of pasta/day.
Cancino-Espinoza, et al. 2018	Peru/ Bolivia	Conventional production practices for a 500 g packet of quinoa
Pathak, et al. 2010	India	Conventional Growing Practices
Pathak, et al. 2010	India	Total emission of CO2 was calculated from the amount of diesel used for transport and processing, and liquid petroleum gas (LPG) for preparation of food.
Pathak, et al. 2010	India	Total emission of CO2 was calculated from the amount of diesel used for transport and processing and liquid petroleum gas (LPG) for preparation of food.
Pathak, et al. 2010	California	N fertilizer application rates were within the range of 100 to 165 kg N/ ha;
González-García, et al. 2016	Thailand	Conventional cultivation practices
Xu, et al. 2017	USA	Fertilized with 170 kg of cattle slurry/ ha
Noya, et al. 2015	China	Cao et al. (2014) investigated the carbon emissions for rice production in Shanghai, and reporte that the electricity used for brown rice was 0.0264 kWh/kg rough rice.
Pathak, et al. 2010	Italy	Conventional growing practices
Biswas, et al. 2010	India	Conventional Growing Practices
Fallahpour, et al. 2012	Iran	Irrigated; Fertilizer Rates (160-180 kg N/ha)
Fallahpour, et al. 2012	Iran	Rainfed; Fertilizer Rates (0-10 kg N/ha)
Noya, et al. 2015	Italy	Conventional Growing Practices

Table 16. Descriptive information for studies in Figure 6

Authors	Geographical Region	Summary
González-García, et al. 2016	USA	Conventional Growing Practices
Mekonnen & Hoekstra, 2014	Global	Green-blue water usage, conventional fertilization practices
Aldaya, et al. 2010	Italy	Green water usage, conventional fertilization practices
Aldaya, et al. 2010	Italy	Blue water usage, conventional fertilization practices
Aldaya, et al. 2010	Italy	Gray water usage, conventional fertilization practices
Su, et al. 2014	France	Conventional growing practices for each country
Su, et al. 2014	Canada	Conventional growing practices for each country
Su, et al. 2014	US	Conventional growing practices for each country
Su, et al. 2014	China	Conventional growing practices for each country
Su, et al. 2014	Taiwan	Conventional growing practices for each country
Su, et al. 2014	Nepal	Conventional growing practices for each country
Su, et al. 2014	Brazil	Conventional growing practices for each country
Su, et al. 2014	Thailand	Conventional growing practices for each country
Su, et al. 2014	Indonesia	Conventional growing practices for each country
Su, et al. 2014	India	Conventional growing practices for each country
Mubako & Lant, 2008	Illinois	Calculated the mean application of N, P, and pesticides using data published by Hill et al.[2006]
Mubako & Lant, 2008	Iowa	Calculated the mean application of N, P, and pesticides using data published by Hill et al.[2006]
Mubako & Lant, 2008	Nebraska	Calculated the mean application of N, P, and pesticides using data published by Hill et al.[2006]
Mubako & Lant, 2008	Italy	Conventional growing practices
Tuninetti, et al. 2015	USA	Conventional production practices
Tuninetti, et al. 2015	Argentina	Conventional production practices
Tuninetti, et al. 2015	China	Conventional production practices
Aldaya, et al. 2010	Canada	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Aldaya, et al. 2010	Australia	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Aldaya, et al. 2010	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
González-García, et al. 2016	USA	Conventional growing practices for each country
Aldaya, et al. 2010	Kazakhstan	Conventional growing practices for each country
Aldaya, et al. 2010	Tajikistan	Conventional growing practices for each country
Aldaya, et al. 2010	Turkmenistan	Conventional growing practices for each country
Aldaya, et al. 2010	Uzbekistan	Conventional growing practices for each country
Aldaya, et al. 2010	Thailand	Conventional growing practices for each country
Tuninetti, et al. 2015	Vietnam	Conventional growing practices for each country
Tuninetti, et al. 2015	China	Conventional growing practices for each country
González-García, et al. 2016	USA	Conventional production practices
Aldaya, et al. 2010	Kazakhstan	Conventional growing practices for each country
Tuninetti, et al. 2015	USA	Conventional growing practices for each country
Tuninetti, et al. 2015	Canada	Conventional growing practices for each country
Tuninetti, et al. 2015	France	Conventional growing practices for each country
Tuninetti, et al. 2015	Australia	Conventional growing practices for each country
Tuninetti, et al. 2015	Argentina	Conventional growing practices for each country

Table 17. Descriptive information for studies in Figure 7

Authors	Geographical Region	Summary
Fallahpour, et al. 2012	Iran	Irrigated; Fertilizer Rates (160-180 kg N/ha)
Kulak, et al. 2014	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2014	France	Southern France, bread from horse farming
Kulak, et al. 2014	France	Conventional growing practices
Kulak, et al. 2014	Portugal	Conventional growing practices
Fallahpour, et al. 2012	Iran	Irrigated; Fertilizer Rates (160-180 kg N/ha)
Nguyen, et al. 2013	Denmark	For use in biofuels; straw gasification
Nguyen, et al. 2013	Denmark	For use in biofuels; straw direct combustion

Table 18. Descriptive information for studies in Figure 7

Authors	Geographical Region	Summary
Bartzas, et al. 2015	Spain	For use in biofuels, conventional growing practices
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
Yodkhum, et al. 2017	China	Use of conventional rice; conventional growing practices
Yodkhum, et al. 2017	China	Use of long-term organic rice; conventional growing practices
Nguyen, et al. 2013	Switzerland	Fertilizer Rates= 140 kg N/ha

Table 19. Descriptive information for studies in Figure 7

Authors	Geographical Region	Summary
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming

