Master's Thesis of Science in Agriculture

Environmental Impacts of International Crop Trade on Supply Chain from Farm to Market

국제 곡물 공급망 분석을 통한 수입곡물의 환경영향평가

February 2020

Chanwoo Kim

Department of International Agricultural Technology
Graduate School of International Agricultural Technology
Seoul National University

Environmental Impacts of International Crop Trade on Supply Chain from Farm to Market

A thesis
submitted in partial fulfillment of the requirements to the faculty
of Graduate School of International Agricultural Technology
for the Degree of Master of Science in Agriculture

By
Chanwoo Kim

Supervised by
Prof. Kyo Suh

Major of International Agricultural Technology
Department of International Agricultural Technology
Graduate School of International Agricultural Technology
Seoul National University

December 2019

Approved as a qualified thesis
for the Degree of Master of Science in Agriculture
by the committee members

Chair	**Joonweon Choi, Ph.D.**	최준원
Vice Chair	**Kyo Suh, Ph.D.**	Suhkyo
Member	**Hakkwan Kim, Ph.D.**	Hakkwan Kim

Abstract

Environmental Impacts of International Crop Trade on Supply Chain from Farm to Market

Chanwoo Kim
Department of International Agricultural Technology
Seoul National University

The environmental impacts of the international crop trade have increased due to higher trade volume and longer transportation distances, which have caused increased greenhouse gases (GHGs), fine particulate matter ($PM_{2.5}$), and other environmental pollutants. Environmental concerns about the international crop trade have steadily grown as citizens become more aware of global environmental issues related to GHGs and PMs. One of the major challenges for the international food supply is how to alleviate the environmental impacts of crop trade.

Food miles have been generally used to measure the environmental implications of crop transportation because it is a useful indicator to evaluate the environmental impacts associated with food transportation from field to plate considering volume and distance. Buying local food is a movement to encourage people to purchase food locally in an

effort to reduce the environmental impacts of food miles. However, most studies on food miles have focused on the transportation of imported crops even though crop production typically has a greater environmental impact than crop transportation.

Crop production is a major contributor to environmental emissions such as GHG emissions and N_2O because crop cultivation requires fertilizers, pesticides, energy, and various synthetic inputs. In addition, the impact of these input on crop production varies widely by region because farming conditions such as tillage practices, water availability, regional climate, and resource productivity are spatially different. The regional farming districts that supply the crops also impacts the environmental variation of imported crops.

It is difficult, however, to examine both crop mobility and supply regions. Thus, most related studies have not included the environmental implications of the stages (i.e., production, transportation stages) of imported crop production. Tracing counties that supply food and insights on spatial variation based on supply chain analysis provides a transparent environmental record of imported crops.

Thus, the goal of this study is to evaluate the implications of regional variability in terms of the embedded environmental impacts of imported crops on the supply chain from farm to market. First, the categorical environmental impacts of the transportation stages of South Korea’s major imported crops are analyzed using food miles. Second, the county-level subnational mobility from field to port of exported corn in the US, the highest number of food miles to South Korea, is estimated and the associated environmental impacts of exported corn are evaluated including production and transportation stages. Finally, the potential environmental benefits of port choices for eco-friendly corn are evaluated considering both production and transportation.

The environmental impacts of food miles for major imported crops (i.e., corn, wheat, and soybeans) was analyzed using a food-mile minimization model focusing on the transportation stages of the major crops. The food-mile model was designed so the major crops travel the shortest distance from farm to market. The origins of imported corn from the US was estimated based on the cost minimization model, which spatially links the corn supply chain of export ports and producing counties, and their associated GHG emissions and irrigated water use intensity in the production stage.

The environmental impact of minimum food miles for major imported crops were evaluated from GHG and $PM_{2.5}$ emissions perspectives using life-cycle assessment (LCA). This study reflected the unit impact (per ton·km) of GHG and $PM_{2.5}$ emissions by the transportation modes for each stage: land (field-to-export), maritime (export-to-import), and land (import-to-end points). The study showed that GHG emissions were mostly generated in the land transportation stage of the major crops (over 50%). In contrast, the $PM_{2.5}$ emissions tended to be higher in maritime shipping, representing about 70%.

The key contributor of the categorical differences was the transportation mode. The unit impact of GHG emissions was even greater for trucking (1.29e-01 kg CO_2e/ton·km) than rail (1.51e-02 kg

CO_2e/ton·km) and bulk carrier (3.24e-03 kg CO_2e/ton·km). However, the $PM_{2.5}$ emissions showed comparatively few differences in the modes. Thus, the most significant impact was caused by the maritime stage, which had the most food miles from all export countries and items. The categorical differences in the transportation modes highlight the need for further examination of other environmental impact categories.

The cost minimization model connected 191 US export corn producing counties and 32 ports for exported corn and their associated environmental impact. The main findings were the port-level variability of GHG emissions and irrigated water use intensity during the production stage of US export corn. The corn production impact of GHG at the port level ranged from 0.187 to 0.549 kg CO_2e/kg (on average 0.363 kg CO_2e/kg). The average consumed irrigated water was 0.135 m^3/kg was consumed for corn production, but the maximal use was 0.873 m^3/kg. Some ports that were linked with many non-irrigating counties revealed a large difference between the average and maximal use of irrigated water. The port-level variability makes it possible to export corn with fewer environmental impacts considering the spatial trends of corn production.

This study estimated the environmental benefits of port selection for US corn exported into South Korea. The optimal export ports that can minimize the environmental impact were selected considering the port-level variability of the impact. The results show that GHG emissions can be reduced up to 10 million kg CO_2e (totaling ▼5.3%; production impact ▼7%, transportation impact △1.5%) based on the

selected port. Despite the negative implications of GHG emissions in the transportation stages according to the port selection, high-tech transportation modes such as future innovations in renewable energy-driven initiatives will significantly reduce in transportation impact in the future. From the irrigated water use perspective, the expected reduction based on the recommended selected ports in this study was roughly 90% (from 49.9 million m^3 to 5.9 million m^3). Counties linked to the optimal selected ports from largely non-irrigated regions contributed to a sizable reductions in irrigated water consumption.

The approaches described in this study show how crop trading companies and their partners can estimate the environmental impact of the traded crops considering the production impact. Based on the results, companies can explore better ways to reduce the environmental impact of exported or imported crops. This study discusses environmental labeling like "eco-labeling," that can help decision-makers choose environmentally better crops. In addition, supporting subsidies for importing companies and cutting tariffs on the lower-impact crops will make these crops more attractive. These options will help address the growing calls for the crop trade to promote a better environment and encourage efforts to trade eco-friendly crops.

Keywords : International crop trade, food mile, environmental LCA, crop-mobility optimization

Student Number **:** 2017-21224

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AMIS	:	Agriculture Management Information System
BCC	:	Bulk-commodity carrier
CCS	:	Corn-corn-soybean rotation
COA	:	Census of Agriculture
CO_2e	:	Carbon dioxide equivalent
CS	:	Corn-soybean rotation
CTS	:	Centre for Transport Strategies
DDGs	:	Dried Distiller's Grains with solubles
ERS	:	Economic Research Service
FAO	:	Food and Agriculture Organization of the UN
FDI	:	Future Directions International
fine PM	:	Fine Particulate Matter ($PM_{2.5}$)
GHGs	:	Greenhouse gases
ISO	:	International Organization for Standardization
KCS	:	Korea Customs Service
KFA	:	Korea Feed Association
KOFMIA	:	Korea Flour Mills Industrial Association
KOSIS	:	Korean Statistical Information Service
LCA	:	Life-Cycle Assessment
LCI	:	Life-Cycle Inventory
NASS	:	National Agricultural Statistics Servics
NCGA	:	National Corn Growers Association
NOAA	:	National Oceanic and Atmospheric Administration
$PM_{2.5}e$	:	$PM_{2.5}$ (fine PM) equivalent
USDA	:	the US Department of Agriculture
WASDE	:	World Agricultural Supply and Demand Estimates

Chapter I. Introduction

1. Background

International crop trade volume has continuously increased by 78% from 296 million tons in 2001 to 526 million tons in 2016 (FAOSTAT, 2019). The international crop trade value reached 356 billion US dollars in 2016, which was a 242% increase from 104 billion US dollars in 2001. These volumes and values of the international crop trade are expected to continue to grow (Dellink et al., 2017; FAO, 2017). Regional variation in the surplus and deficit of crops have given rise to this spectacular expansion of the international crop trade (Smith et al., 2005; Foley et al., 2011; Wakeland et al., 2012; Kastner et al., 2014). The US and China are good examples of the variations of surplus and deficit of crops. The US has exported increasing amounts of crops to other countries over the past 15 years, rising 32% from 110 million tons in 2001 to 145 million tons in 2016. In contrast, China has relied heavily on other countries for their crops, representing a 321% increase in crop imports from 26 million tons in 2001 to 111 million tons in 2016 (FAOSTAT, 2019).

The surplus and deficit of crops are not the only drivers of the crop trade. Advanced transportation and storage technologies have made it possible for large amounts of crops to travel much longer distances and at higher speeds (Ślusarczyk, 2010). People's changing preferences in the variety of foods is also an important factor in the growth of the crop trade. These factors have greatly increased crop availability and accessibility (Pavlović and Radoš, 2016). International trade is particularly important for countries that do not have access to certain types of crops or whose domestic agricultural industries do not produce enough crops at a sufficient scale. For instance, South Korea cannot produce coffee but it consumes about 1.6 million tons of coffee per year (aT, 2017). With a strong international crop trade, the limited production of certain crops in a country no longer restricts people's preferences.

Despite the advantages of the International crop trade, the greater volume and transportation distances have led to an increased environmental impact across the supply chain (Lewis and Mitchell, 2013; Kim, 2018). Trading of crops has resulted in environmental pollutants such as greenhouse gases (GHGs), fine particulate matter ($PM_{2.5}$) and a number of other undesirable substances that are released into the environment. Since an increase in the international crop trade volume is expected to continue to grow, researchers, politicians, and the general public have increasingly called for better environmental protections of imported crops and the concerns have rapidly become more prominent in the global conversation (Kim, 2012; Kastner et al., 2014). Reducing the environmental impact of the crop trade is a major challenge in achieving the environmental and sustainability goals of global agriculture (IPCC, 2007; Dalin and Rodríguez-Iturbe, 2016).

South Korea imports a large amount of crops from far away such as the US, Australia, and Brazil. This long shipping distance has also heightened environmental concerns among South Koreans about imported crops.

With the growth of environmental concerns about the extended distance and volume of trade, the environmental implications of "food miles" for the transportation process of the international crop trade have received much attention in recent years (Wynen and Vanzetti, 2008; Bernatz, 2010; Kim et al., 2018). The food mile concept is a representative indicator of the environmental impact of the food trade (Lang, 1999; Pretty et al., 2005). In 2006, Farmers Weekly magazine launched a campaign to reduce the food miles of agri-food with the slogan "Local food is miles better" (FW, 2006). Thus, many people are increasingly inclined to purchase food from nearby places to alleviate the environmental impact of food miles (Ballingall and Winchester, 2008; Christensent et al., 2018). However, food mile studies have mostly focused on the transportation of traded crops and have not take into account the environmental impact in crop production.

The environmental impact of crop production is generally larger than that caused by crop transportation. However, it is not easy to calculate the production impact of imported crops (Knudsen et al., 2010; Cristea et al., 2013). Crop production using fertilizers, pesticides, and other natural and synthetic inputs and resources is widely acknowledged to cause high GHG emissions and deteriorating water quality (Matson et al., 1997; Vörösmarty et al., 2000; Godar et al., 2016). In the US, the

GHG emissions associated with food are prevalent in the production stage, contributing to 83% of life-cycle GHG emissions, while the transportation stage as a whole represents only 11% of the emissions (Weber and Matthews, 2008). Knudsen et al. (2010) showed that the GHG emissions of the production stage for soybeans transported from China to Denmark contributes over 55% in the overall trade flow.

The calculations of these impacts are also difficult because the crop production impact differs depending on the region where the crop is produced given the regional variability of climate, water availability, and inputs (Carlson et al., 2017; Smith et al., 2017; Pelton, 2019). More importantly, the spatial trends of the crop production impact are found at a subnational level as well as at an international level. Thus, the origin of imported crops can clearly affect the environmental impact of the crop trade. Importing and exporting crops from lower environmental-impact regions, for example, can significantly decrease the environmental impact of crops produced in relatively high-impact regions. This important issue of the crop production impact warrants focused research to better understand the environmental implications considering both food miles and spatial variations of the production stage.

It is difficult, however, to track the mobility and supply regions of crops. Although there is considerable information associated with the international crop trade, little or no data exist on the regions that supply crops (Lang, 1999; Kissinger, 2012; Lewis and Mitchell, 2014; Kim et al., 2018). Due to this lack of data, most related studies on environmental implications of the international crop trade have not included measures of the crop production impact. One exception is Smith et al.’s (2017) study that offered ways to estimate consumption-based subnational mobility of US corn with a cost minimization model to analyze the embedded environmental impact from the corn consumed in the US. Their method makes it possible to estimate the producing regions of imported crops based on the optimal distribution from farm to export port.

Environmental thinking for imported crops can also be integrated into the supply chain to assist trading eco-friendly crops. Environmental thinking represents how firms care about the natural environment and minimize the negative environmental impacts of their entire operations including production and transportation (Chin et al., 2015). Tracing the crop supply counties and insights on regional variation based on supply chain analysis can provide a transparent environmental record of imported crops and will help meet the sustainability objectives of global agriculture.

2. Objectives

The objective of this study is to analyze the regional variability of the environmental impacts embedded in major imported crops on the supply chain from farm to market. First, the GHG and $PM_{2.5}$ emissions of transportation stages for the major imported crops (wheat, corn, and soybeans) of South Korea are evaluated using food miles. Second, the county-level subnational mobility from corn fields to export ports in the US is estimated and the embedded environmental impacts of the US export corn supply are evaluated including both the production and transportation stages.

To evaluate the environmental impacts of the imported crops, this study builds two mobility optimization models to minimize food miles and transportation costs:

(1) The food mile minimization model incorporates the optimal distribution to minimize transport distances from origin to destination of the major imported crops. In this model, the major imported crops travels the shortest distances from major producing regions in major exporting countries to consumption locations in South Korea.

(2) The Cost minimization model encompasses county-level corn mobility from fields to ports and the movement of embedded

GHGs and irrigated water use of the US export corn supply. The model spatially links the supply chain of export ports and export corn producing counties, and their associated environmental impact.

Finally, the potential GHGs reductions and irrigated water savings by selected export port for eco-friendly corn are evaluated considering both production and transportation. The environmental benefits are based on the results of the port-level variation in the impacts of US corn exported to South Korea. The potential motivation to improve the environmental impact of the international crop trade is discussed in the last section of the results and discussion chapter.

Chapter Ⅱ. Literature Review

1. Regional Variability of Environmental Impacts for Crop Production

The regional input amounts for crop production vary widely because farming conditions such as tillage practices, water availability, regional climate, and resource productivity are spatially different. Thus, the environmental impact of crop production depends heavily on the supply region. This spatial variation in the crop production impact can be found not only at the national level but also at the subnational level. Therefore, to evaluate the environmental impact of imported crops, the variation of the impact at the subnational-level should be considered.

Dalin and Rodríguez-Iturbe (2016) reviewed the environmental impact of the food trade, focusing on water use and GHG emissions. Their research highlighted key issues related to the spatial variation of the production impact. In particular, they argued that there is an urgent need for a more comprehensive, integrated approach to estimate the global impact of the food trade on the environment considering both the production and transportation impact.

Carlson et al. (2017) analyzed spatial variation in GHG emissions intensity including CH_4 emissions, of global croplands. They found that India provides 22% of the global rice and is one of the major emitters of CH_4 in rice production, representing 27% of global emissions. China produces about 33% of global rice; however, their rice CH_4 emissions are only 23% of the global total. In addition, Vietnam is the sixth largest emitter of GHG but has the highest cropland production intensity. Based on these findings, they noted that targeting mitigation efforts to locations with high intensities and high emissions could be a more effective strategy than focusing solely on large emitters.

Suh et al. (2011) evaluated state-level variation in the water footprint of corn ethanol production and the total water use to grow corn in 30 US corn ethanol-producing states. They found that there are considerable differences in the water footprint and total water use at the state level, ranging from 7 to 2043 Lw/Le and from 1 to 745 billion liters, respectively. Based on the results of their study, they suggested that importing corn feedstock from the lower-impact states could significantly reduce the water footprint of ethanol produced in relatively high-impact states.

Smith et al. (2017) also estimated US county-level variability of GHG emissions and irrigated water use associated with one bushel of corn production. Their results showed that the GHG emissions and irrigated water use in one bushel of corn production varied significantly across US counties. For example, they found that corn produced in western South Dakota emits 3-4 times more GHG than a similar bushel of corn produced in southern Minnesota. The western plains region is the largest user of water; in contrast, 97% of corn producing counties in Minnesota, Iowa, Illinois, and Indiana did not use irrigation water.

2. Environmental Implications of Food Miles for Transportation Stages of Imported Crops

To analyze the environmental impact of imported crop food miles, the transportation processes of the crops from origin to destination must first be identified. However, detailed route information of crop mobility is scarce. Therefore, several food mile studies have created transportation routes of crops to calculate shipping distances.

Bernatz (2009) built distribution routes of some imported fruits from fruit growing regions in exporting countries to the US to calculate the food mile. They separated the routes into two stages; truck routes (the major fruit growing region ~ export port or airport); and boat or air routes (between ports or between airports). They assumed that the location of the port or airport was the nearest one to the major fruit growing region.

Suh (2012) also examined the transportation processes from origin to destination of imported carrots and onions in South Korea, assuming that the crops were supplied from the central point of the exporting country. The transportation processes in his study consisted of land transportation by truck from the origin to the main export port and maritime shipping by ocean-container between ports.

Food miles can be simplified as a single environmental indicator focusing on the transportation stage of food. Thus, it seems logical that imported food that came from far away would have a greater environmental impact than local food. More food miles, however, does not represent greater environmental impact. Instead, the environmental impact and fuel consumption of the food trade are highly dependent on the transportation mode (Smith et al., 2005). However, the number of food miles does not reflect the environmental impacts of various transportation modes (i.e., flight, ship, truck, and rail).

Using environmental life-cycle assessment (LCA), Smith et al. (2005) demonstrated that the carbon emissions of air transportation is 0.038 kg CO_2e/ton·km, which is over 10 times greater than those of maritime transportation (0.003 kg CO_2e/ton·km). According to their research, the reason for the large disparity in the emissions from air and maritime transportation is that the flights release CO_2 into the atmosphere at high altitudes where the emissions do even more harm.

Kim et al. (2018) also used environmental LCA to assess the environmental impact of each transportation mode. They argued that the GHG emissions per ton·km of truck (0.081 kg CO_2e/ton·km) are 140% and 200% greater than those of rail (0.049 kg CO_2e/ton·km) and ocean-container (0.008 kg CO_2e/ton·km), respectively. Their study concluded that the environmental impact of different modes of transportation must be taken into account for the different transportation stages (i.e., land and waterway) to effectively evaluate the environmental impact of food miles.

3. Optimal Distribution from Origin to Destination of Imported Crops

Some countries cannot produce enough crops to supply their own demand, so many crops are shipped from crop surplus countries to crop deficit ones. However, although considerable data on the international crop trade are available, information associated with the regions that supply crops is scarce. To address this scarcity and estimate the origins of imported crops, several researchers have built optimal distribution models for the crops (Bernatz, 2009; Suh et al., 2011; Smith et al., 2017).

The optimal distribution is the most common way to estimate crop mobility from origin to destination. The optimization functions can be separated into two objectives: maximizing and minimizing. Maximizing aims to maximize profits or the speed of transportation and minimizing aims to minimize transportation distances, fuel consumption or costs.

Bernatz (2009) modeled optimal transportation routes of imported fruit from exporting countries to the US using great-circle routes, a concept of minimizing fuel consumption and shipping distances. His results showed the optimal fruit transportation routes between ports and between airports using the optimal allocation approach.

Suh et al. (2011) also simulated a supply model for the optimal corn feedstock allocation to minimize the total feedstock costs, considering the state-level corn prices and transportation costs. Their study included the fuel charge and the hopper car cost for rail transportation between states, and the ownership cost for trucking for the local supply as well as the corn price.

Smith et al. (2017) also developed a cost minimization transport model to estimate US corn mobility from corn producing counties to processing facilities. They modeled the optimal allocation to minimize the total delivered corn costs, including the county-level corn price and transportation cost. In this process, they used linear programming to estimate the US optimal allocation for direct corn consumption by demand sector.

Chapter Ⅲ. Materials and Methods

1. Global Status of Crop

1.1. Crop Production

Global crop production has increased over 30% for the last 10 years from 2,569 million tons in 2007 to 3,335 million tons in 2017 (FAO, 2019). Major crops have accounted for 95% of the total crop production including corn, rice, wheat, soybeans, and barley (Figure 1). The production of these major crops has also increased by 32% in the same period. In particular, corn was the largest share (1,135 million tons, 34%) of crop production in 2017. Crops with the second highest share were rice and wheat, accounting for 25% each.

China, the US, India, and Brazil have led global crop production accounting for over 50% of the world's crop production. Figure 1 shows the share of these major countries. The US and China, in particular, have been the major producers of the world's crops over the past 10 years, producing almost 20% of the crops, respectively. However, China was the largest crop producing country in 2012, producing 21% of the crops and still has the highest production (19% in 2017) of crops. India is also known as a major producing country of crops, with 10% of the global crop production. For another major producing country, Brazil, the share of global crop production increased

2% from 5% in 2007 to 7% in 2017. However, South Korea has remained the 40-50th among 185 crop producing countries for the last decade.

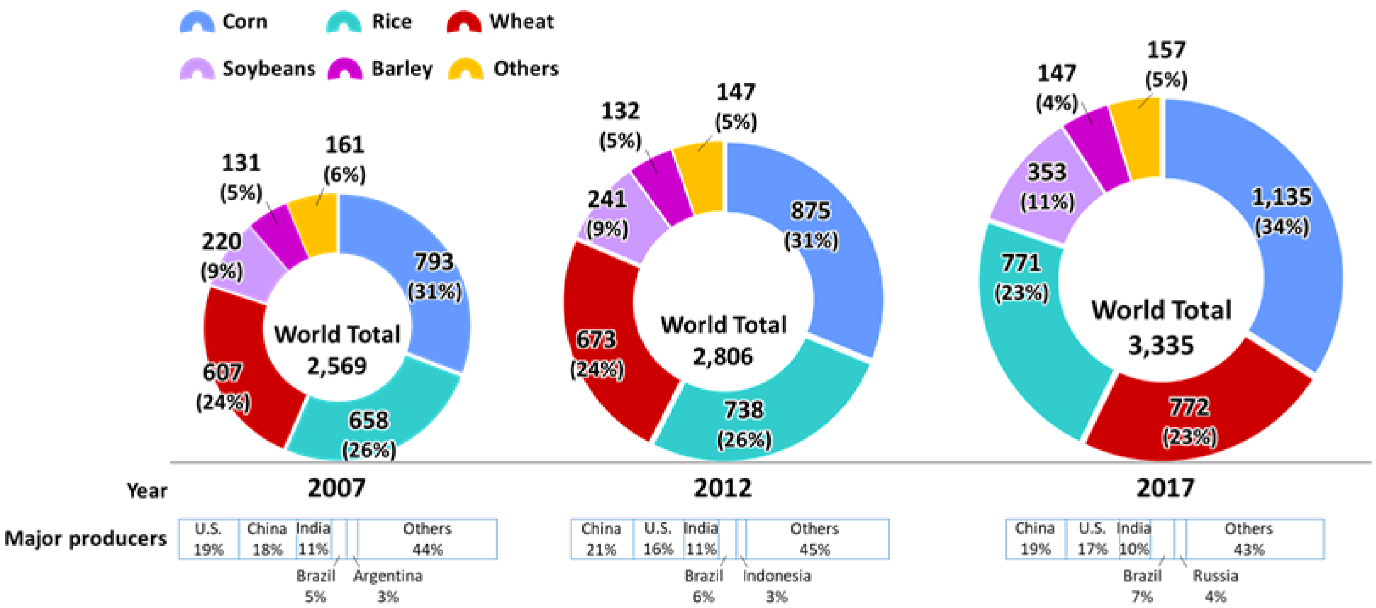


Figure 1. Global crop production (million tons) and major crop-producing countries (2007-2017).

1.2. Crop Trade

The volume of the international crop trade grew 78% over 15 years from 2001 to 2016 (an annual growth rate of 3%) (FAO, 2019). In particular, the annual growth rate was 6% per year between 2011 and 2016 (Figure 2), mainly because global crop consumption increased including food and feed use. The major traded crops accounting for almost 85% of the international trade were wheat, corn, and soybeans. From 2001-2016, the trade volume of these major crops increased 100%, which was greater than other crops and the growth in trade volumes of wheat and corn was 61% and 76%, respectively. Soybeans had the most marked change, increasing by 140% in trade volume from 57 million tons in 2001 to 135 million tons in 2016.

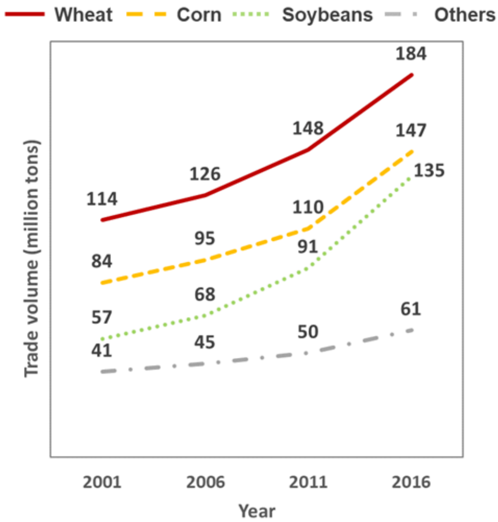


Figure 2. International trade volume of wheat, corn, soybeans, and other crops (2001-2016).

The global import volume of crops increased by 79% (232 million tons) from 294 million tons in 2001 to 526 million tons in 2016. The import volume, especially over five years (2011-2016), has notably expanded by 128 million tons (Table 1). The global export volume shows a similar pattern to the imports in the 15 year period, rising from 296 million tons to 526 million tons, an increase of about 5% per year (Table 2).

The leading countries in the crop trade from 2001-2016 included the US, China, Mexico, South Korea, and Brazil. The major importing countries were China, Mexico, and South Korea, and the major exporting countries were the US, Argentina, and Brazil.

Importing countries also continued to import crops from other exporting countries with a few exception (FAO, 2017). China mostly exported crops until 2001, even though they had a population of 1.4 billion. However, with economic growth and increased personal incomes, China became a major importing country of crops with a 10% annual growth rate in import volume (FDI, 2014). In 2016, China's imports constituted 111 million tons (38%) of global imports. Vietnam's position also shifted as a major importing country, importing 14 million tons of crops in 2016, which was about 1,450% higher than its 2001 imports. However, the import volume of other major importing countries (e.g., Japan, Mexico, South Korea, and the Netherlands) did not have a significant change over 15 years from 2001.

The US remains the most exporting country, occupying approximately 30% of global crop exports. The export volume of crops in the US reached 145 million tons in 2016, indicating that many countries heavily depend on the US for their crops. In addition, the share of the international crop export market has grown in the major exporting countries including Argentina, Brazil, Russia, Ukraine, and Romania. In particular, the crop export volume has rapidly grown from Russia and Romania, with a 17% and 21% of annual growth, respectively. China also increased exports from 7 million tons of crops in 2001, compared to only 0.3 million tons of Chinese crops that were supplied to the world in 2016.

Table 1. Crop import volume (thousand tons) of major importing countries.

Importing countries	2001	2006	2011	2016	Annual growth rate
China	26,314	40,109	65,587	110,741	△ 0.10
Japan	30,425	29,425	27,255	25,844	▼ 0.01
Mexico	19,309	17,728	19,561	23,913	△ 0.01
South Korea	13,622	13,420	13,701	15,678	△ 0.01
Netherlands	12,595	13,061	12,914	15,969	△ 0.02
Spain	10,896	14,207	13,957	17,868	△ 0.03
Italy	9,883	11,150	12,346	14,524	△ 0.03
Egypt	9,589	12,361	18,616	15,669	△ 0.03
Brazil	8,960	7,921	7,514	11,234	△ 0.02
Germany	7,156	8,128	11,741	13,245	△ 0.04
Belgium	6,803	7,617	7,403	8,382	△ 0.01
Algeria	6,637	7,317	11,005	13,249	△ 0.05
Vietnam	867	1,781	4,277	14,302	△ 0.21
U.S.	5,357	4,770	5,204	6,734	△ 0.02
Indonesia	5,171	8,039	11,605	14,136	△ 0.07
Saudi Arabia	4,358	8,991	10,813	14,298	△ 0.08
Others	115,642	128,392	143,973	189,807	△ 0.03
Total	**293,584**	**334,417**	**397,472**	**525,593**	△ **0.04**

Table 2. Crop export volume (thousand tons) of major exporting countries.

Exporting countries	2001	2006	2011	2016	Annual growth rate
U.S.	110,314	114,747	116,950	145,264	△ 0.02
Argentina	30,160	28,753	40,016	48,092	△ 0.03
France	27,943	28,020	31,835	30,423	△ 0.01
Canada	22,039	24,158	23,340	29,296	△ 0.02
Brazil	21,391	29,559	44,835	74,179	△ 0.09
Australia	18,895	20,368	23,143	22,872	△ 0.01
Germany	11,079	11,192	10,268	14,812	△ 0.02
China	7,197	5,192	886	354	▼ 0.18
Ukraine	5,312	11,302	15,367	25,858	△ 0.11
Kazakhstan	3,474	5,712	5,336	7,679	△ 0.05
Hungary	3,398	4,875	5,655	6,016	△ 0.04
India	3,118	819	4,770	1,173	▼ 0.06
Russia	3,362	11,261	18,732	34,319	△ 0.17
Paraguay	2,976	4,402	7,331	8,408	△ 0.07
Romania	691	1,322	4,743	11,945	△ 0.21
Turkey	1,471	2,561	2,085	3,835	△ 0.07
Others	22,170	30,292	43,827	61,964	△ 0.07
Total	**295,530**	**334,535**	**399,119**	**526,489**	△ **0.04**

2. South Korea’s Major Crop Trading Partners

2.1. Crop Self-Sufficiency and Major Imported Crops in South Korea

Crop self-sufficiency is defined as the extent to which a country can satisfy its food needs from its own domestic production (FAO, 1999). Self-sufficiency is widely recognized as an important measure representing the country’s food security level around a coming global food crisis (Choi et al., 2010). Highly dependent countries for crops, such as South Korea, have to seriously consider their food security in the future since any changes including climate change and even market prices would have a detrimental impact on these countries. The food security in South Korea is expected to become worse in the future due to its low crop self-sufficiency (Shin et al., 2018).

South Korea, with a huge population (52 million people) living in a small area (10 million ha), is a typical crop import country (Hopkinson, 2018). The area of arable land in South Korea is 0.03 ha/cap. Excluding rice paddies, the remaining area is only 0.01 ha/cap. for agriculture (KOSIS, 2018), so South Korea must import most crops. South Korea’s self-sufficiency of crops was almost 80% in the 1970s, but it dropped sharply to 43% in the 1990s (Park and Seung, 2013) when South Korea entered into the Uruguay Round Agreements. In 2017, the crop self-sufficiency of South Korea reached 23% (Figure 3) indicating that South Korea's crop import dependency was over 70%.

Based on the market database from the Agriculture Management Information System (AMIS), the international crop self-sufficiency in 2017 was 102%, on average (AMIS, 2019). Australia is a major agricultural producing and exporting country with 270% crop self-sufficiency, which was 240%p greater than South Korea. Canada and the US are also higher than the international average level at 190% and 125%, respectively. China has almost 100% crop self-sufficiency. In comparison, South Korea still has considerably low self-sufficiency. More importantly, South Korea's crop self-sufficiency ranked 32nd out of 36 member countries in Organization for Economic Cooperation and Development (OECD) (Shin et al., 2018).

Since South Korea's domestic crop self-sufficiency has become worse, there is rising demand for crop imports (Yoon et al., 2010). In addition, most (50-75%) consumed crops in South Korea have been imported to meet the difference between demand and supply over the last 30 years (Figure 3). The crop import volume has gone up 7% from 14.3 million tons in 2000 to 15.4 million tons in 2017. The volume peaked in 2015 with 16.2 million tons. Although the government of South Korea set a target of 32% self-sufficiency by the end of 2020 to improve domestic crop production (Kim et al., 2012; Kim, 2017), the current self-sufficiency of crops falls well short of the target.

South Korea is a major importing country, accounting for 6.8% (10 million tons) of global imports of crops as of 2017 (USDA, 2019a). In

2017, South Korea's self-sufficiency of crops was only 23.8% and overall food self-sufficiency was 50.2%. In particular, South Korea has to import more than 90% of its corn (99.2%), wheat (99.1%), and soybeans (93.0%). According to the trade statistics from the Korea Customs Service (KCS), imports of wheat and corn were 4.0 million tons and 10.0 million tons in 2017, respectively (KCS, 2019). It also imported 1.3 million tons of soybeans, with a domestic production of only 0.1 million tons.

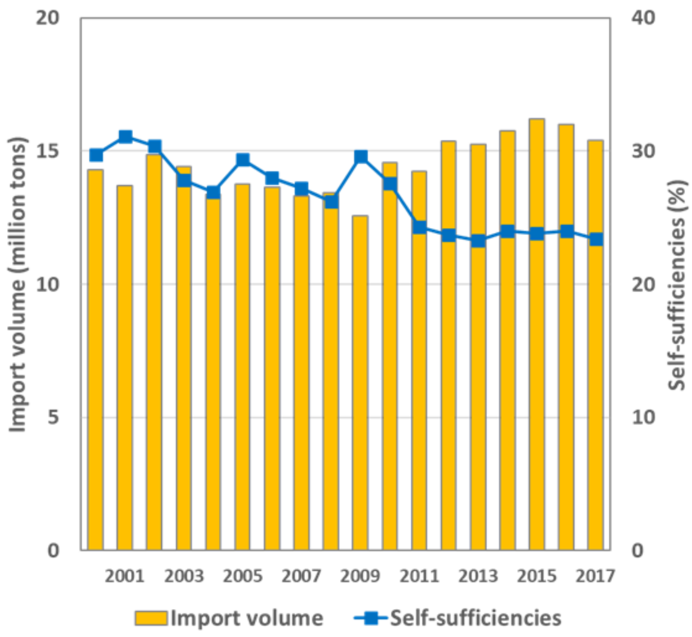


Figure 3. Crop self-sufficiency (%) and imports (million tons) in South Korea (2000-2017).

2.2. Trends of US Corn Production and Consumption

The US is a major producing and exporting country of agricultural products to South Korea, especially corn. The global corn production in 2017 was 1,135 million tons, with the US producing 371 million tons of corn, accounting for 33% of the global production (USDA, 2019a). The World Agricultural Supply and Demand Estimates (WASDE) from the US Department of Agriculture (USDA) reported that corn is the highest value crop in the US (USDA, 2019b). The value of US corn was about 52 billion US dollars in 2017, which was double and five times greater than that of soybeans (32 billion US dollars) and wheat (10 billion US dollars) (USDA, 2019c). The US produces corn in broad areas of approximately 30 million ha (NASS, 2019), which represents 20-25% of the harvested area for crops (113 million ha) and 7% of the surface area in the US (443 million ha).

Since corn needs many nutrients such as nitrogen (N), phosphorus (P), and potassium (K), it is difficult to produce in the same fields year after year (Krueger, 2018). Thus, soybeans are a good alternative to deposit nitrogen into the soil, because soybeans can fix atmospheric nitrogen and require less nitrogen to be applied to the field (Stockton and Broadhead, 2018). Thus, many farmers in the US plant corn one year and soybeans in the same field the following year. Since this approach has many agronomic benefits such as avoiding disease resistance and keeping the soil healthy, farmers commonly use corn-soybean (CS) crop rotation (Westhoff, 2010). In addition, due to the increased demand for corn ethanol, the Southeast and Midwest, US farmers often use corn-corn-soybean (CCS) crop rotation to increase corn production (Bajgain, 2018). Figure 4 illustrates the crop rotation in the US, showing trends of yields and harvested areas of US corn and soybeans for 17 years from 2000. When the corn area was expanded, the soybean area was reduced and vice versa.

The corn area and yields in 2007 were much larger than the previous years due to a sharp increase in corn prices because of the heightened demand for corn ethanol (Fortenbery and Park, 2008). This demand prompted many farmers to shift their cropland to corn from soybeans and other crops because they believed that corn prices and ethanol production would rise even further in 2007 and 2008 (Westhoff, 2010). Indeed, the corn prices were unprecedented from 2007 to early 2008 (Wallander et al., 2011), which increased input costs such as fertilizer and falling nutrients in the soil. Since corn production is more dependent on fertilizer than soybean production (Pimentel et al., 2005), higher input costs discouraged corn production and encouraged soybean production. These reasons contributed to a decrease in the corn harvested area and an increase in the soybean harvested area in 2008.

Although the corn area in 2017 was 4% smaller than in 2007, corn production costs rose by 20% from the previous 10 years from 331 million tons in 2007 (the final data point in Figure 4). This finding indicates that agricultural productivity improved through enhanced farming practices and agricultural technologies. However, corn production decreased between 2010 and 2012 even though the corn area had been steadily expanding. This decrease was due to historical droughts each summer in these years (NOAA, 2019). However, the increase in corn production seems to have recovered back to normal outputs since 2013, producing much higher production in the same area as those of 2012 (Figure 4).

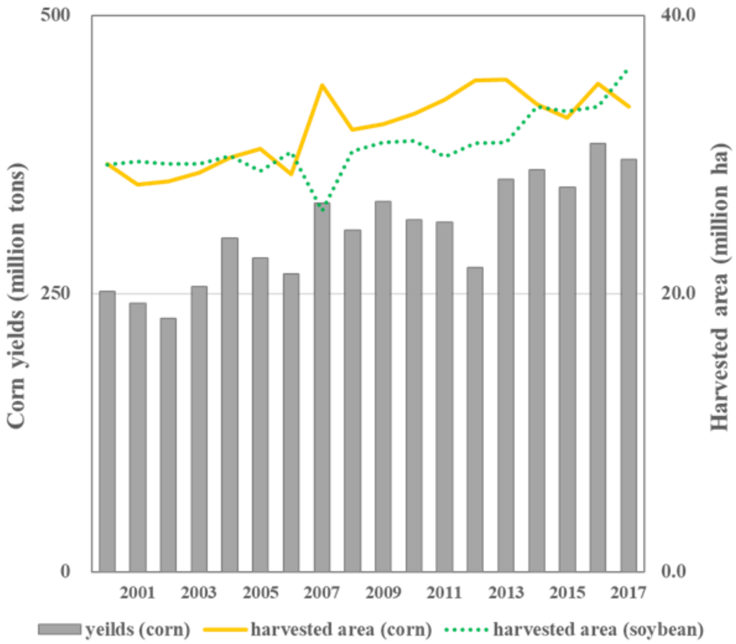
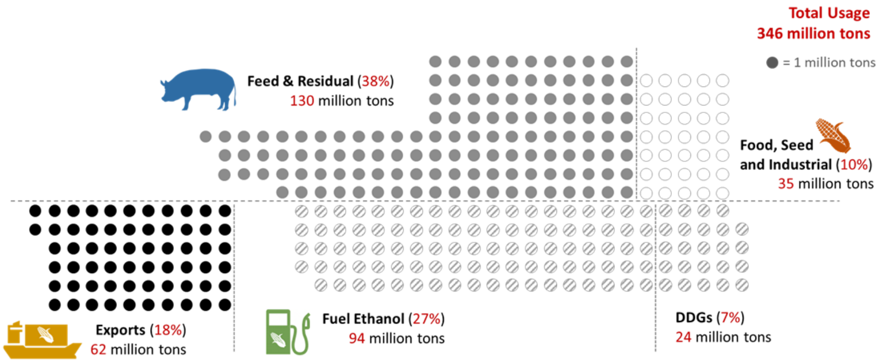


Figure 4. Change in corn yields and comparison of harvested area of US corn and soybeans (2000-2017).

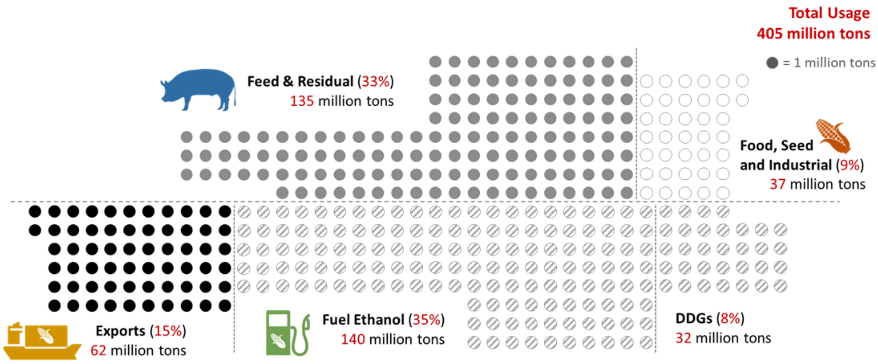
This study shows how the increase in US corn production can affect the corn demand in the US. The dataset of the World of Corn from the National Corn Growers Association (NCGA) was used to derive data for the US corn usage (NCGA, 2008; NCGA, 2018). The demand of US corn included several factors: feed and residuals; food, seed and industrial; fuel ethanol; dried distiller's grains with solubles (DDGs); and exports (Figure 5). DDGs is the nutrient rich coproduct of fuel ethanol containing 27-35% protein, and can be used as a major feed or feed ingredient (Wadhwa and Bakshi, 2016). In addition, the US government has encouraged fuel ethanol production as an alternative fuel due to the increase in fuel prices. These factors led to an increase in DDGs production.

The amount of US corn for fuel ethanol production has increased rapidly over the last decade from 2007 to 2017. In 2007, the amount of US corn for fuel ethanol production was only 27% (94 million tons) of 346 million tons of the total use of US corn. However, in 2017, it had increased to 35% (140 million tons) of 405 million tons of the total use of US corn. For the same period (2007-2017), DDGs production increased by 34% from 24 million tons to 32 million tons. The US corn usage for feed and residuals and food, seed and industrial uses also increased by 3%, respectively, but it was an insignificant rate compared to the growth of the usage for fuel ethanol production.