Table 20. Descriptive information for studies in Figure 7

Authors	Geographical Region	Summary
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Kulak, et al. 2015	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2015	France	Southern France, bread from horse farming
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Noya, et al.2015	Italy	Conventional growing practices
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
Kulak, et al. 2014	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2014	France	Southern France, bread from horse farming
Kulak, et al. 2014	Portugal	Grown on farms using integrated crop and livestock production
González-García, et al. 2016	USA	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices
Kulak, et al. 2014	France	Grown on farms using integrated crop and livestock production
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010

Table 21. Descriptive information for studies in Figure 8

Authors	Geographical Region	Summary
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Noya, et al. 2015	Italy	Conventional growing practices
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
González-García, et al. 2016	USA	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010

Table 22. Descriptive information for studies in Figure 8

Authors	Geographical Region	Summary
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Noya, et al. 2015	Italy	Conventional growing practices
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
González-García, et al. 2016	USA	Conventional growing practices
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
Kulak, et al. 2014	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2014	France	Southern France, bread from horse farming
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
Noya, et al. 2015	Italy	Conventional growing practices
Kulak, et al. 2014	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2014	France	Southern France, bread from horse farming

Noya, et al. 2015	Italy	Conventional growing practices
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010

Table 23. Descriptive information for studies in Figure 8

Authors	Geographical Region	Summary
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
Yodkhum, et al. 2017	Thailand	Based on use of manual labor, no fertilization, and transportation via 7-tonne trucks
Yodkhum, et al. 2017	China	Based on heavier use of machinery, no fertilization, and transportation using railways and rivers
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010
Koraseth, et al. 2013	Norway	95 farms using conventional cereal growing practices in 2010

Table 24. Descriptive information for studies in Figure 8

Authors	Geographical Region	Summary
Bartzas, et al. 2015	Spain	For use in biofuels, conventional growing practices
Lechón, et al. 2005	Spain	Data obtained from the European Fertilizer Manufacturers Association from the year 2000 for data pertaining raw materials, energy, and fertilizer
González-García, et al. 2016	USA	Conventional growing practices
Kulak, et al. 2015	France	Northern France, bread from integrated crop and livestock production
Kulak, et al. 2015	France	Southern France, bread from horse farming
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Noya, et al. 2015	Italy	Conventional growing practices
González-García, et al. 2016	USA	Conventional growing practices
Khoshnevisan, et al. 2014	Iran	Mass-based consolidated farming
Khoshnevisan, et al. 2014	Iran	Mass-based traditional farming
González-García, et al. 2016	USA	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices

Table 25. Descriptive information for studies in Figure 9

Authors	Geographical Region	Summary
González-García, et al. 2016	USA	Conventional growing practices
Guzmán-Soria, et al. 2019	Mexico	90 kg N/ ha applied w/ 20% at pre-plant, 40% at tillering, 40% at stem elongation
Noya, et al. 2015	Italy	Conventional growing practices
González-García, et al. 2016	USA	Conventional growing practices
González-García, et al. 2016	USA	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices
Noya, et al. 2015	Italy	Conventional growing practices

Table 26. Descriptive information for studies in Fig. 9

Authors	Geographical Region	Summary
Searchinger, et al. 2008	USA	Conventional farming practices used.
Shafie, et al. 2011	Malaysia	Entire life cycle of rice used in measurements.

Table 27. Descriptive information for studies in Fig. 9

Authors	Geographical Region	Summary
Chungsangunsit, et al. 2004	Thailand	Only rice production used in measurement.
Sastre, et al. 2016	Spain	Conventional farming practices used.
Nguyen, et al. 2013	Denmark	Straw underwent gasification.
Sastre, et al. 2015	Spain	Bottom end of 95% confidence interval.
Sastre, et al. 2015	Spain	Top end of the 95% confidence interval.

Table 28. Descriptive information for studies in Fig. 9

Authors	Geographical Region	Summary
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.
Gerbens-Leenes, et al. 2009	Global	Conventional farming practices used.

Table 29. Descriptive information for studies in Fig. 10

Authors	Geographical Region	Summary
Chungsangunsit, et al. 2004	Thailand	Only rice production used in measurement.
Shafie, et al. 2011	Malaysia	Entire life cycle of rice used in measurement.
Sastre, et al. 2016	Spain	Conventional farming practices used.
Nguyen, et al. 2013	Denmark	Straw underwent gasification.

Table 30. Descriptive information for studies in Fig. 10

Authors	Geographical Region	Summary
Shafie, et al. 2011	Malaysia	Entire life cycle of rice used in measurement.
Sastre, et al. 2016	Spain	Conventional farming practices used.
Nguyen, et al. 2013	Denmark	Straw underwent gasification.

Table 31. Descriptive information for studies in Fig. 10

Authors	Geographical Region	Summary
Sastre, et al. 2016	Spain	Conventional farming practices used.

Table 32. Descriptive information for studies in Fig. 10

Authors	Geographical Region	Summary
Sastre, et al. 2016	Spain	Conventional farming practices used.

Table 33. Descriptive information for studies in Fig. 11

Authors	Geographical Region	Summary
Sastre, et al. 2016	Spain	Conventional farming practices used.

Table 34. Descriptive information for studies in Fig. 11

Authors	Geographical Region	Summary
Sastre, et al. 2016	Spain	Conventional farming practices used.

Table 35. Descriptive information for studies in Fig. 11

Authors	Geographical Region	Summary
Sastre, et al. 2016	Spain	Conventional farming practices used.

Table 36. Descriptive information for studies in Fig. 11

Authors	Geographical Region	Summary
Chungsangunsit, et al. 2004	Thailand	Only rice production used in calculation.
Sastre, et al. 2016	Spain	Conventional farming practices used.