US corn exports were 62 million tons in both 2007 and 2017, but it does not represent a trend of exporting the same or a similar amount of US corn over time. The total amount of US exported corn was 528 million tons in the last 10 years (ERS, 2018), and the annual exports, on average, were 44 million tons, indicating that the exports in 2007 and 2017 were significantly greater than the 10-year average (2007-2017). By contrast, the US exported only 18 million tons of corn in 2012 when it had low corn production because of a severe drought. Moreover, although the exports of US corn in 2007 and 2017 accounted for each 12% of the total exports of US corn for the 10 year period, the exports in 2012 only made up 4% of the total exports. This large decrease in US corn exports due to the reduced production implies that exporting US corn has not been a priority over other uses of the corn.



(a) 2007



(b) 2017

Figure 5. US corn consumption by demand in 2007 and 2017: Feed and Residual, Dried Distiller's Grains with Solubles (DDGs), Food, Seed and Industrial, Fuel Ethanol, and Exports.

2.3. Major Importing Countries of US corn

The US is the world's largest exporting country of corn with about 30% of global corn exports, and is a major partner for South Korea's crop trade (Knoema, 2019). The US has a large potential for crop production with a low population density (0.3 people/ha) and 125% high crop self-sufficiency (AMIS, 2019). In 2016, the share of the US for traded wheat, corn, and soybeans was 13% (24 million tons), 38% (56 million tons), and 42% (58 million tons), respectively (FAO, 2019). Among these crops, South Korea has the highest import dependency on US corn.

The major importing countries of US corn are based on the US corn export data from the Economic Research Service (ERS) of the USDA (ERS, 2018). The six largest markets for US corn were Japan, Mexico, South Korea, Taiwan, China, and Venezuela, together importing 68% of the average exports (47 million tons) over the last 10 years from 2006 to 2016 (Figure 6) and almost 86% of the total US corn exports in 2012. Japan had the largest share at 21-37% and Mexico had 16-26% for the 10 year period (2006-2016). South Korea imported 3-14% of US export corn over the last decade.

The exports of US corn to China were not significant until 2010 with the exception of 2009, because China had a small gap between domestic corn prices and international corn prices. In 2009, however, the demand for corn in China rose drastically because of the growth of their livestock industry. In addition, they experienced record-breaking drought and had to import more US corn than previous years to meet the demand. China’s imports of US corn also showed a significant increase from 2011 to 2013. The international corn prices had weakened due to the increased global corn production in 2011. However, the domestic corn prices in China remained steady because of the domestic policy so they had a large gap (up to 40%) between the international and domestic corn prices. More severely, droughts occurred in Guizhou, a major corn producing state in Southwest China, in early 2011 causing China’s corn production to fall considerably. The weakening of the international corn prices and poor weather caused an increase in China’s imports of US corn over the three years from 2011.

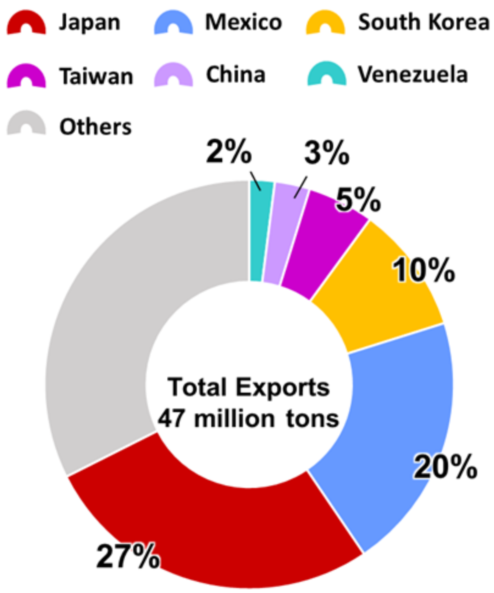


Figure 6. Major importing countries of US corn. The export volume is the 10-year average from 2006 to 2016.

3. Optimal Distribution of Major Imported Crops from Farm to Market

The optimal distribution is the most common way to decide on the best and most effective allocation of available resources within a product's supply chain. Optimization problems include maximizing and minimizing. The objective of maximizing is to maximize profits or speed, and the objective of minimizing is to minimize travel distances or transportation costs. The objective function depends on the problem being addressed and the research goals.

Most exported and imported crops must be transported over long distances from origin to destination (Conley and George, 2008; Kim et al., 2018). However, information on the distribution path of traded crops is scarce even though there is a substantial amount of data available on the international crop trade such as trade volume, exporting and importing countries, and trade value (Smith et al., 2017; Yang and Heijungs, 2017). Due to the lack of actual data on supply origins and mobility of crops, this study modeled the supply networks to estimate the optimal distribution path for the major imported crops of South Korea.

To estimate the optimal distribution path, the major imported crops were categorized into via two crop-mobility optimization models. This study models the optimal distribution considering food miles and transportation costs based on one-way transportation from the origin to the destination. The food mile minimization model connects major producing regions of the major imported crops and consumption locations in South Korea focusing on transportation stages. The cost minimization model links county-level producing regions of US corn, which has the most significant number of food miles to reach South Korea, and export ports. This model spatially links the environmental impact associated with both the production and transportation stages of corn. Details are provided in Figure 7.

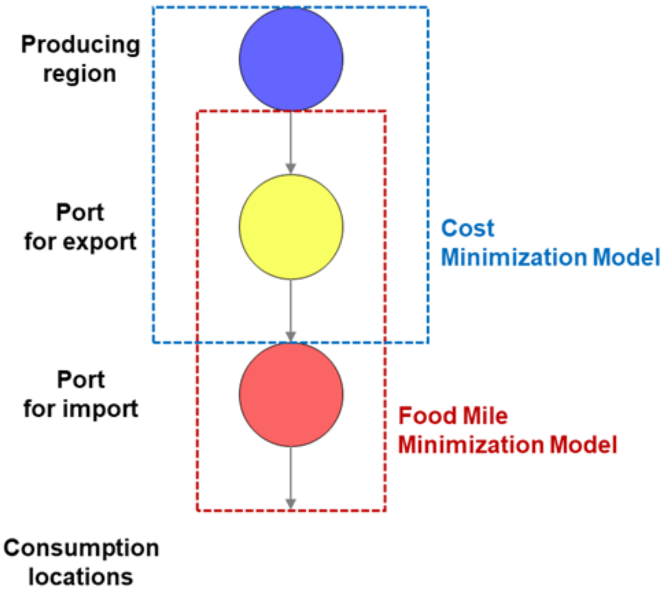


Figure 7. Graphic illustration of two optimal distribution models for major imported crops of South Korea. The food mile minimization model focuses on transportation stages. The cost minimization model includes both the production and transportation stages.

3.1. Crop Mobility Optimization from Farm to Market

3.1.1. Transport Model of Major Imported Crops for Food Mile Minimization

Definition of Food Mile. The “food mile” concept was introduced by Tim Lang in 1994 (Paxton, 1994). Food miles refers to the energy consumption along the supply chain from producer to consumer or other end-users with respect to the transportation distance and volume of food (Coley et al., 2009; Wakeland et al., 2012). Weber and Matthews (2008) explained that food miles is an indicator representing how many miles food has moved from the production point to consumption point. Ballingall and Winchester (2010) simply defined food miles as the distance food travels to the plate. The food mile measure is a representative method to assess the environmental impacts of the food trade focusing on the transportation stages (Engelhaupt, 2008).

Food miles are calculated by multiplying shipping quantity and transportation distance as shown in equation (1). Calculating the food mile indicates that transporting food from faraway places means higher number of food miles.

$$F_{ij} = Q_{ij} \times D_{ij} \qquad \textbf{Equation (1)}$$

where, F_{ij} is the food miles (ton・km) of crops from the origin point i to the destination point j; Q_{ij} is the transport quantity (ton) of crops from i to j; and D_{ij} is the transport distance (km) of crops from i to j.

Food Mile Model. To analyze the optimal distribution to minimize food miles of major imported crops, the major crops were first distributed from the major producing region in the major exporting countries to the consumption locations in South Korea. This study applied the minimum distances that could minimize the food miles of the major imported crops to estimate the mobility of crops. This minimum distance is based on a scenario that the major imported crops move the shortest distance from the production point to consumption point.

Specifically, the production point is the nearest region from the main port for export among the major producing regions of each crop of each major exporting country. The consumption point also follows this scenario. In addition, the consumption point is divided by the three types of demand of the major imported crops (market, food facility, and/or feed facility). Finally, the transportation stages include (1) land transportation from the major producing region to the main port for export; (2) maritime transportation from the main port for export to the main port for import; and (3) land transportation from the main port for import to the consumption location (Figure 8).

The World Agricultural Outlook Board from the USDA was used to compile the crops' major producing regions and the main ports for export in the US, Australia, China, and Ukraine (USDA, 2014; USDA, 2016). For Brazil, this study derived a dataset of regional crop production and the portion of exports at the port level in Brazil provided by the Van Trump Report (TVTR, 2015). The major producing regions and the export ports of imported wheat, corn, and soybeans include the following:

Wheat: the US (Montana; port of Portland, Oregon), Australia (Mallee; port of Fremantle), and Ukraine (Odessa; port of Odessa).

Corn: the US (Iowa; port of Portland, Oregon), Brazil (Panama; port of Santos), and Ukraine (Dnipro; port of Odessa).

Soybeans: the US (Iowa; port of Portland, Oregon), Brazil (Panama; port of Santos), and China (Hebei; port of Xingang).

The major imported crops were primarily transported through the port of Busan, the main port for imported crops in South Korea. The main port for Chinese soybeans was chosen as the port of Incheon with a scenario of minimum distance. This study separated the domestic transportation routes in South Korea into three categories based on the demand of the major imported crops: market, food facility, and feed facility. Imported wheat was used for food and imported corn and soybeans were split between food and feed (KCS, 2017). Thus, the consumption locations of food crops were selected as food facility (wheat) and market (corn and soybeans), and feed crops were consumed in a feed facility.

The food facility for imported wheat was selected as Daehan Flour Mills Corporation’s Busan plant, the closest location from the port of Busan among the nine milling facilities registered with the Korea Flour Mills Industrial Association (KOFMIA) (KOFMIA, 2018). The feed facility was chosen as the feed facility in Yangsan-si, Gyeongnam, which is the nearest location from the port of Busan among the 69 facilities registered with the Korea Feed Association (KFA) (KFA, 2018). For corn and soybeans used for food, the selected market based on the minimum distance scenario did not carry imported crops. Thus, the crop wholesale market in Yangjae-dong, Seoul, was selected as the end-point for corn and soybeans. The trade volumes of imported crops in the market account for more than 60% of the total trade volume.

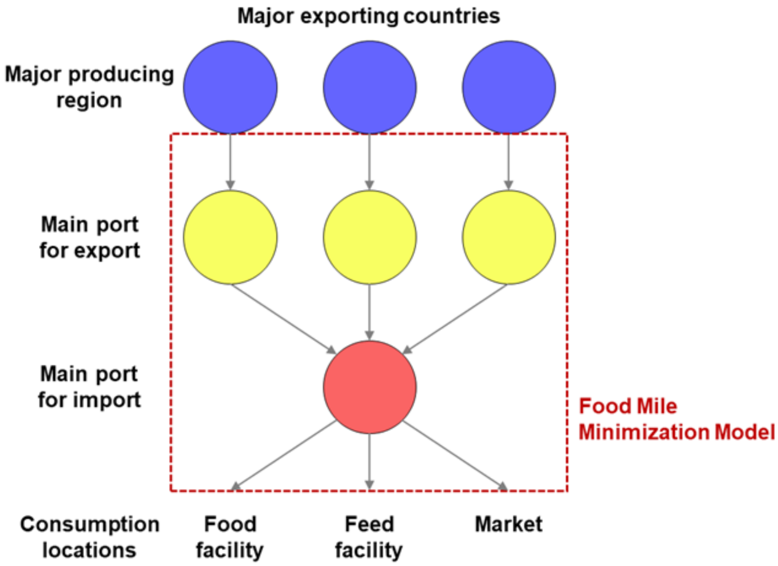


Figure 8 Graphic illustration of the food mile minimization model for South Korea's major imported crops. The major producing region is the nearest location from the main port for export. The food and feed facilities are the closest to the main port for import.

3.1.2. Cost Minimization Model for US Export of Corn

A cost minimization model was built to estimate crop mobility from fields to ports and the embedded environmental impacts of the crops including both production and transportation stages. Corn was selected as the crop to analyze the distribution path in the exporting country. South Korea has 99% import dependency and 80% import volume of corn, which is the largest share of the total imported crops in South Korea. South Korea also depends on the US for over 30% of its corn. Thus, this study analyzed county-level subnational mobility from the field to the export port to assess the environmental impacts of US export corn.

This study modeled the optimal distribution to minimize transportation costs using intermodal impedance factors from origin to destination. A simulation model was built using linear programming of the Gurobi Optimizer 6.5 for optimal allocation to minimize the transportation costs from 191 corn producing counties to 32 ports. The cost minimization model spatially links the supply chain of export ports and export corn producing counties, and their associated environmental implications. To build the model, the overall procedures are represented by equation (2) and Figure 9.

For the intermodal impedance factors, this study used the county-to-county distance matrix provided by Oak Ridge National Laboratory (ORNL) (ORNL, 2018). The ORNL dataset contains a matrix of distances and network impedances between the center of counties via highways, railroads, waterways, and combined highway-rail paths (ORNL, 2018). Among the various impedance factors, “all modes impedance” was used as the transport distance and the cost between each pair of origin counties and destination ports. The “all modes impedance” in the ORNL dataset is based on the lowest impedance path regardless of transportation mode.

In the model, origin counties were linked to each port. Therefore, the types of transportation mode between the two points (an origin county-destination port pair) were decided using the miles and impedance factors from the ORNL dataset. Specifically, if the “W-mi” (water miles) factor existed and the land-miles factor was zero, the barge (waterway) was determined as the transportation mode. The opposite case would be that truck (highway) or rail (railroad) was used for land transportation. Between truck and rail, this study compared “H-imp” (highway impedance) and “R-imp” (rail impedance) to determine the more efficient (smaller impedance factor) transportation mode between truck and rail.

$$\text{Minimize: } \sum_{i=1}^{n}\sum_{j=1}^{n} I_{ij} \times Q_{ij}^{*}, \qquad \textbf{Equation (2)}$$

Subject to:

$$\sum_{i=1}^{n} Q_{ij}^{*} = Q_j^E, \text{ for } j = 1, ..., n$$

$$\sum_{j=1}^{n} Q_{ij}^{*} \leq Q_i^S, \text{ for } i = 1, ..., n$$

$$Q_{ij}^{*} \geq 0, \text{ for } i = 1, ..., n \text{ and } j = 1, ..., n$$

where, I_{ij} is the all-modes impedance between county i and county j, Q_{ij}^{*} is the quantity of exported corn (kg) transported from the origin county (corn producing county) i to the destination county (export port) j. Q_j^E is the amount of corn exported at the port j and Q_i^S is the supply of corn from origin county i.

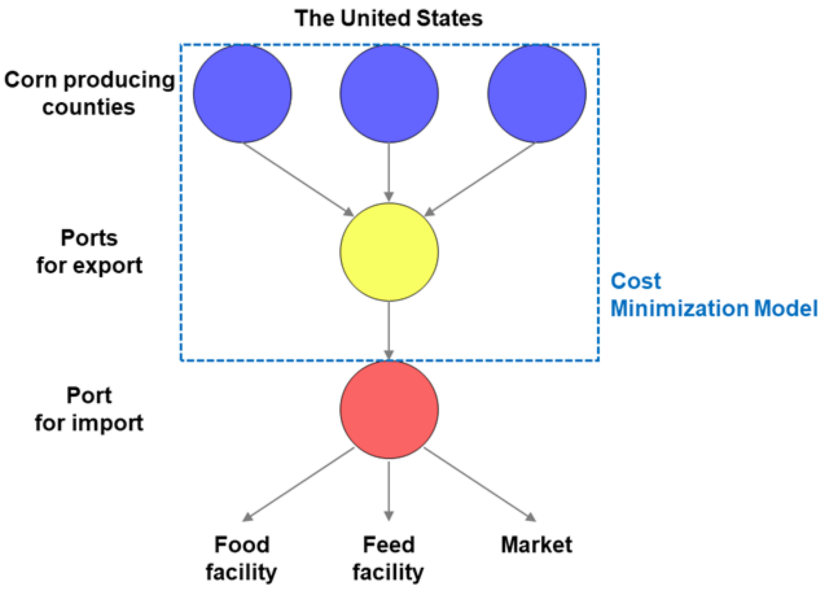


Figure 9. Graphic illustration of cost minimization model for US export corn supply.

3.2. Major Imported Crop Data Accounting

3.2.1. Supply and Demand of Major Imported Crops

The food miles for major imported crops in South Korea was estimated for 2015 and 2017. The trade statistic of the Korea Customs Service (KCS) was used to compile the major imported crops in South Korea (KCS, 2019). The year 2015 had the largest amount of overall crops imported over a 17 year period (see Figure 3), with 2017 being the most recent data available in the KCS. This study grouped crop demand into two categories: food crops and feed crops. The major exporting countries for the major imported crops were chosen based on the top three countries exporting to South Korea. The imports of major imported crops and major exporting countries in 2015 and 2017 are presented in Figure 10. The major exporting countries were the same in both years.

Imported Wheat. More than 99% of the wheat consumed in South Korea came from other countries. The overall imported wheat was used for food such as noodles and bread in 2015 and 2017 (see Table 3). The wheat imports were 4.0 million tons in 2015, which were 0.2 million tons less than 2017. The imports from the US, Australia, and Ukraine were 3.0 million tons overall (76% of total imports in 2015) (Table 3) and the 4.2 million tons of wheat were imported from the same top three countries and other countries in 2017.

These three major exporting countries occupied about 80% of the total amount of imported wheat of South Korea in 2015 and 2017. South Korea’s wheat imports slightly increased in 2017 compared to 2015, even though domestic production of wheat rose by 42.3% from 26 thousand tons in 2015 to 37 thousand tons in 2017 (KOSIS, 2019). However, since increased domestic consumption was much larger than the higher production, the increase in wheat imports surged drastically.

Imported Corn. The total corn imports were 10.3 million tons in 2015, with 78% (8.2 million tons) of the total imports from the US, Brazil, and Ukraine, the major exporting countries. In 2017, the total corn imports were 9.3 million tons, a 10% decrease compared to 2015. In 2017, 6.5 million tons, 70% of the total amount of imported corn, was imported from the major exporting countries. The imports of US corn increased 1.0 million tons from 2015; however, the imports from Brazil and Ukraine both declined to 3.0 million tons and 1.6 million tons, respectively (Figure 10).

The imported corn from the major exporting countries was mostly consumed for food (15%) and feed (85%) in 2015 and 2017. The demand for imported corn from the major exporting countries was as follows: the US (for food: 13%, for feed: 87%), Brazil (for food: 13%, for feed: 87%), and Ukraine (for food: 17%, for feed: 83%) in 2015. In 2017, exporting countries included the US (for food: 17%, for feed: 83%), Brazil (for food: 13%, for feed: 87%), and Ukraine (for food: 16%, for feed: 84%).

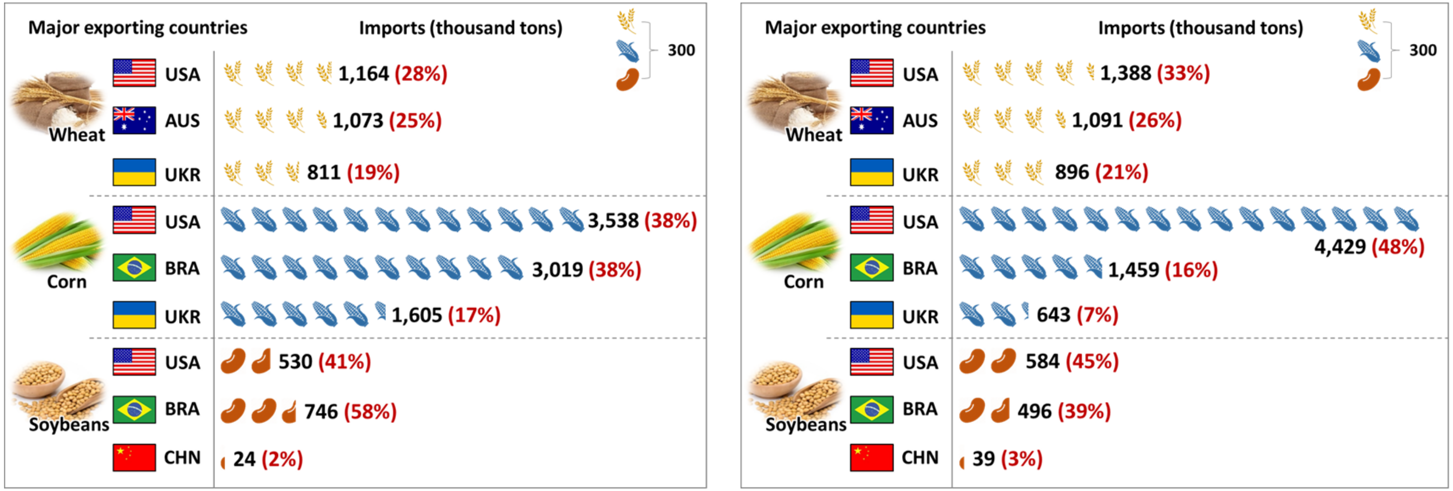
Imported Soybeans. The major exporting countries for soybeans in

2015 and 2017 were the US, Brazil, and China, totaling 98% of the 1.3 million tons of total imports in 2015 and 87% of 1.3 million tons in 2017. The demand for imported soybeans was separated into food (20%) and feed (80%) in the given two years. However, the imported soybeans from the US to South Korea were had the only ones classified by use for feed (53% in 2015 and 67% in 2017). The overall soybeans imported from Brazil were for feed, and soybeans from China were for food.

Among the major imported crops, the imports of wheat in South Korea grew by 9% from 2015 to 2017; however, corn and soybeans imports declined by 20% and 14%, respectively, in the same period. In particular, for imported corn and soybeans, the percentage for feed declined by 22% and 14%, respectively. This reduction could have been affected by the change in livestock imports. The import volumes of livestock increased by 8% from 991 million tons to 1,074 million tons between 2015 and 2017 (APQA, 2019).

Table 3. Imports (thousand tons) of major imported crops in South Korea from major exporting countries in 2015 and 2017. By use, crops were divided into two categories: food crops and feed crops.

Crops	2015			2017			Differences in total imports
	Food	Feed	Total	Food	Feed	Total	
Wheat	3,048	-	3,048	3,376	-	3,376	△ 9%
Corn	1,119	7,043	8,162	1,055	5,476	6,531	▼ 20%
soybeans	277	1,023	1,300	235	884	1,119	▼ 14%



(a) 2015 (b) 2017

Figure 10. Imports of wheat, corn, and soybeans from each major exporting country in 2015 and 2017. Major exporting countries in both years were the United States (USA), Australia (AUS), Ukraine (UKR), Brazil (BRA), and China (CHN). The percent beside the imports indicates the portion of the imports from each exporting country.

3.2.2. Transportation Modes and Distances for the Transportation Stage of Major Imported Crops

Transportation Modes for Food Miles. The food mile measurement can be simplified as a single environmental indicator focusing on the transportation stages of food. A higher number of food miles, however, does not represent greater environmental impact trends. The environmental impact and fuel consumption of the food trade are highly dependent on the transportation mode (Smith et al., 2005). Therefore, the impact of different transportation modes (i.e., land and waterway) must be considered for the different transportation stages to evaluate the environmental impact of food miles. This study suggests how to evaluate the environmental impacts of food miles as in equation (3).

$$E_f = \sum_{k=1}^{n} (F_{ij,k} \times e_{l,k}) \qquad \textbf{Equation (3)}$$

where, E_f is the total environmental impacts (kg impacts) by food mile; F_{ij} is the food mile (ton・km) of crops from i to j; k is the transportation stage such as origin-to-port, port-to-port, and port-to-end; e is the environmental impact per ton・kilometer (kg impacts/ton・km); l is the transportation mode such as truck, rail, barge (on land), and bulk commodity carrier (oceangoing) by each transportation stage.

Various Transportation Modes for Each Stage. The transportation modes were chosen based on the transportation stages of land transportation in the major exporting countries, maritime transportation between the ports, and land transportation in South Korea. The transportation modes with rail and truck are the main modes of transportation by land (Envision Transportation, 2011).

Rail is commonly used for crop transportation in the US, Australia, and China since the crops in these countries have to travel long distances and these countries have sufficient freight infrastructure (DIRDC, 2009; Sparger and Nick, 2015). In Ukraine, truck is used as more efficient mode for crops than rail. Although they have a relatively good railway system to transport freight, the railways are concentrated in other regions not the major crop producing regions of the country (CTS, 2014). The crops in Brazil are mainly transported by truck because of the poor infrastructure (Park, 2013).

For the maritime transportation, the bulk-commodity carrier (BCC) was selected as the transportation mode since most crops are put on bulk-model ships (Kosior et al., 2002; Denicoff et al., 2014). The domestic transportation for crops in South Korea was by truck considering the higher efficiency and penetration of trucks compared to other modes such as rail and barge (waterway).

Traveling Distances of Major Imported Crops. The most direct route from Google Maps was used to determine the shortest distance from the midpoint of the major producing region to the export port (Google Maps, 2018). The shipping distances for maritime stage were based on the suggested path by Searates (Searates, 2018). Searates provides a Great Circle Route based on the optimal shipping path using their optimization system considering types of freight and ship, load capacity, and origin and destination. The Great Circle Route means the optimal route that can minimize both the shipping distance and fuel consumption during maritime transportation. This study inputs the type of crops and BCC into the system. Finally, the directions using a map from Naver Corporation was used to estimate the most direct route from the import port to the consumption location.

The major imported crops traveled, on average, about 13,000 km (8,078 miles (mi.)) to reach the consumption locations from the production point. However, there were significant differences in the transportation distances of major imported crops. Imported soybeans from China moved the shortest distance at 1,213 km (754 mi.) and corn and soybeans transported from Brazil traveled the longest distance: 22,186 km (13,786 mi.) (Figure 11). Among the major imported crops, corn traveled the longest distance of 50,000 km (31,069 mi.). Imported wheat and soybeans were shipped 37,000 km (22,991 mi.) and 34,000 km (18,645 mi.), respectively.

Wheat from Ukraine was mainly produced in Odessa and the distance from the midpoint of Odessa to the port of Odessa was only 4 km (2 mi.). However, wheat from Australia moved a long distance of 2,962 km (1,840 mi.) for the land transportation, because the major producing region of the Australian wheat was located at the opposite side of the country from the main port (Mellee). The transportation distance of Australian wheat was more than double the average traveling distance (1,184 km, 736 mi.) for land transportation to export the major imported crops. The US crops moved relatively long distances of 1,306 km (812 mi., wheat) and 1,924 km (1,196 mi., corn and soybeans). The crops that traveled the shortest distances (less than average) was Chinese soybeans (343 km, 213 mi.), Brazilian corn and soybeans (834 km, 518 mi.), Ukrainian corn (834 km, 518 mi.) and Ukrainian wheat (4 km, 2 mi.).

The traveling distance of maritime transportation accounted for 70-99% of all transportation distances for major imported crops (see Figure 11). Brazil is the most farthest away from South Korea. Thus, the Brazilian crops had to travel the longest shipping distance of 20,000 km (12,427 mi.), which was considerably more than from other countries. The shipping distances of the US and Australian crops were each 8,000 km (4,971 mi.). Although the direct distance (also called the flight distance) between Ukraine and South Korea is about 7,000 km (4,350 mi.), when crops were transported by ship, the crops from Ukraine had to go around Africa. Thus, they traveled a substantially long distance of 16,038 km (9,966 mi.) to arrive in South Korea.

For the land transportation stage in South Korea, Daehan Flour Mills Corporation’s Busan Plant was 7 km (4 mi.) away from the port of Busan and the selected feed facility for feed crops was located 37 km (23 mi.) from the port. The distance between the market for food crops and ports of Busan and Incheon was 377 km (234 mi.) and 44 km (27 mi.), respectively.

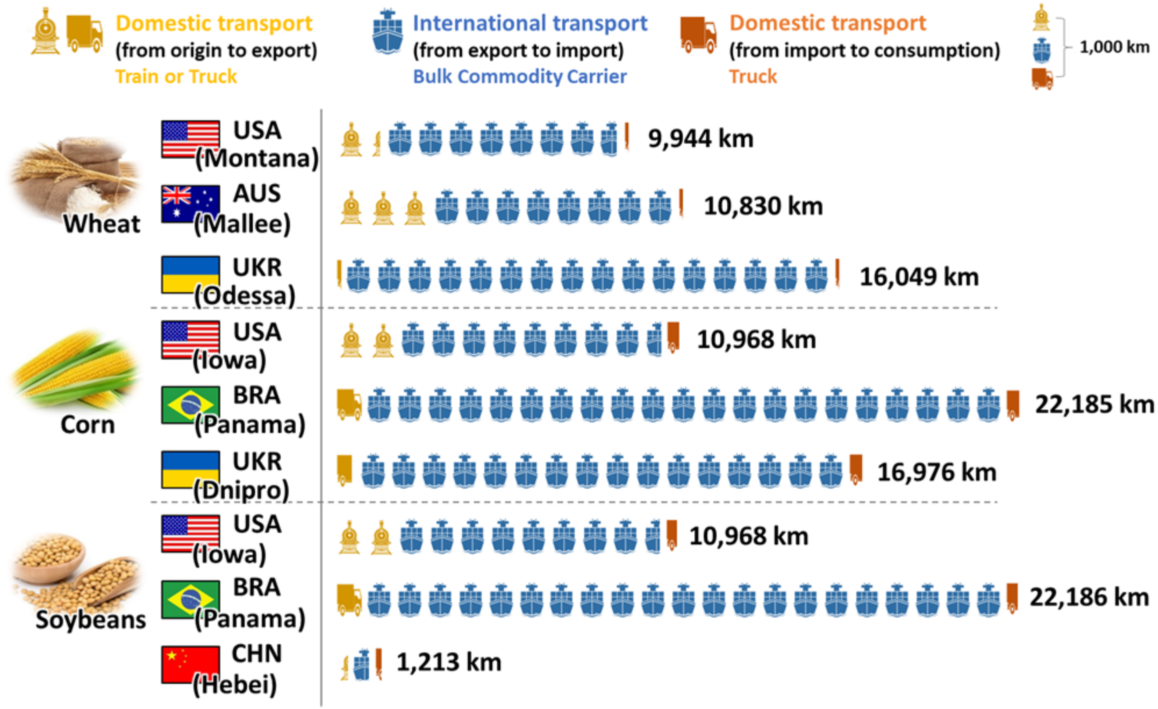


Figure 11 Transportation modes and distances by transportation stage for imported wheat, corn, and soybeans of South Korea: the United States (USA), Australia (AUS), Ukraine (UKR), Brazil (BRA), and China (CHN). The state listed below the nation indicates the major producing region.

3.2.3. Supply Data for US Corn Export

County-level Corn Production. The Census of Agriculture (COA) from the USDA was used to derive data for corn production at the county level for 2012 (COA, 2018). This census is conducted every five years by the USDA and 2012 is the most recent data available in the COA (COA, 2018). To compile the data for corn producing counties for export, this study referred to Smith et al.'s (2017) study, which introduced the US corn allocation model using supply and demand data accounting. The exported corn was produced in 191 counties in 2012 and most counties were located in traditional area in the Midwestern US, known as the Corn Belt.

Port-level Corn Exports. The amount of exported corn at the port level in the US was estimated to build the county-to-port supply chain of US corn. To estimate the port-level exports of US corn, this study used total exports (ton) of US corn in the 2012-2013 Marketing Year (MY) as made available by the Economic Research Service (ERS) of the US Department of Agriculture (USDA) (ERS, 2018). The dataset of the corn export value (US dollars) by port from the USA Trade Census of the US Department of Commerce (USDC) was also used to estimate the amount of corn exports at the port level (UStrade, 2018). The Dataset of the quantified corn trade volume and value of the ERS and the US Trade Census is based on the USDA Federal Grain Inspection Service and the US Import and Export Merchandise Trade Statistics, respectively.

The corn exports of all 32 ports for exported corn from the US were estimated by applying the portion of the export value of the total export value (US dollars) for corn in each port. More specifically, the export value for the port of New Orleans for 2012-2013 MY was 5.3 billion US dollars, which is 56% of the total export value of 9.4 billion US dollars (UStrade, 2018). Accordingly, the estimated amount of exported corn from the New Orleans port was 10.4 billion kg, 56% of 18.5 billion kg of the total corn exports (ERS, 2018). This estimate shown in Table 4. Finally, the US Trade Census dataset was used to determine the export ports for the major importing countries, including South Korea.

Table 4 Estimates of the port-level export volume of US corn (kg) based on the ratio of the port-level export value (US dollars).

Ports (County, State)	Export value (thousand US dollars, %)	Export volume (thousand kg)
New Orleans, LA	5,278,680 (56.1)	10,404,127
Seattle, WA	1,118,510 (11.9)	2,204,552
Laredo, TX	995,910 (10.6)	1,962,911
El Paso, TX	770,212 (8.2)	1,518,065
Portland, OR	634,972 (6.7)	1,251,512
Los Angeles, CA	207,909 (2.2)	409,782
Houston-Galveston, TX	111,390 (1.2)	219,546
Pembina, ND	110,511 (1.2)	217,814
Norfolk, VA	48,896 (0.5)	96,373
Detroit, MI	29,737 (0.3)	58,610
San Francisco, CA	25,855 (0.3)	50,960
San Diego, CA	19,921 (0.2)	39,263
New York City, NY	13,907 (0.1)	27,411
Mobile, AL	9,711 (0.1)	19,141
Port Arthur, TX	9,390 (0.1)	18,507
Savannah, GA	4,221 (0.0)	8,320
Buffalo, NY	3,946 (0.0)	7,777
Cleveland, OH	3,332 (0.0)	6,567
Ogdensburg, NY	2,612 (0.0)	5,147
Great Falls, MT	2,448 (0.0)	4,826
Milwaukee, WI	2,271 (0.0)	4,475
Miami, FL	2,110 (0.0)	4,159
Philadelphia, PA	1,275 (0.0)	2,513
Duluth, MN	910 (0.0)	1,794
Baltimore, MD	145 (0.0)	285
Tampa, FL	85 (0.0)	168
Nogales, AZ	62 (0.0)	123
Chicago, IL	30 (0.0)	59
Charleston, SC	26 (0.0)	51
Portland, ME	24 (0.0)	48
Dallas-Fort Worth, TX	21 (0.0)	42
Boston, MA	17 (0.0)	33
Sum	**9.409.044 (100.0)**	**18,544,959**

4. Environmental Life-Cycle Assessment on Transportation Stages of Imported Crops

4.1. Introduction of Environmental Life-Cycle Assessment

Life-Cycle Assessment (LCA) is a systematic analysis to evaluate the environmental implications of inputs and outputs of products throughout the of life cycle. The International Organization for Standardization (ISO) issued standards and reports for the LCA process (ISO, 1997). The ISO 14040 series defines the LCA as follows.

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by 1) compiling an inventory of relevant inputs and outputs of a product system; 2) evaluating the potential environmental impacts associated with those inputs and outputs; and 3) interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave, cradle-to-gate, gate-to-gate) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.

As referred to in the 14040 series, LCA standards describe the four phases of an LCA study framework (Figure 12) including the following:

1) **Goal and Scope Definition**: identifying the purpose, system boundary, functional unit, and level of detail;
2) **Life-Cycle Inventory (LCI) Analysis**: compiling inputs and outputs with regard to the system;
3) **Life-Cycle Impact Assessment (LCIA)**: evaluating the potential impacts associated with the life-cycle inventory results;
4) **Interpretation**: interpreting the results in accordance with the goal and scope definition.

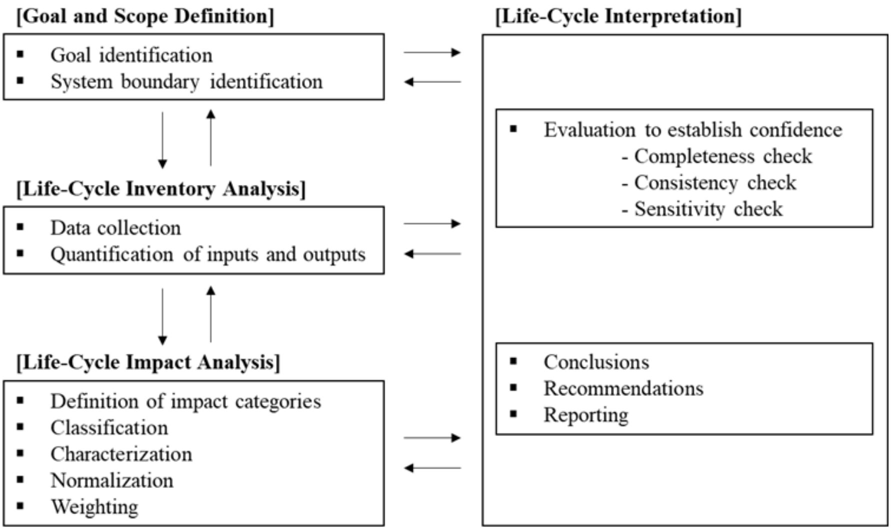


Figure 12 Life-cycle assessment (LCA) framework defined by the International Organization for Standardization (ISO) 14040. The arrows indicate that each step is iterative due to the uncertainty of the results.

4.2. Goals and Scope Definitions of the Crop Trade

The “Goal and Scope Definition” step is the starting point of the LCA. In this step, the purpose of the study must be clearly identified, and the product system, system boundary, and functional unit are defined for the assessment.

The system boundary is established from various perspectives of the product’s life cycle. The perspective on cradle-to-grave includes overall procedures from raw materials acquisition (cradle) to disposal (grave) throughout manufacturing, distribution, consumption and recycling. The cradle-to-gate is a perspective on a partial product life cycle from the cradle to a particular point (gate) such as a facility. The system boundary of this study focuses on the gate-to-gate perspective (producing region-to-consumption locations) for the production and transportation stages of major imported crops (Figure 13).

The functional unit is a quantified description of the service provided by the product system and provides a reference to which the inputs and outputs are related (ISO, 2006). In the LCA study on the transportation mode for the food trade, the functional unit represents the per unit food mile (e.g., 1 ton·km of transportation) (Meisterling et al., 2009; Fries and Hellweg, 2014; Kalluri, 2016; Merchan et al., 2017; Kim et al., 2018). Therefore, the environmental implications of the transportation modes in this study are all evaluated on a ton·km basis.

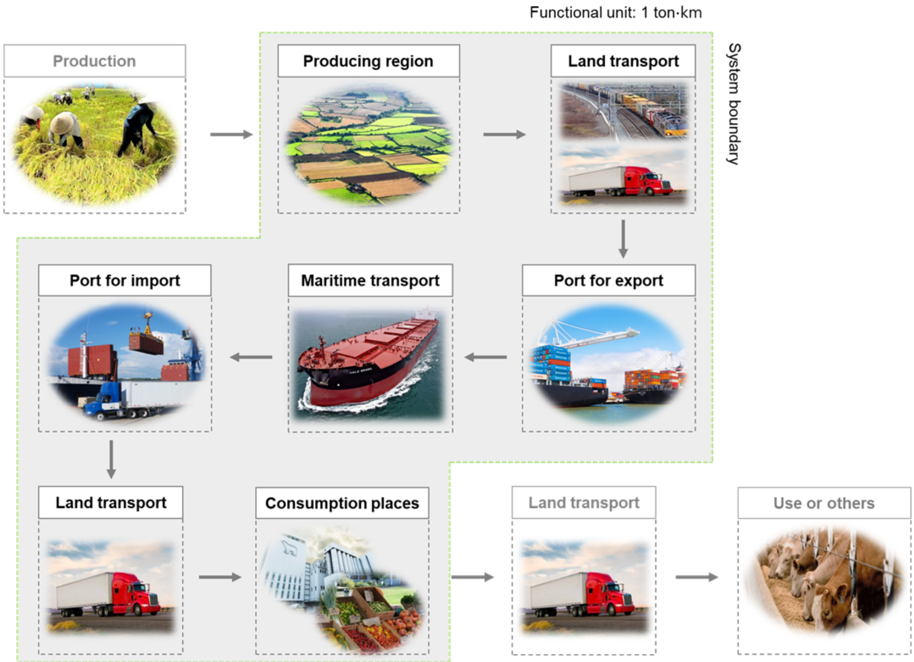


Figure 13 System boundary of the transportation stages of major imported crops: Gate-to-gate perspective.

4.3. Life Cycle Inventory Analysis of Imported Crops

The LCI analysis is used to quantify the energy use and raw material inputs and environmental emissions and other elements released into the air, land and water for the overall life cycle of a product. The inventory analysis involves data collection and compilation of data in an LCI table. This process is iterative because the new data requirements or limitations could be identified in the data collection and calculation procedures.

To evaluate the environmental implications of food miles considering the transportation modes, the Ecoinvent database was used (Ecoinvent, 2019), which provides the LCI for several types of transportation modes. The transportation modes were selected on the bulk model, which is commonly used for crop distribution (Denicoff et al., 2014). The selected models of each mode are as follows:

---

1) for the land transportation:

Truck: US heavy/bulk

Rail: Rail transport cargo-diesel, extra-large train

2) for inland-waterway transportation:

Barge: inland

3) for the maritime transportation:

Bulk-commodity carrier (BCC): average, oceangoing

4.4. Life Cycle Impact Assessment of the Production and Transportation Stages of Traded Crops

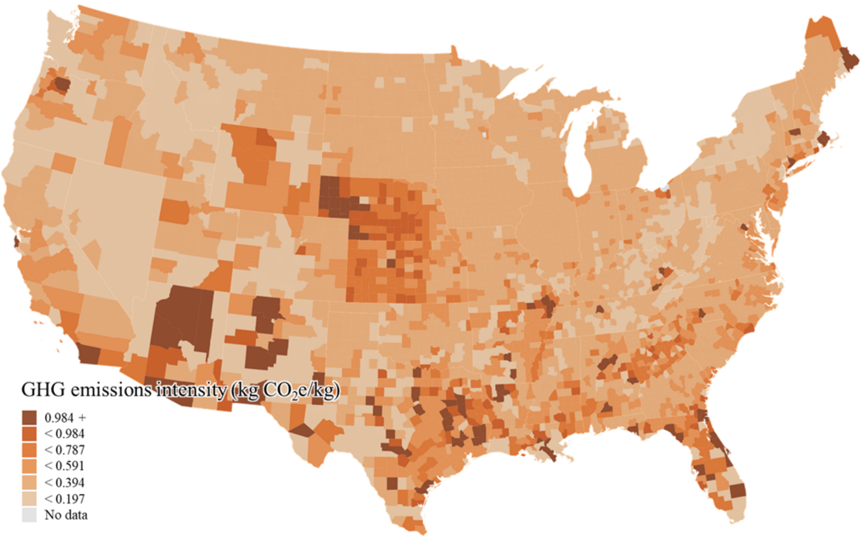
The Life-Cycle Impact Assessment (LCIA) phase evaluates the potential human and environmental effects identified in the LCI results by translating the inventory data into indicators of environmental impact (ISO, 2000). The LCIA includes four steps: classification, characterization, normalization, and weighting. The goal of classification is to assign and possibly combine the LCI results to one or more environmental impact categories. The characterization step describes and quantifies the environmental impact of the product system. Impact characterization uses science-based conversion factors, also called as characterization factors, to convert and combine the LCI results into representative indicators of impacts on environment and human health. Normalization and weighting are optional steps. Normalization is used to express the impact indicator in a way that can be compared to impact categories. The weighting step assigns weights or relative values to the different impact categories based on their importance and is used to compare the impact indicators.

This study focused on the characterization step to analyze the environmental impact of transportation processes. GaBi software, LCA software, was used to assess the environmental impact of the transportation modes. The impact categories were greenhouse gas (GHG) emissions and fine particulate matter (fine PM, $PM_{2.5}$) per ton·km of each transportation mode provided by the LCIA Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (EPA, 2017). $PM_{2.5}$ is a pollutant that has rapidly become a critical issue for human health, especially cardiovascular and respiratory systems, and the overall environment around the world (Kampa and Castanas, 2008). GHG emissions are being discussed as a climate change issues since it has a significant impact on global warming (IPCC, 2007; EIA, 2018).

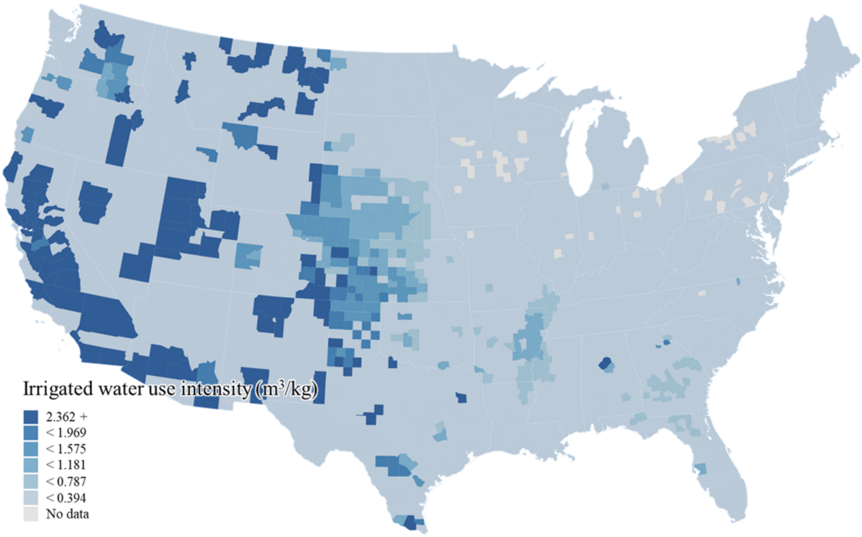
To evaluate the environmental impact of US corn production, this study referred to Smith et al.'s (2017) study, which provides spatial LCA that considers corn production practices associated with GHG emissions and irrigated water use across US corn-producing counties. They captured the substantial spatial variation of county nitrogen application rates, types of nitrogen fertilizer used, direct and indirect nitrous oxide emissions, and irrigation quantity. Agricultural production accounts for about 70% of the global water withdrawals and water in agriculture is expected to continue to play an important role in the future (Chaves and Oliveira, 2004; Rosegrant et al., 2009; Hoekstra et al., 2012). Irrigation practices are the primary driver of the decision to anthropogenic water use considering spatial variations (Kerridge et al., 2008; Chukalla et al., 2015). Thus, irrigated water use is suitable as data on the spatial differences of water use for county-level corn production.

Smith et al.'s (2017) results revealed that the variability of county-level GHG emissions intensity of corn production is substantial

(Figure 14(a)), ranging from as low as 0.144 kg CO_2e/kg to as high as 11.260 kg CO_2e/kg (on average, 0.504 kg CO_2e/kg). Their analysis also showed that the county-level irrigated water use was 0.221 m^3/kg on average. However, some counties relied heavily on irrigation, as high as 46.750 m^3/kg, whereas other counties used very little or no irrigated water in the given years (Figure 14(b)). Based on the county-level environmental implications and supply-chain model, this study estimated GHG emissions and irrigated water use of corn supplied to each port for export.



(a) GHG emissions intensity of one kilogram of corn production (kg CO_2e/kg)



(b) Irrigated water use intensity of one kilogram of corn production (m^3/kg)

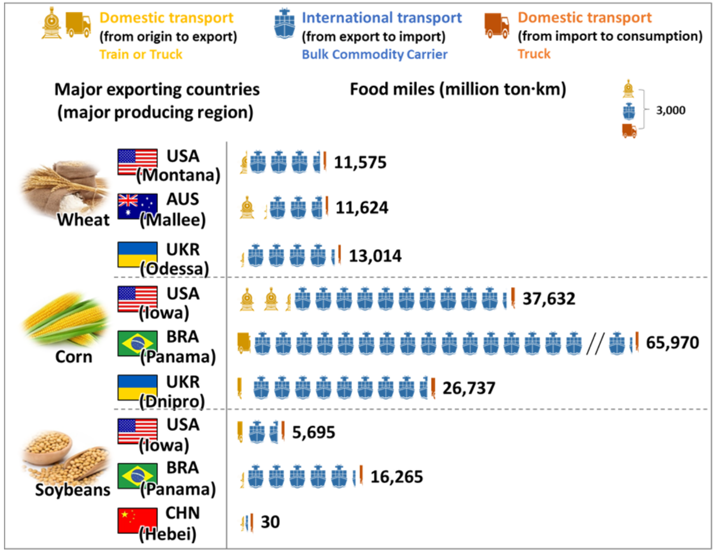
Figure 14 Spatial variation of greenhouse gas (GHG) emissions and irrigated water use intensity associated with one kilogram of corn production at the county level in the US in 2012.

Chapter IV. Results and Discussion

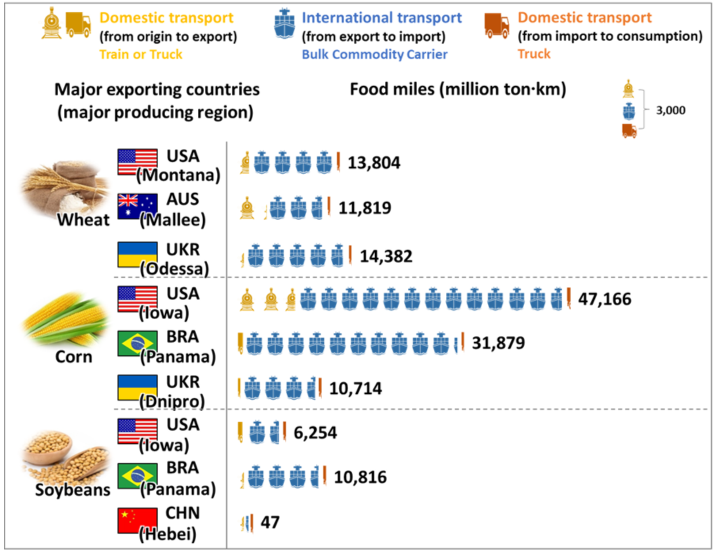
1. Environmental Impacts of Food Miles for Transportation Stages of Major Imported Crops

1.1. Food Miles of Major Imported Crops

The food miles of major imported crops in South Korea were calculated and compared based on the import amount and shipping distance in 2015 and 2017 (Figure 15). The food miles of the major crops in 2015 was 189 billion ton·km, which was 28% larger than 2017 at 147 billion ton·km. The major trade partners of the crops and their major producing region were the same in 2015 and 2017. This indicates that the difference in the food miles between the two years 2015 and 2017 was affected by changes in imports of the major crops. The imported crops were 13 million tons in 2015 and 11 million tons in 2017, which was 10% less than those of 2015 (see Figure 4). The estimated food miles per capita in South Korea for the crops was 2,856 ton·km/cap. in 2017, which was 30% less than the food miles per capita in 2015 (3,705 ton·km/cap.).



(a) 2015



(b) 2017

Figure 15 Food miles (million ton · km) for imported wheat, corn, and soybeans from each major exporting country to South Korea in 2015 and 2017. The major exporting countries in both years were the United States (USA), Australia (AUS), Ukraine (UKR), Brazil (BRA), and China (CHN) and the state listed below the name of nation was the major producing region.

Since wheat imports were relatively low compared to the amount of imported corn, the food miles of wheat was also lower than that of corn. Wheat imports increased by 13% from 3.0 million tons in 2015 to 3.4 million tons in 2017 and the food miles also rose by 11% for the two years (2015-2017) from 36 billion ton·km to 40 billion ton·km. US wheat occupied the largest share of imported wheat in South Korea, but Ukraine had the highest food miles. Ukrainian wheat traveled a relatively long distance of 16,049 km (9,972 mi.) compared to 9,944 km (6,179 mi.) of shipping distance of US wheat. This long distance made Ukrainian wheat the most wheat food miles, accounting for the largest share (36%) for all imported wheat in South Korea. The food miles of US wheat had the most significant change, expanding to 13.8 billion ton·km from 11.5 billion ton·km, with the imports in 2017 increasing 20% from 2015.

Among the major imported crops, corn had the most severe food miles. The overall food miles for imported corn declined by 44% from 130 billion ton·km in 2015 to 90 billion ton·km in 2017. In contrast, the food mile of US corn rose by 24% from 38 billion ton·km to 47 billion ton·km in the same period. Brazil and Ukraine were the main drivers of the decrease in corn food miles. The food miles for corn from these two countries diminished by 50%, respectively, and the shipping distance of Brazilian (22 thousand km) and Ukrainian corn (17 thousand km) was 50% and 100% longer than that of US corn (11 thousand km), respectively (Table 5). This wide difference in traveling distance of the countries and reduced food miles of corn from Brazil and Ukraine caused the decrease in food miles for the total imported corn.

The imports of soybeans from the major exporting countries decreased only 18% (2 million tons) from 1.3 million tons in 2015 to 1.1 million tons in 2017. However, the ratio of reduced food mile was even larger than that of other imports. The reduction of food mile was 30% (5 billion ton·km) from 22 billion ton·km to 17 billion ton·km in the two years. US soybean imports were up slightly (10%) and Chinese soybean imports increased sharply (60%) from 2015 to 2017. While the imports from Brazil, which was 22 thousand km from South Korea, decreased by 50%. The decline in food miles could be influenced by the change in the import amount of Brazilian soybeans. Despite the reduced imports in Brazilian soybeans, Brazil continued to have the most food miles, accounting for 63% of food miles for all imported soybeans in 2017.

Table 5 Data used to calculated food miles of imported wheat, corn, and soybeans in South Korea in 2015 and 2017: The major exporting countries were the United States (USA), Australia (AUS), Ukraine (UKR), Brazil (BRA), and China (CHN). The state listed below the nation was the major producing region.

Crops	Major exporting countries	Transportation volume (thousand tons)						Transportation distances (km)					
		2015			2017			land[a)]	ocean	land[b)]			sum
		food	feed	sum	food	feed	sum			food	feed	subsum	
Wheat	USA (Montana)	1,164	0	**1,164**	1,388	0	**1,388**	1,306	8,631	7	0	7	**9,944**
	AUS (Mallee)	1,073	0	**1,073**	1,091	0	**1,091**	2,962	7,861	7	0	7	**10,830**
	UKR (Odessa)	811	0	**811**	896	0	**896**	4	16,038	7	0	7	**16,049**
Corn	USA (Iowa)	461	3,077	**3,538**	760	3,669	**4,429**	1,924	8,631	377	37	414	**10,968**
	BRA (Panama)	383	2,636	**3,019**	192	1,267	**1,459**	834	20,938	377	37	414	**22,185**
	UKR (Dnipro)	275	1,331	**1,605**	104	539	**643**	524	16,038	377	37	414	**16,976**
soybeans	USA (Iowa)	250	280	**530**	196	388	**584**	1,924	8,631	377	37	414	**10,968**
	BRA (Panama)	0	746	**746**	0	496	**496**	834	20,938	377	37	414	**22,186**
	CHN (Hebei)	24	0	**24**	39	0	**39**	343	825	44	0	44	**1,213**

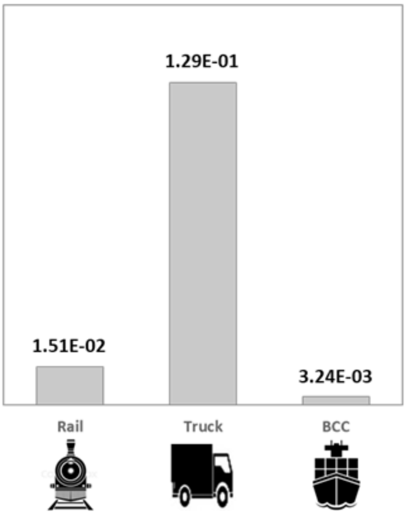
a) The land transportation from field to export
b) The land transportation from import to consumption locations

1.2. GHGs and PMs of Various Transportation Modes

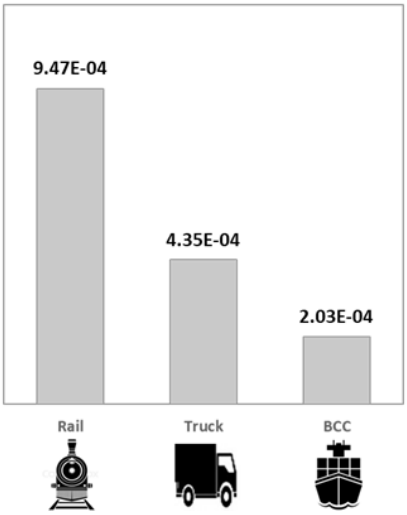
This study selected two environmental categories to evaluate the environmental impacts per unit food mile considering transportation modes (Figure 16). The GHG and $PM_{2.5}$ emissions are two major contributors to climate change and have become a significant indicators of human health and environmental issues. To evaluate the environmental implications of food mile for the major crops, this study calculated the food miles and analyzed the impact of each transportation mode (truck, rail, and BCC). The environmental impact categories for transportation stages were GHG and $PM_{2.5}$ emissions per ton·km shipping of each transportation mode.

The GHG emissions of truck transportation was 1.29e-01 kg CO_2e/ton·km, which was 753% and 3,875% higher than those of rail (1.51e-02 kg CO_2e/ton·km) and BCC (3.24e-03 kg CO_2e/ton·km), respectively (Figure 16(a)). However, the $PM_{2.5}$ emissions of truck (4.35e-04 kg $PM_{2.5}$e/ton·km) was 118% less than those of rail (9.47e-04 kg $PM_{2.5}$e/ton·km). The $PM_{2.5}$ emissions of BCC is 2.03e-04 kg $PM_{2.5}$e/ton·km, which was 367% less than those of rail (Figure 16(b)). Generally, BCC has a low environmental impact because a huge amount of crop can be shipped at a time, thus the unit environmental implications are lower than other transportation modes.

Most food mile studies have focused on GHG emissions in the transportation stage. However, the primarily results of the current study show that this perspective does not sufficiently explain the whole picture of the crop trade. The results also reveal the limitations of a food mile evaluation with GHG emissions and highlight the need for further examination of other environmental impact categories.



(a) GHG emissions ($kg\ CO_2e/ton \cdot km$)



(b) $PM_{2.5}$ emissions ($kg\ PM_{2.5}e/ton \cdot km$)

Figure 16 Environmental impact per ton·km of each transport mode. In this figure, GHG is greenhouse gas and $PM_{2.5}$ is fine particulate matter. BCC is bulk-commodity carrier (ocean-going ship).

1.3. GHGs and PMs of Food Miles for Major Imported Crops

This study evaluated the environmental impact of food miles for major imported crops in 2015 and 2017 considering transportation modes following importing routes via land-maritime-land. Based on this result, this study briefly discuss how the increase or decrease in imports of the major crops affected the two environmental impact categories of GHG and $PM_{2.5}$ (fine PM) emissions.

GHG Emissions (GHGs) of Major Imported Crops. The GHG emissions of major imported crops from the transportation stage declined by about 38% from 1.4 million tons CO_2e in 2015 to 1.0 million tons CO_2e in 2017, even though those of imported wheat, US corn, and US soybeans slightly increased (Figure 17). The reason for this decrease in GHG emissions was the decrease in imports of the major crops, which had a 14% reduction from 12.5 million tons in 2015 to 11.0 million tons in 2017.

Imported corn showed the largest drop in GHG emissions to 0.66 million tons CO_2e in 2017 (67% of total GHG emissions for major imported crops in 2017) from 1.0 million tons CO_2e in 2015 (74% of the total GHG emissions in 2015). Despite the sharp decrease in the GHG emissions, corn was still the largest share of the total GHG emissions for the whole major imported crops. The large amount of corn imports contributed to the higher GHG emissions beyond the food miles for importing corn. The imported wheat and soybeans had relatively low GHG emissions of 0.2 million tons CO_2e in both 2015 and 2017.

The GHG emissions for the major exported crops in the land transportation stage (field-to-port) contributed almost 50% of the all emissions in all transportation stages. In 2015, 0.70 million tons of CO_2e of all GHG emissions were emitted from the land transportation accounting for 51% of those in all transportation stages. In addition, the GHG emissions generated in the land stage were 0.48 million tons CO_2e (48% of total emissions in all stages). In terms of maritime transportation, GHG emissions accounted for 41% (0.55 million tons CO_2e) of the total emissions in 2015 and 42% (0.42 million tons CO_2e) in 2017. The land transportation from the ports to the consumption locations was less than 10% of the total in 2015 and 2017.

GHG emissions for imported wheat increased by 9% (16,716 tons CO_2e), which coincided with the rising imports (Figure 17). South Korea had largely imported wheat from the US; however, GHG emissions generated the largest amount for Australian wheat imports. In 2015, the imports of Australian wheat emitted 76,318 tons of GHG emissions, which were 35% (19,757 tons CO_2e) greater than importing US wheat. In addition, the transportation emissions of Australian wheat was 15% higher than those of US wheat in 2017. The two countries had a similar shipping distance in the transportation stages to South Korea, but the land distance for exports from Australia was double that of the US. This variation of the distance drove the huge difference in their GHG emissions. Since the longer land transport distance causes higher GHG emissions (see Figure 16), the unit impact of GHG by land transportation mode was even greater than that for the maritime transportation mode.

For imported corn, Brazilian corn produced the largest amount of GHG emissions in 2015, contributing 0.6 million tons CO_2e, 55% of total emissions for importing corn. In 2017, the largest port of imported corn shifted to US corn (0.3 million tons CO_2e; 46% of the total emissions) due to the change in corn imports from these countries. When comparing the shipping distance for each stage of the countries, the land distance for export crops in the US (1,924 km; 1,196 mi.) was 130% more than that of Brazil (834 km; 524 mi.). However, the GHG emissions of the land transportation for Brazilian corn was estimated at 216% (2015) and 22% (2017) larger than emissions from the US corn in the same years.

In the US, rail was the main mode for transporting crops, but Brazil primarily used truck. Although the land distance was less in Brazil than in the US, the difference in transportation modes had a considerable impact for Brazilian corn. In addition, the impact of corn transportation in the land stage from import to consumption was substantially high compared to the other major crops. The corn used for food (20% of all corn imports) traveled relatively long distance (377 km; 234 mi.) from the port of Busan to the market and South Korea mainly used truck to distribute crops. These reasons made the corn transportation impact even higher.

There were fewer soybean imports compared with the other major crops; thus the GHG emissions of importing soybeans were lower than the others. For importing soybeans, the 0.17 million tons and 0.13 million tons of GHG were produced in 2015 and 2017, respectively. Brazilian soybeans were estimated to have the most significant impact in both years. US soybean imports made up the largest share of total imported soybeans in 2017; however, Brazilian soybeans generated the highest GHG emissions. The transportation modes for the land stage in the countries can be a critical contributor as land transportation using truck in Brazil drove up the GHG emissions in this stage. Chinese soybeans had the lowest transportation impact even though their imports rose slightly.

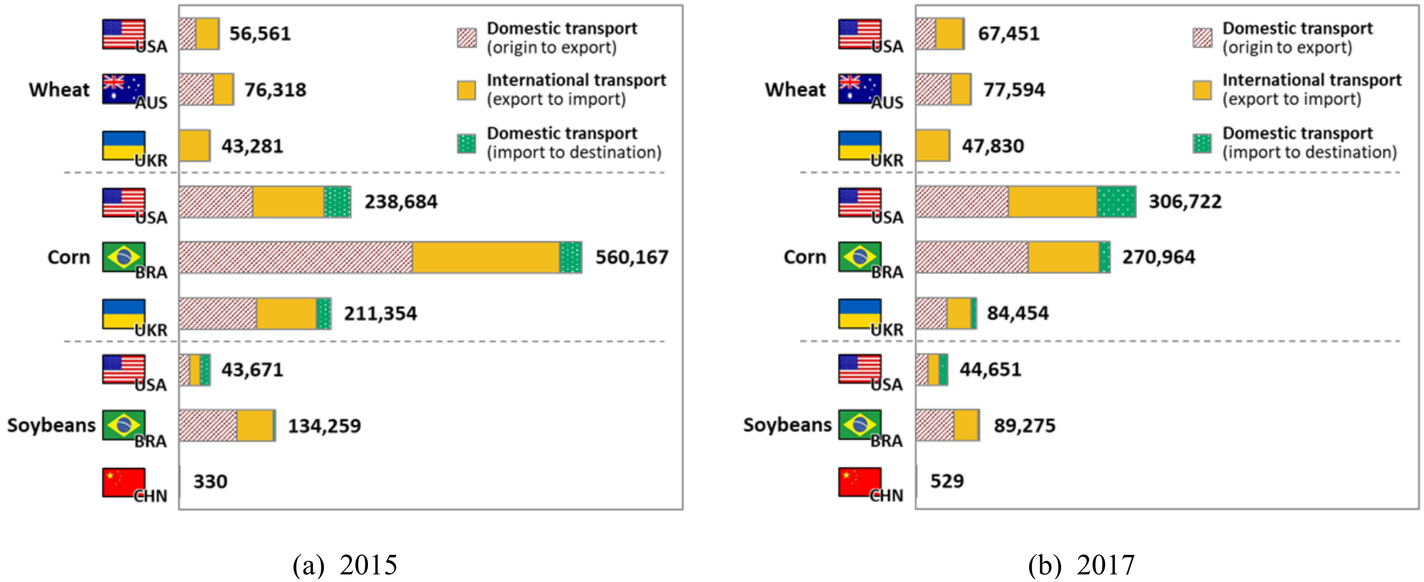


Figure 17 Greenhouse gas (GHG) emissions (tons CO_2e) of food miles for each transportation stage of imported wheat, corn, and soybeans in South Korea in 2015 and 2017. USA, AUS, UKR, BRA, and CHN represent the United States, Australia, Ukraine, Brazil, and China, respectively.

$PM_{2.5}$ Emissions (fine PMs) of Major Imported Crops. From the perspective of $PM_{2.5}$ emissions, imported wheat, US corn, and US soybeans also slightly increased for the two years from 2015 to 2017. However, the emissions of the all major imported crops fell by 18% from 48.7 thousand tons $PM_{2.5}e$ in 2015 to 41.4 thousand tons $PM_{2.5}e$ in 2017. $PM_{2.5}$ emissions for corn imports, in particular, declined by 30% from 32.5 thousand tons $PM_{2.5}e$ in 2015 to 25.1 thousand tons $PM_{2.5}e$ in 2017. The emissions of imported wheat were 10.8 thousand tons $PM_{2.5}e$ and 11.9 thousand tons $PM_{2.5}e$ in 2015 and 2017, respectively. For soybeans, 5.4 thousand tons $PM_{2.5}e$ (2015) and 4.4 thousand tons $PM_{2.5}e$ (2017) of fine PM were emitted in all transportation stages.

The $PM_{2.5}$ emissions generated in each transportation stage of the major crops are shown in Figure 18. $PM_{2.5}$ emissions tended to be substantial for maritime transportation, while the GHG emissions were highly produced in land transportation. The unit impact of both $PM_{2.5}$ and GHG of transportation modes were the lowest in the BCC, but the variation of $PM_{2.5}$ between the modes did not differ remarkably compared to that of GHG emissions. Therefore, the $PM_{2.5}$ emissions from maritime transportation accounted for 71% (34.8 thousand tons $PM_{2.5}e$) and 64% (26.3 thousand tons $PM_{2.5}e$) of the total transportation impact in 2015 and 2017, respectively. The share of land transportation for exporting was 28% (13.6 thousand tons $PM_{2.5}e$ in 2015) and 36% (14.8 thousand tons $PM_{2.5}e$ in 2017) and the land transportation for importing was only 1% (0.3 thousand tons $PM_{2.5}e$) in both 2015 and

2017.

Australian wheat had the highest $PM_{2.5}$ emissions during the transportation stages. The imported wheat from the US and Ukraine generated substantial $PM_{2.5}$ in the maritime transportation, representing over 60% of the total transportation emissions in all stages in both 2015 and 2017. In contrast, the land transportation of Australian wheat exporting produced nearly 60% of the $PM_{2.5}$ emissions (3.0 thousand tons $PM_{2.5}e$) for all transportation stages. This difference in the emissions primarily depended on the distance traveled and the transportation mode. Australian wheat traveled a relatively long distance by rail in the land transportation stage and the unit impact of rail had the largest impact at 9.47e-04 kg $PM_{2.5}e$/ton·km. The land transportation for exporting wheat within Ukraine indicated little $PM_{2.5}$ emissions because the wheat producing region was located in the same state as the export port.

The transportation emissions of $PM_{2.5}$ for Brazilian corn were 14.0 thousand tons $PM_{2.5}e$ in 2015, which were the highest amount of the total imported corn. Brazil is 22 thousand km (13,670 mi.) of distance from South Korea; thus, $PM_{2.5}$ emissions from the maritime transportation contributed 80% of all stages in 2015. In 2017, soybeans imports from Brazil fell and imports from the US increased. This shift drove up the transportation impact of US corn to 16.0 thousand tons $PM_{2.5}e$ in 2017 from 12.7 thousand tons $PM_{2.5}e$ in 2015. In addition, the land transportation impact for exporting US corn was 8.1 thousand tons $PM_{2.5}e$, which was 0.3 thousand $PM_{2.5}e$ greater than that of maritime transportation of US corn. The transportation impact for Brazilian and Ukraine corn in 2017 declined by 107% and 150%, respectively, compared to that of 2015.

soybeans contributed the least $PM_{2.5}$ emissions in the transportation stage of major imported crops, representing 11%. In particular, soybeans from China emitted nearly 100 times less $PM_{2.5}$ than from Brazil and the US. Among these countries, Brazil had the most substantial emissions of $PM_{2.5}$, even though the emissions of Brazilian soybeans sharply decreased by 32% from 3.4 thousand tons $PM_{2.5}e$ in 2015 to 2.3 thousand tons $PM_{2.5}e$ in 2017. Particularly in 2017, although the US soybean imports were 90 thousand tons more than imports of Brazilian soybeans, the $PM_{2.5}$ emissions were heavily generated from Brazilian soybeans due to the high food miles.

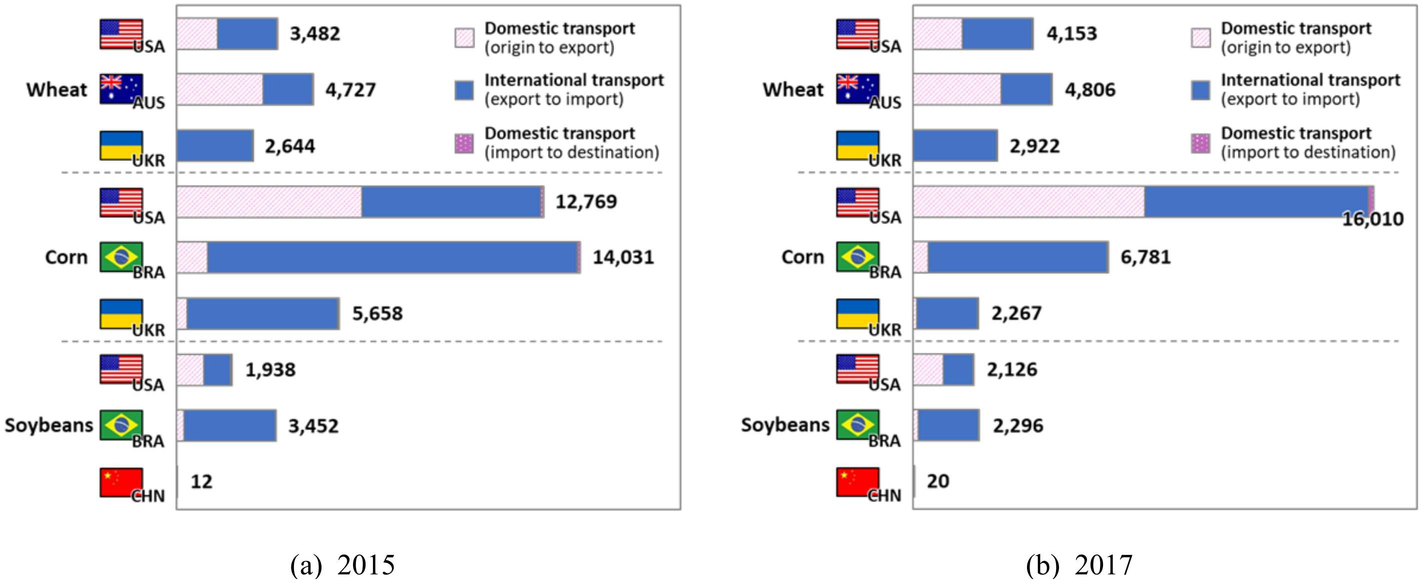


Figure 18 Fine particulate matter emissions ($PM_{2.5}$, tons $PM_{2.5}e$) of food mile for each transportation stage of imported wheat, corn, and soybeans in South Korea in 2015 and 2017. USA, AUS, UKR, BRA, and CHN are the United States, Australia, Ukraine, Brazil, and China, respectively.

2. Environmental Impacts of US Corn on Major Export Ports

2.1. Port-level Environmental Implications of US Exported Corn based on the Optimal Supply Chain

US corn was selected as the target to evaluate the environmental impact of both transportation and production stages. This study built a cost minimization model to estimate US corn mobility from fields to export ports. The simulated model connects the origins of supplied corn to the export ports through county-level supply networks meeting demand for the corn exports of each port. The results identified the amount of exported corn that moved between the 191 producing counties to the 32 ports in the US. The amounts of exported corn supply and demand at the port-level is presented in Figure 19 with circles (dots) representing the port, and the arrows indicating the movement of the corn.

The model shows that at least one county and as many as 63 counties were allocated across ports (Figure 19). The port of New Orleans, Louisiana had the largest number of counties allocated. The county-level average production of exported corn was 97 million kg, ranging from 75 kg to 2.5 billion kg per county. New Orleans was the county that produced the highest amount of exported corn, and

Milwaukee, Wisconsin was the least producing county.

Environmental Impacts Embedded in Exported Corn. The GHG emissions associated with one kilogram of corn production represented the regional variation of producing counties. Greene county in New York had the lowest GHG emissions in the production stage (0.16 kg CO_2e/kg), which produced 61 thousand kg of exported corn. In contrast, Perry county in Louisiana contributed 2.42 kg CO_2e/kg of GHG emissions, which was 15 times higher than those of Greene county. Perry county produced huge amounts of exported corn at 26 million kg. In addition, Morrill county in Nebraska and Champaign county in Illinois both produced about 250 million kg of exported corn. However, GHG emissions from corn production in Champaign county (0.47 kg CO_2e/kg) were estimated to be 1.4 times higher than a similar amount of exported corn produced in Morrill county (0.33 kg CO_2e/kg).

For irrigated water use, there were also considerable differences for each producing county. No irrigated water was used in 79 counties for corn production, while Dona Ana county in New Mexico relied heavily on irrigation with the highest use at 3.54 m^3/kg. In addition, in Morrill and Champaign counties, which produced similar amounts of exported corn, the GHG emissions of the production stage tended to be higher in Champaign county, but the irrigated water in Morrill county (0.68 m^3/kg) was about 70 times higher than that of Champaign county (0.01 m^3/kg).

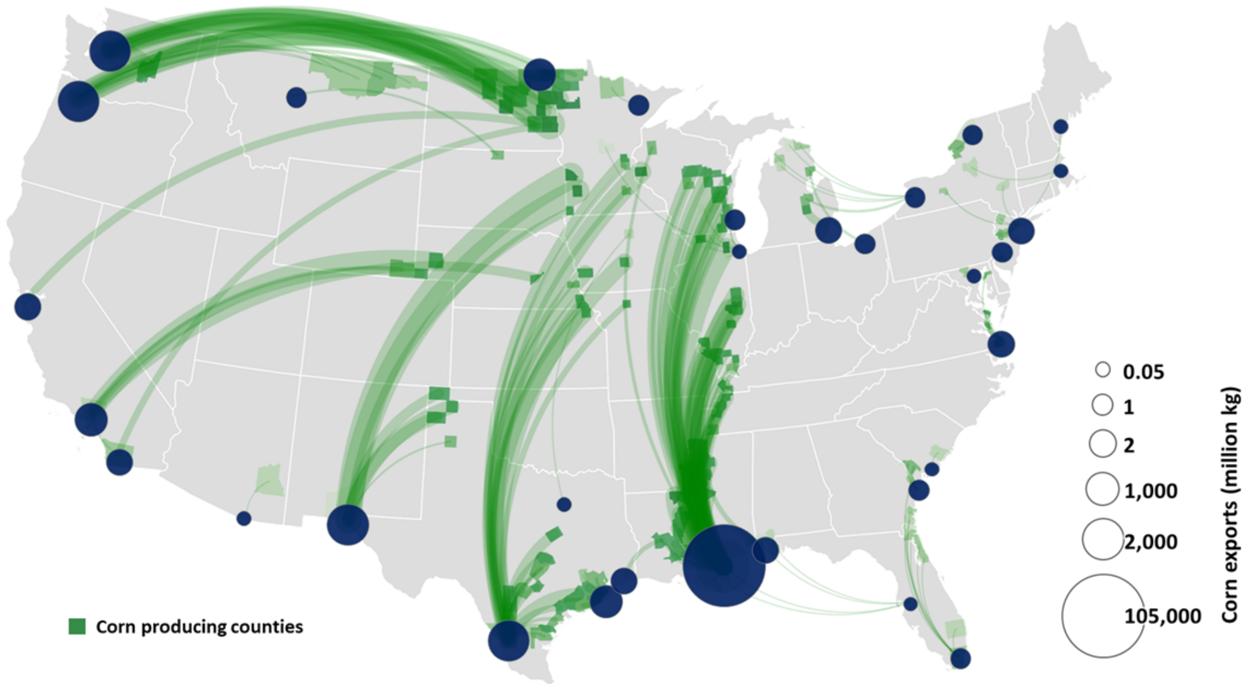


Figure 19 County-level exported corn supply chain connections with the link between corn producing counties and ports for export. Dots (blue) represent the location and corn exports of the ports.

Port-level Environmental Impacts. Considering the US export corn supply chain, this study evaluated port-level intensities of both GHG emissions and irrigated water use in the production stage of exported corn. The corn production impact at the port level tended to be relatively high in ports with large export volume (Table 6). For instance, the port of New Orleans, Louisiana was ranked 11th (0.376 kg CO_2e/kg) in GHG emissions and 5th (0.149 m^3/kg) in irrigated water use among the 32 ports for corn exports and accounted for the largest share of total corn exports at 56% (10.4 billion kg). In Seattle, Washington, the second-highest exports at 2.2 billion kg, GHG emissions and irrigated water use in the corn production stage, had 0.368 kg CO_2e/kg and 0.093 m^3/kg, 13th and 7th, respectively. In comparison, the Boston, Massachusetts port exported the lowest amount of 33,235 kg with a relatively low production impact: 0.187 kg CO_2e/kg of GHG emissions (32th) and 1.5e-04 m^3/kg of irrigated water use (24th).

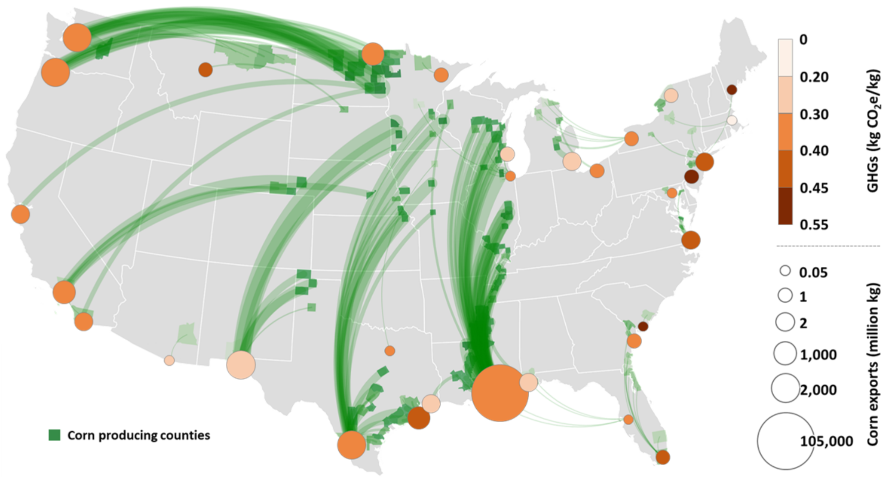
Table 6 Port-level greenhouse gas (GHG) emissions and irrigated water use per kilogram of exported corn production in the US based on the simulated supply chain from corn producing counties to ports for export. Ranks are recorded from highest level to lowest level.

Ports (City, State)	Exports (thousand kg)	rank	GHG emissions (kg CO_2e/kg)	rank	Irrigated water use (m^3/kg)	rank
New Orleans, LA	**10,404,127**	**1**	0.376	11	0.149	5
Seattle, WA	2,204,552	2	0.368	13	0.093	7
Laredo, TX	1,962,911	3	0.390	9	0.073	9
El Paso, TX	1,518,065	4	0.243	29	0.202	4
Portland, OR	1,251,512	5	0.343	20	0.020	17
Los Angeles, CA	409,782	6	0.356	17	0.621	2
Houston-Galveston, TX	219,546	7	0.444	4	0.013	18
Pembina, ND	217,814	8	0.347	19	0.026	15
Norfolk, VA	96,373	9	0.431	6	0.001	23
Detroit, MI	58,610	10	0.296	25	0.002	21
San Francisco, CA	50,960	11	0.368	12	0.003	20
San Diego, CA	39,263	12	0.361	15	0.024	16
New York City, NY	27,411	13	0.426	8	0(1.1e-05)	25
Mobile, AL	19,141	14	0.278	27	0.283	3
Port Arthur, TX	18,507	15	0.287	26	0.057	12
Savannah, GA	8,320	16	0.358	16	0.106	6
Buffalo, NY	7,777	17	0.300	24	0.002	22
Cleveland, OH	6,567	18	0.315	21	**0**	**26**
Ogdensburg, NY	5,147	19	0.201	30	**0**	**26**
Great Falls, MT	4,826	20	0.438	5	0.028	14
Milwaukee, WI	4,475	21	0.250	28	**0**	**26**
Miami, FL	4,159	22	0.430	7	0.065	11
Philadelphia, PA	2,513	23	**0.549**	**1**	0.076	8
Duluth, MN	1,794	24	0.353	18	**0**	**26**
Baltimore, MD	285	25	0.300	23	**0**	**26**
Tampa, FL	168	26	0.366	14	0.065	10
Nogales, AZ	123	27	0.200	31	**0.873**	**1**
Chicago, IL	59	28	0.385	10	0.005	19
Charleston, SC	51	29	0.493	3	0.056	13
Portland, ME	48	30	0.503	2	**0**	**26**
Dallas-Fort Worth, TX	42	31	0.306	22	**0**	**26**
Boston, MA	**33**	**32**	**0.187**	**32**	0(1.5e-04)	24
Sum	18,544,959					

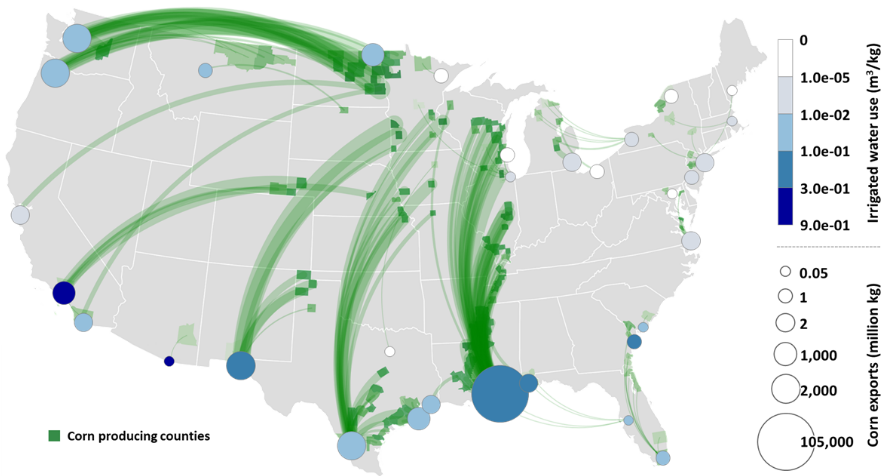
The port-level difference in corn production impacts is illustrated in Figure 20. Figure 20(a) compares the GHG emissions embedded in exported corn based on the supply-chain model. The average GHG emissions from the production stage of corn for the whole port was estimated at 0.363 kg CO_2e/kg (0.187-0.549 kg CO_2e/kg). The port with the lowest GHG emissions was Boston with the least exports, whereas the port with the highest GHG emissions was Philadelphia, Pennsylvania, which exported 2.5 million kg of corn. In addition, the Houston-Galveston, Texas port (0.444 kg CO_2e/kg) generated 1.3 times higher GHG emissions compared to the Pembina, North Dakota port (0.347 kg CO_2e/kg), which exported a similar amount of corn.

The average irrigated water use of all ports was 0.135 m^3/kg. The port that used the most irrigated water in the production stage was Nogales, Arizona (0.873 m^3/kg), which had the 27th largest exports (0.1 million kg) among the 32 ports (Figure 20(b)). In addition, the embedded irrigated water use of the ports of Seattle, Washington, Laredo, Texas, and El Paso, Texas was 0.093 (7th), 0.073 (9th), and 0.202 m^3/kg (4th), respectively. The corn export volume of these ports was second largest after New Orleans, whereas the corn exports through the Portland, Oregon port were the 5th largest volume and it was 17th for irrigated water use at 0.020 m^3/kg. Some ports including Portland, Maine and Dallas-Fort Worth, Texas were estimated to have no irrigated water use and had less corn exports than the other ports.

The findings of these port-level differences imply that the actual environmental implication of corn production based on the supply model could differ from the single national average of the US, 0.390 kg CO_2e/kg of GHG emissions and 0.110 m^3/kg of irrigated water use. It is also possible to import or export corn that has lower environmental impacts by choosing a port with less corn production impacts considering the spatial differences of corn producing counties.



(a) GHG emissions intensity (kg CO_2e/kg)



(b) Irrigated water use intensity (m^3/kg)

Figure 20 Port-level (a) greenhouse gas (GHG) emissions and (b) irrigated water use intensities embedded in exported corn. The link between corn producing counties and ports for export are shown with dots that represent the location and export volumes of ports. The color intensity of the dots indicates GHG emissions and irrigated water use per kg. The shaded regions identify the corn producing counties.

Actual Impact VS US Average Impact. Based on the US average (0.390 kg CO_2e/kg) of GHG emissions generated in the corn production stage for the total amounts of US export, the total GHG emissions of US corn were found to be 7.2 billion kg CO_2e (Table 7). However, the total GHG emissions based on the simulated-supply chain (on average 0.363 kg CO_2e/kg) were 6.7 billion kg CO_2e (7% less than the US average). This finding indicates that the actual GHG emissions of corn exports could be 0.5 billion kg CO_2e less than the US average. In other words, if the national average is used, the environmental impacts of US export corn could be evaluated higher compared to the actual environmental impacts.

The port that has the largest difference from the US average emissions was Boston as they have minimal GHG emissions per kg. Their actual GHG emissions were 6,000 kg CO_2e, which were 117% lower than the US average. In Philadelphia, the actual GHG emissions (1.4 million kg CO_2e) were 29% higher than the US average (1.0 million kg CO_2e). Ports with high export volumes, such as New Orleans and Seattle, were estimated to have a 4% and 6% difference, respectively, between the actual and US average emissions, but Laredo and Chicago did not have a significant difference between the actual and US average emissions.

The irrigated water use (2.5 billion m^3) for exported corn production was estimated at 18% (0.5 billion m^3) greater than that of the US average (2.0 billion m^3) by comparing the US average of 0.110 m^3/kg and the actual use of 0.135 m^3/kg. Therefore, the actual irrigated water use of US export corn could also be underestimated when using the national average value. In particular, the consideration had not been taken into account for non-irrigating counties in the US average. A significant outlier such as non-irrigating counties can be a limitation of the national average when describing the irrigated water use in the production stage.

Ports including Chicago, Dallas-Fort Worth, and Boston had no irrigated water use in the supply-chain model, but 4,000 m^3 to 6000 m^3 of irrigated water use would be included when the US average is applied. Corn transported to the New York City port were produced using very little irrigation based on the supply-chain model, so the overall irrigated water use was nearly zero. However, the irrigated water use would be estimated at 3 million m^3 when the US average is reflected. Even in Norfolk and San Francisco ports, where exports were relatively high, the supply chain-based irrigated water use was 0.1 million m^3 and 0.2 million m^3, respectively, whereas the US average-based use was estimated at 10.6 million m^3 and 5.6 million m^3, respectively. This calculation was over 30 times higher than the supply chain-based result.

Table 7 Comparing greenhouse gas (GHG) emissions and irrigated water use of US export corn based on simulated supply chains and the US average impact. The US average emissions of GHG and irrigated water use are 0.390 kg CO_2e/kg and 0.110 m^3/kg, respectively.

Ports	GHG emissions (thousand kg CO_2e)		Irrigated water use (thousand m^3)	
	simulated supply chains-based	US average-based	simulated supply chains-based	US average-based
New Orleans	3,909,068	4,054,960	1,549,596	1,146,857
Seattle	810,601	859,214	204,793	243,010
Laredo	766,438	765,035	143,798	216,374
El Paso	369,239	591,659	306,302	167,338
Portland, OR	428,747	487,771	25,518	137,955
Los Angeles	145,988	159,711	254,613	45,171
Houston-Galveston	97,538	85,567	2,913	24,201
Pembina	75,490	84,892	5,583	24,010
Norfolk	41,511	37,561	113	10,623
Detroit	17,335	22,843	121	6,461
San Francisco	18,757	19,862	178	5,617
San Diego	14,177	15,303	953	4,328
New York City	11,678	10,683	0	3,021
Mobile	5,328	7,460	5,407	2,110
Port Arthur	5,303	7,213	1,055	2,040
Savannah	2,975	3,243	879	917
Buffalo	2,331	3,031	15	857
Cleveland	2,068	2,559	0	724
Ogdensburg	1,037	2,006	0	567
Great Falls	2,112	1,881	137	532
Milwaukee	1,118	1,744	0	493
Miami	1,788	1,621	269	458
Philadelphia	1,379	979	190	277
Duluth	634	699	0	198
Baltimore	86	111	0	31
Tampa	61	65	11	18
Nogales	25	48	107	14
Chicago	23	23	0	6
Charleston	25	20	3	6
Portland, ME	24	19	0	5
Dallas-Fort Worth	13	16	0	5
Boston	6	13	0	4
Sum	**6,732,902**	**7,227,812**	**2,502,552**	**2,044,230**
Average (per kg)	**0.363**	**0.390**	**0.135**	**0.110**

2.2. Environmental Variations of Export Ports for Major Corn Buyers

The six major corn buyers listed in Table 8 accounted for 86% of all US corn exports in 2012. Japan and Mexico imported 37% and 25% of the total exports of US corn, respectively, followed by China (13%), Venezuela (6%), Taiwan (3%), and South Korea (2%). The share of these six countries indicates that the major importing countries could contribute to more than 80% of the overall environmental impact of US corn exports.

The major buyers accounted for 88% of the total GHG emissions (6.7 billion kg CO_2e) in the production stage of US export corn. Japan had the largest share of GHG emissions of exported corn at 38%, generating 2.6 billion kg CO_2e. The exported corn to Mexico contributed 1.7 billion kg CO_2e of the GHG emissions, representing 26%. For irrigated water use, corn exported to the major importing countries made up 88% of the total use (2.5 billion m^3). The use for Japan and Mexico were estimated at 37% (0.9 billion m^3) and 25% (0.6 billion m^3), respectively. For South Korea, the import amount of US corn in 2012 was relatively small compared to other countries for both GHG emissions and irrigated water use at only 2% of the total amounts.

Table 8 Greenhouse gas (GHG) emissions and irrigated water use intensities for US corn exported to the major importing countries in 2012. The percent listed below the nation is the portion of total US corn exports.

Major importing countries	Ports for export in the US	Exports (thousand kg)	GHG emissions (thousand kg CO_2e)	Irrigated water use (thousand m^3)
Japan (37%)	New Orleans	5,793,939.8	2,176,915.5	862,952.6
	Portland (Oregon)	539,541.7	184,837.9	11,001.2
	Seattle	472,948.7	173,900.6	43,934.7
	Mobile	22,116.2	6,156.7	6,247.9
	Los Angeles	19,720.2	7,025.5	12,252.9
	San Francisco	16,385.1	6,030.8	57.1
	New York	719.2	306.4	0(4.8 m^3)
	Sum	**6,865,371.0**	**2,555,173.4**	**936,446.3**
Mexico (25%)	New Orleans	4,254,846.7	1,598,643.1	633,719.2
	Houston-Galveston	326,165.3	144,906.5	4,327.1
	Sum	**4,581,012.0**	**1,743,549.6**	**638,046.3**
China (13%)	New Orleans	938,731.7	352,702.9	139,815.2
	Seattle	895,118.3	329,130.0	83,152.3
	Portland (Oregon)	479,631.9	164,313.8	9,779.6
	Los Angeles	73,714.3	26,261.2	45,801.4
	San Francisco	1,384.2	509.5	4.8
	Norfolk	1,302.6	561.1	1.5
	New York	139.9	59.6	0(4.8 m^3)
	Sum	**2,390,023.0**	**873,538.2**	**278,554.9**
Venezuela (6%)	New Orleans	943,650.0	354,550.8	140,547.7
	Houston-Galveston	91,701.1	40,740.3	1,216.6
	Port Arthur	25,009.4	7,165.9	1,426.1
	Norfolk	9,389.8	4,044.5	11.0
	New York	363.7	155.0	0(4.8 m^3)
	Sum	**1,070,114.0**	**406,656.6**	**143,201.4**
Taiwan (3%)	Los Angeles	226,346.0	80,637.2	140,637.0
	Seattle	186,700.5	68,648.7	17,343.6
	Portland (Oregon)	70,097.8	24,014.3	1,429.3
	Orleans	26,759.5	10,054.1	3,985.6
	San Francisco	16,143.5	5,941.8	56.2
	Norfolk	3,454.3	1,487.9	4.0
	Duluth	731.6	258.5	0.0
	Sum	**530,233.0**	**191,042.6**	**163,455.8**
South Korea (2%)	Seattle	213,312.0	78,433.6	19,815.7
	New Orleans	156,705.1	58,877.7	23,339.7
	Portland (Oregon)	68,912.2	23,608.2	1,405.1
	Los Angeles	8,603.6	3,065.1	5,345.7
	San Francisco	2,606.4	959.3	9.1
	New York City	441.8	188.2	0(4.8 m^3)
	Savannah	105.4	37.7	11.1
	Norfolk	12.5	5.4	0(14.6 m^3)
	Sum	**450,699.0**	**165,175.2**	**49,926.5**

The unit impact of GHGs and irrigated water use according to export destinations tended to be different from the total impacts (Figure 21). Total GHG emissions associated with exported corn production for Mexico was the second highest, whereas the unit impact of corn was maximal at 0.381 kg CO_2e/kg. This is because about 10% of the corn was exported from the Houston-Galveston port, which had the fourth highest GHG emissions among the 32 ports (see Table 6). In contrast, the first major exporting country, Japan, generated 0.372 kg CO_2e/kg of GHG, making them the third highest. For South Korea, which had the lowest US corn imports for 2012, GHG emissions were 0.366 kg CO_2e/kg.

The irrigated water use for US corn exported to their major importing countries were between 0.111 and 0.139 m^3/kg except for Taiwan, which only had 0.308 m^3/kg of irrigated water use in the production stage. The US export corn for Taiwan was mostly (43%) transported through the Los Angeles port, the second highest (0.621 m^3/kg) use of irrigated water per kilogram of corn production. Next were Mexico (0.139 m^3/kg), Japan (0.136 m^3/kg), and Venezuela (0.134 m^3/kg). Nearly 90% of US corn to these three countries were exported through the New Orleans port, which had relatively lower irrigated water use (0.149 m^3/kg). Much of the US corn to China and South Korea was exported through the ports of Seattle (0.093 m^3/kg) and Portland (Oregon; 0.020 m^3/kg); the unit corn production impacts for the two countries were 0.117 m^3/kg and 0.111 m^3/kg, respectively.

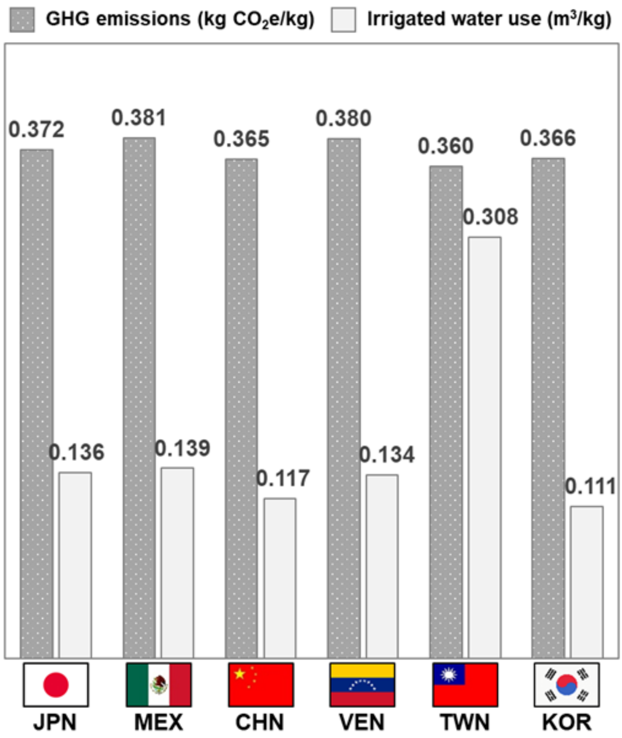


Figure 21 Unit impact (per kg) of greenhouse gas (GHG) emissions and irrigated water use intensities of US export corn to the major importing countries in 2012: Japan (JPN), Mexico (MEX), China (CHN), Venezuela (VEN), Taiwan (TWN), and South Korea (KOR).

3. Environmental Benefits of Better Choices for Imported Corn

The approaches and results of port-level variability of environmental impact facilitate transactions of environmentally better crops. This study evaluated potential reductions in the GHG emissions and potential savings of irrigated water use based on port choices (better choices), which could minimize the impact of imported corn from the US to South Korea. First, among eight ports for corn export to South Korea, ports were chosen based on the criterion of minimizing the environmental impact. The capacity of each port was also considered for US corn exports to South Korea. Furthermore, the GHG emissions were analyzed based not only on the production stage but also transportation stages; thus, the environmental implications of the GHG emissions in the transportation stages were analyzed reflecting the food miles.

To evaluate the environmental implications of the corn transportation stages, the GHG emissions associated with food mile based on the selected port were analyzed and compared to the existing eight ports. The transportation stages consisted of land transportation from counties to ports and maritime transportation from the export ports to the import port (port of Busan, South Korea). This study used the unit impact of GHG (per ton·km) to analyze the GHG emissions of transportation modes for each transportation stage. Figure 22 displays the GHG emissions per ton·km of each transportation mode. The GHG emissions from truck were significantly larger than those of barge (650%), rail (754%), and BCC (3,881%), respectively.

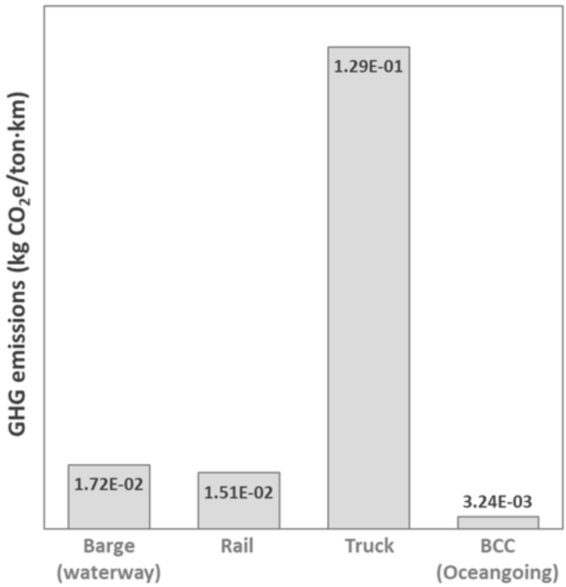


Figure 22 Unit impact (ton · km) of greenhouse gas (GHG) emissions of barge, rail, truck, and BCC.

Imports of US corn into South Korea totaled 451 million kg in 2012. Some of the corn was exported through ports of Seattle (47%), New Orleans (35%), and Portland (15%) (Figure 23). However, from an environmental perspective, the ports that had less GHG emissions were Portland (0.343 kg CO_2e/kg), Los Angeles (0.356 kg CO_2e/kg), and Savannah (0.358 kg CO_2e/kg). In addition, ports that had less irrigated water use were New York City (1.1e-05 m^3/kg), Norfolk (0.001 m^3/kg), and San Francisco (0.003 m^3/kg). This variation in the environmental impact of each port implies that the environmental implications can be lower when corn has less of an environmental impact. Therefore, the environmental implications of the ideal choices for US corn imports can be evaluated by taking this variation into consideration.

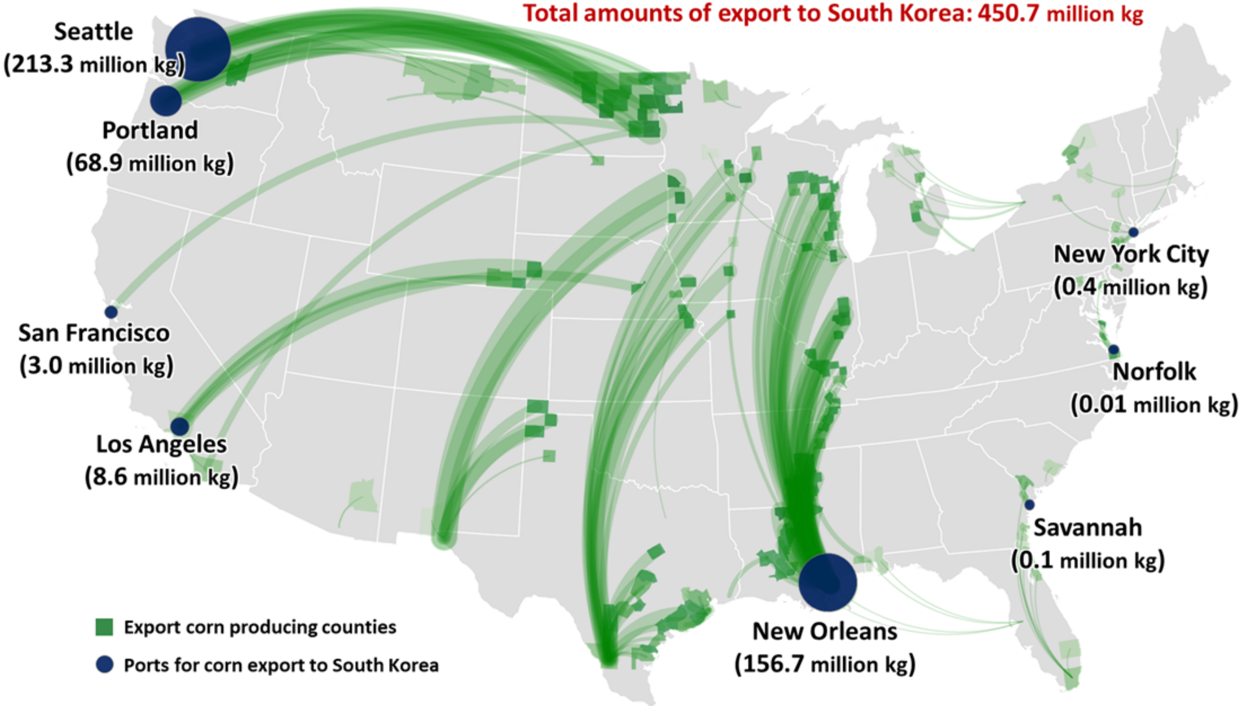
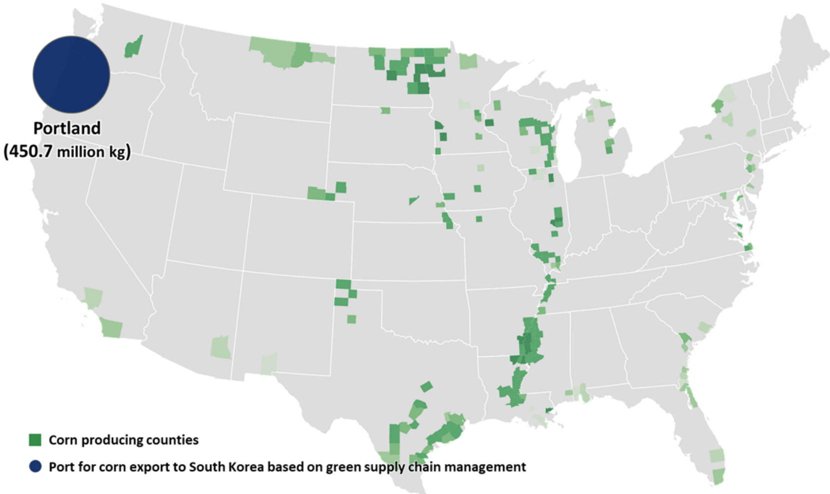


Figure 23 US corn supply chain for exports to South Korea. Dots (blue) represent the location of export ports to South Korea. The size of the dots displays the amount of exports. The shaded region indicates the counties of corn production.

3.1. Potential GHGs Reduction by Selected Port for Imported Corn

The Portland port can best minimize GHG emissions and accommodate imports into South Korea (Figure 24). Global corn exports from the Portland port were 1,252 million kg, which was triple the total exports to South Korea. The GHG emissions in corn production can be reduced by 7% from 165.2 million kg CO_2e to 154.4 million kg CO_2e by exporting all of Korea's US imports from Portland.



Selected port	Capacity (million kg)	Exports (million kg)	GHG emissions (kg CO_2e/kg)
Portland	1251.5	450.7	0.343

Figure 24 Selected export port to minimize greenhouse gas (GHG) emissions of US corn exported to South Korea. Capacity represents global exports of the port.

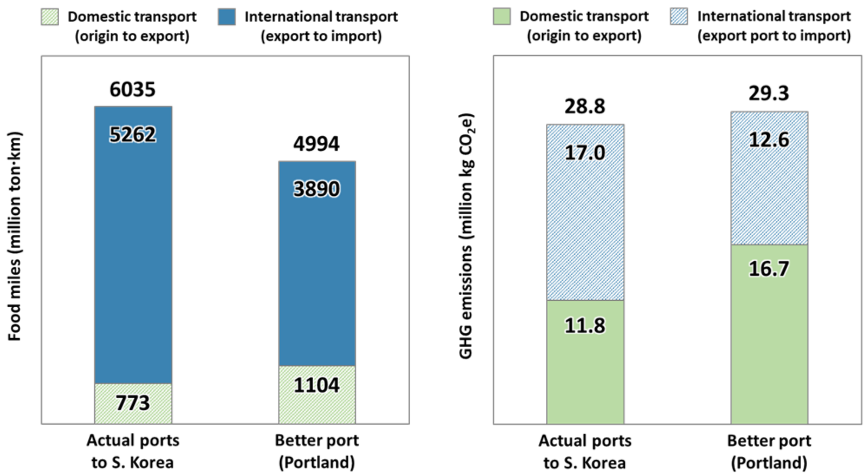
This study also estimated changes in GHG emissions in each transportation stage (land and maritime transportation) based on the port. The food miles for maritime transportation from the US to South Korea was estimated to be 26% lower (1,372 million ton·km) from 5,262 million ton·km to 3,890 million ton·km. However, in land transportation from counties to ports for export, the food mile rose by 43% (331 million ton·km) from 773 ton·km to 1,104 million ton·km (Figure 25(a)).

The increased food miles were evidently attributed to the land transportation from counties to the port of Portland. The transportation distance (2,450 km; 1,522 mi.) was significantly farther than the average transportation distance to the current ports (1,715 km; 1,066 mi.). However, despite the increase in the distance of land transportation, by transporting the crops to Portland, Oregon, the overall food miles decreased by 17% from 6,035 million ton·km to 4,994 million ton·km because the decrease in the food miles of maritime transportation from other ports was higher than the increase in the food miles of land transportation.

Even if the overall food miles were reduced, the GHG emissions during the transportation stages were likely to increase by 1.5% (0.5 million kg CO_2e) (Figure 25(b)). The GHG emissions of maritime transportation diminished by 26% (4.4 million kg CO_2e) from 17.0 million kg CO_2e to 12.6 million kg CO_2e; however, those of land transportation were estimated to rise by 42% from 11.8 million kg CO_2e to 16.7 million kg CO_2e. Thus, the differences in GHG emissions of each stage contributed to the rising overall GHG emissions from 28.8 million kg CO_2e to 29.3 million kg CO_2e.

These results can be explained by the fact that the food miles for maritime transportation decreased when the export ports were switched, but the increase in food mile for land transportation had a greater negative effect in terms of GHG emissions. Specifically, the food miles during maritime transportation was evaluated to decrease by 1,372 ton·km; in contrast, the food miles during land transportation was analyzed to increase by 331 ton·km. However, due to the differences in GHG emissions of the transportation modes, the GHG emissions of the land transportation were more affected by changes in the food miles. The findings of this study show that understanding the data from a food mile perspective does not provide a whole picture of food trade. In other words, an increase or decrease in food miles cannot be assessed as the sole variable to determine the environmental impact.

As a result of the model, the estimated reduction in GHG emissions of corn export based on the selected port was 5.3% (10 million kg CO_2e) from 194 million kg CO_2e to 184 million kg CO_2e, considering both production and transportation stages. The value of the reduced GHG emissions can be estimated using the prices of GHG (about 0.022 US dollars per kg) that are traded through the Certified Emission Reductions in South Korea in January 2019. The reduced GHG emissions are equivalent to about 0.22 million US dollars. In other words, crop trading companies and their partners can save 0.22 million US dollars by selecting the optimal port, as described in this study.



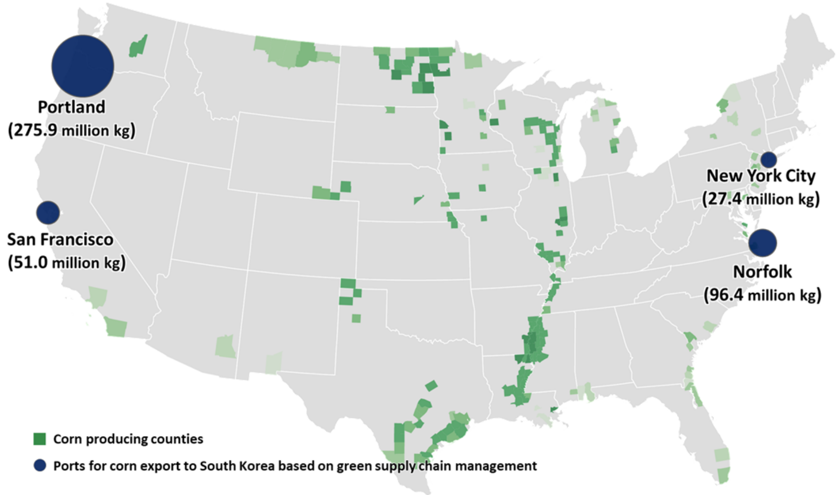
(a) food miles (b) GHG emissions

Figure 25 Comparison of (a) food miles and (b) greenhouse gas (GHG) emissions during transportation stages for US corn exported to South Korea according to actual ports and optimally selected port. The value of actual ports is the average of Seattle, New Orleans, Portland (OR), Los Angeles, San Francisco, New York, Savannah, and Norfolk. The optimal selected port represents Portland which has less GHG emissions.

3.2. Potential Irrigated Water Savings by Selected Ports for Imported Corn

Figure 26 illustrates the selected ports to minimize irrigated water use including the ports of New York City (1.1e-05 m^3/kg), Norfolk (0.001 m^3/kg), San Francisco (0.003 m^3/kg), and Portland (0.020 m^3/kg). Because global exports of corn were only 27 million kg, from the port of New York City, which had the lowest irrigated water use, this port cannot meet the export needs of South Korea. Therefore, this study allocated corn exports to ports based on less irrigated water use by considering the level of global exports of each port. Norfolk and San Francisco, with 96 million and 51 million kg of exported corn, respectively, were assigned as optimal selected ports according to the capacity of the ports. The remaining 276 million kg of corn would be exported from the port of Portland.

The benefits of port selection on irrigated water use are significantly greater than those of GHG emissions. It is expected that the corn exports can reduce irrigated water use by 88% from 49.9 million m^3 to 5.9 million m^3 when exporters change ports to selected ports from the current ports such as New Orleans and Seattle, which tended to rely heavily on irrigation.



Selected ports	Capacity (million kg)	Exports (million kg)	Irrigated water use (m^3/kg)
New York City	27.4	27.4	1.1e-05
Norfolk	96.4	96.4	0.001
San Francisco	51.0	51.0	0.003
Portland	1251.5	275.9	0.020
Sum		450.7	

Figure 26 Selected export ports to minimize irrigated water use of US corn exported to South Korea. Dots (blue) represent the location of the ports and size of the dots display exports. The shaded regions indicate corn producing counties. Capacity represents global exports of each port.

3.3. Potential Leverage for Better Choices

Many people prefer to buy crops that generate less environmental impacts. Despite increased GHG emissions in transportation stages with better choices, advanced technologies such as improving fuel efficiency, switching fuel, and renewable energy-based engines can provide a significant reductions in GHG emissions during transportation stages in the future. The International Maritime Organization (IMO) has implemented a new global regulation [IMO 2020 Sulphur Regulation] stating that the maximum amount of sulphur content in ships' fuel oil must be 0.5%, down from the current 3.5%, starting on 1 January 2020 (IMO, 2019).

To meet the new sulphur regulation, ships are forced to either switch to low-sulphur fuel, install abatement technology (so-called scrubbers), or rebuild to be powered by alternative fuels such as the liquefied natural gas (LNG) and liquefied petroleum gas (LPG) (Bergqvist et al., 2015). In this study, two broad options were explored to briefly examine how advanced technologies can affect the unit impact (per ton·km) of GHG emissions from a bulk carrier. The baseline was a heavy-fuel-driven bulk carrier with sulphur content of 1.0 wt.%. The two scenarios are as follows; 1) when the fuel is converted to low-sulphur fuel (light fuel) with a sulphur content of 5 wt.%; and 2) when a LNG-driven bulk carrier is used instead of heavy-fuel driven bulk carrier. The life-cycle inventory (LCI) dataset for the three types of bulk carriers was derived from the Ecoinvent database (Ecoinvent, 2019).

The results reveal that the GHG emissions of the heavy-fuel-driven bulk carrier were 1.05e-02 kg CO_2e/ton·km (Figure 27). If the fuel was switched to a light fuel (sulphur content of 0.5 wt.%), the GHG emissions decreased by 21%, representing 1.2e-02 kg CO_2e/ton·km. In addition, the LNG-driven bulk carrier was also shown to somewhat reduce the GHG emissions, representing 8.8e-03 kg CO_2e/ton·km, which was 41% less than those of the heavy-fuel-driven bulk carrier. This result shows the potential reductions based on two options without political and economic perspectives. With the new IMO regulation, the environmental impacts will be reduced far more to comply with the required limit.

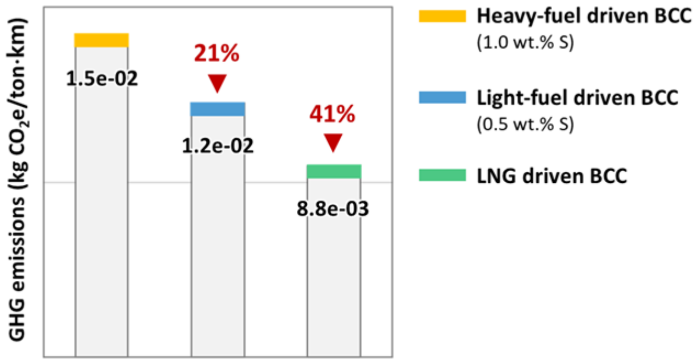


Figure 27 Comparison of greenhouse gas (GHG) emissions of a bulk-commodity carrier (BCC) based on three types of fuel. The sulphur content of heavy and light fuels are 1.0 and 0.5 wt.% S, respectively. LNG is liquefied natural gas.

This study proposes "eco-labeling" as a strategy to encourage better choices, production, and consumption of eco-friendly crops. Eco-labeling, an environmental labeling system, is an effective way to inform consumers about the GHG emissions of products considering the life-cycle (ISO, 2018). This system plays an important role in reducing environmental pollutants and the use of resources and energy during the production stage; it also encourages eco-friendly production and consumption (Hong, 2011).

South Korea is a good example of this eco-certificated system. Eco-labeling for organic, low-pesticide, and non-pesticide (pesticide-free) agricultural products is prevalent in South Korea (Kim, 2017). The market value and overall production area of organic agricultural products have notably increased by 153% and 113% (Figure 28), respectively, over the last 10 years from 142 million US dollars and 9,279 ha in 2007 to 360 million US dollars and 20,673 ha in 2017 (EAPC, 2019; Jung et al., 2018). The production area of non-pesticide agricultural products has also been extended by 118% from 27,888 ha to 59,441 ha in the same period (EAPC, 2019). This change implies that many people have increasingly bought these products even though they have to pay more for the eco-labeling option.

Forest certification of the Forest Stewardship Council is a key example of a starting point for eco-labeling. Forest certification separates the forest management (FM) certification and the chain of custody (CoC) certification (FAO, 2019). The FM certification guarantees that forest owners and managers' processes and operations meet the standards. The CoC certification verifies that products are handled correctly at every stage from forest to shelf for businesses manufacturing or trading products. These certifications help decision makers create incentives for sustainable forest management and the timber trade (Miteva et al., 2015). Similar standards could be applied to the crop trade.

Fair trade is also a good illustration of this type of strategy. People want to buy fair-trade coffee to promote the social welfare of producing countries, even though they have to pay more for a fair-trade option (Goff, 2016). The same concept can be applied to the crop trade

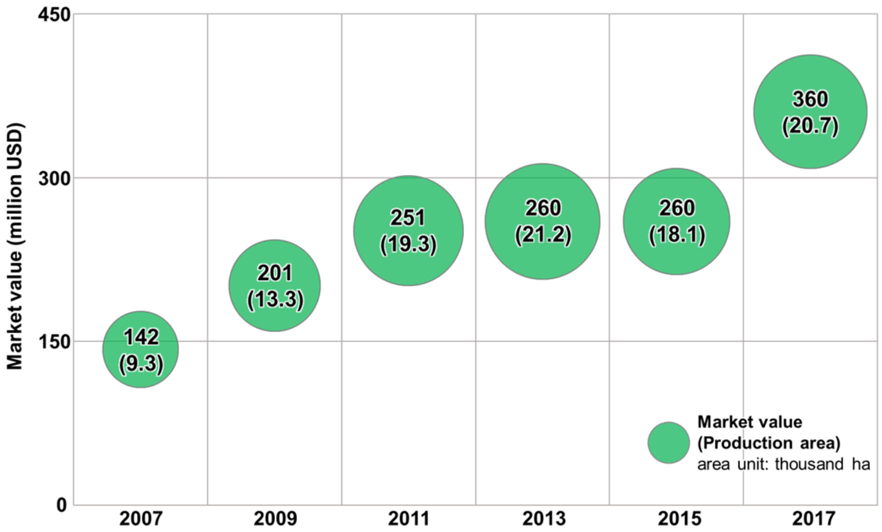


Figure 28 Market value and production area of eco-labeled agricultural products (organic) in South Korea (2007-2017). The size of the green dots displays the size of the production area. The upper value and lower value indicate the market value and production area, respectively.

for a better environment and to motivate production and consumption of eco-certified crops. The eco-labeling option will make traded crops more attractive. In addition, people's preferences can shift away from cheaper crops to environmentally better crops. Appropriate policy instruments will help decision-makers formulate a better environment for the international crop trade.

This study characterizes the spatial environmental impacts associated with port-level corn exports by linking the movement of corn from fields to ports and ultimately to table. Crop trading companies and their partners can refer to the present study to shift crop trading strategies away from exporting or importing high-impact crops to lower-impact ones. Supporting subsidies (or incentives) for importing companies and reducing tariffs on lower-impact crops will have considerable power in encouraging customers to purchase these crops. Importing crop based on the production impact can help generate the economic effects of the large-scale demand for imported crops. Increased demand for lower-impact crops would drive up prices of the crops. Given that the international agriculture sector struggles to deal with environmental challenges, this study can provide a starting point for alleviating the environmental impact of the international crop trade considering both the production and transportation impact of imported crops.

Chapter V. Conclusion

Growth of the international crop trade has increased harmful environmental impacts. In particular, trading crops has resulted in environmental pollutants such as greenhouse gases (GHGs), fine particulate matters ($PM_{2.5}$), and a number of other undesirable substances for the environment. The environmental impacts of the crop trade has rapidly become a concern as the international crop trade is expected to continue growing in the future.

Environmental implications based on “food miles” have received much attention in recent years as environmental concerns about the international crop trade continue to grow. Many studies have used the concept of food mile to analyze the environmental impacts of traded crops. However, most studies on food miles have mostly focused on the transportation of the crops even though crop production typically causes greater environmental impacts than crop transportation.

Crop production is widely known to cause high GHG emissions and deteriorating water quality because crop cultivation needs great amounts of fertilizer, energy, and various synthetic inputs. In addition, the crop production impact depends heavily on the regions where crop are produced because the regional input amounts for crop production vary widely. These spatial differences in crop production impacts widely varies. This spatial differences in crop production impacts can determine the environmental variability of imported crops based on the supply regions.

This study estimated the environmental impacts embedded in the crop trade and evaluated how the export port choice considering the crop supply region can affect the environmental impacts of imported crops. To estimate the mobility of major imported crops (wheat, corn, and soybeans), this study modeled two mobility optimization models. The model with food miles incorporated the optimal distribution to minimize transportation distances from origin to destination. The food mile model focused on evaluating GHG and $PM_{2.5}$ emissions in the transportation stages of major imported crops. The model with transportation costs encompassed the movement of US export corn from the producing counties to the export ports and the movement of embedded GHG emissions and irrigated water use of the corn including both production and transportation stages. Finally, potential GHGs reductions and irrigated water savings based on the optimal selected port was evaluated using the results of the US corn impact. The potential motivations were discussed to support this port decision and eventually for lead to a better environment.

The food miles of major imported crops declined from 2015 to 2017: 189 billion ton·km in 2015 and 147 billion ton·km in 2017. The food miles of Wheat represented 19% (36 billion ton·km) and 27% (40 billion ton·km) of the food miles of the major crops in 2015 and 2017, respectively. The crop with the most food miles was corn, which accounted for 70% (130 billion ton·km) and 60% (90 billion ton·km) of the food mile of the major crops in 2015 and 2017, respectively.

soybeans had the smallest share of the major crops, representing 22 billion ton·km in 2015 (11%) and 17 billion ton·km in 2017 (11%).

The unit impact (per ton·km) of GHG and $PM_{2.5}$ emissions of transportation modes was evaluated to compare the environmental impact of each transportation stage. The environmental impact in two categories differed depending on the transportation mode. The GHG emissions were much greater in truck transportation (1.29e-01 kg CO_2e/ton·km) compared to the other transportation modes. In contrast, $PM_{2.5}$ emissions were highly generated when crops were transported by rail (9.42e-04 kg $PM_{2.5}$e/ton·km). The bulk-commodity carrier (BCC) for maritime transportation showed the least value in both environmental categories, emitting 3.24e-03 kg CO_2e/ton·km of GHG and 2.03e-04 kg $PM_{2.5}$e/ton·km of $PM_{2.5}$. The fleets that are primarily used for the crop trade like BCC have a relatively low environmental impact due to the large volumes of crops that can be shipped at a time.

For the GHG emissions, the land transportation stage (field-to-export) of the major crops had 50% of the total emissions of the transportation stages, largely attributed to the high GHG emissions of truck and rail transportation. In contrast, $PM_{2.5}$ emissions tended to be higher in the maritime stage. The $PM_{2.5}$ emissions in the maritime stage were 71% (35 thousand tons $PM_{2.5}$e) and 64% (26 thousand tons $PM_{2.5}$e) of the total emissions among all transportation stages in 2015 and 2017, respectively. The categorical environmental implications can differ not only in GHG and $PM_{2.5}$ emissions but also other environmental impact categories; thus, these results highlight the need for further examination of the other impact categories.

To estimate the environmental impact in production and transportation stages, US corn was selected as the target. Using a county-level supply chain model of the US export corn, this study evaluated port-level intensities of GHG emissions and irrigated water use in the production stage of exported corn. The corn production impact of GHG embedded in exported corn at the port level was 0.363 kg CO_2e/kg on average (0.187-0.549 kg CO_2e/kg). The maximal irrigated water use at the port level was 0.873 m^3/kg, however, the average irrigated water of 0.135 m^3/kg on average was used in the production of US export corn. The large difference between the maximal and average use was affected by the fact that some ports linked non-irrigating counties, including ports of Portland (Maine) and Dallas-Fort Worth (Texas). This port-level variation in the corn production impact reveals that exporting or importing environmentally better corn is possible by selecting a port with less impacts considering the spatial trends of corn producing counties.

Therefore, this study evaluated how export port selection considering the port-level variation of the environmental impacts can affect GHG emissions and irrigated water use of imported corn. The export ports that could minimize environmental impact were selected considering the regional variability of corn production impact among the eight ports exporting corn to South Korea. From an irrigated water use perspective, the change in corn production impact according to port selection was only considered. The effects of port selection on the GHG emissions were analyzed for production and transportation impacts since emissions are generated from the both production and transportation stages.

In the GHG emissions analysis, the port of Portland, Oregon had minimal GHG emissions and enough capacity for exports to South Korea. When the corn is exported through the Portland port, the corn production impact can be reduced by 7% (11 million kg CO_2e). However, in the transportation stages, the GHG emissions were estimated to increase 1.5% (0.5 million kg CO_2e), even though the food miles of exported corn was expected to decline by 18% (1 billion ton·km). The main drivers of this trend are the differences in the unit impact of transportation modes and the change in food miles of the land and maritime stages.

Even if the food miles of maritime transportation to South Korea were reduced by selecting the optimal port, the food miles of land transportation in the US would rise. This result indicated a more negative effect on the GHG emissions since traveling longer distances by land was extended. As a result, the expected reduction of GHG emissions was 10 million kg CO_2e, including in both the production and transportation stages. The value of reduced GHG emissions was estimated to be 0.22 million US dollars based on the prices of Certified Emission Reductions in South Korea (0.022 US dollars per kg of GHG in January 2019). This finding implies that crop trading companies and their partners can reduce emissions by selecting the optimal port considering the supply regions.

For the irrigated water use, the port with the lowest use of irrigated water did not accommodate the export needs of South Korea. Thus, four ports were selected (ports of New York City, Norfolk, San Francisco, and Portland) by allocating the corn based on the capacity and embedded irrigation water use of each port. Corn trading through the selected ports could save irrigated water use by 88% (44 million m^3) compared to that of the current eight ports.

The approaches and results of this study could help trading companies and their partners trade eco-friendly crops with a spatially explicit environmental impact. Although analyzing how to reduce the GHG emissions by selecting the optimal port was examined to increase for the transportation stages, new-technology such as converted fuel and scrubber installation could improve the environmental impact from transportation in the future. Additionally, the emerging regulation of the International Maritime Organization (IMO) will regulate the maximum amount of sulphur content in ships' fuel oil to 0.5%, down from the current 3.5%. This regulation could lead to far more significant reductions in the environmental impact from transportation.

This study also proposed "eco-labeling" to encourage eco-friendly trading. Eco-labeling is a practical way to inform consumers of the environmental impact of the products they purchase considering the life-cycle of the products. South Korea is a good illustration of purchasing eco-certificated products such as organic agricultural products. The market value of organic agricultural products in South Korea has grown remarkably and has increased 153% over the last decade (2007-2017) from 142 million US dollars to 360 million US dollars. This sharp increase indicates that many people want to buy these products, even though the eco-labeling option is more expensive. Fair trade is also a good example to support the eco-labeling strategy. Many people want to buy fair-trade coffee for the social welfare of the producing countries, even though they must pay more for a fair-trade option.

In closing, trading companies and other consumers can find better ways to choose lower-impact crops. Application of appropriate policy instruments such as supporting subsidies for companies that import lower-impact crops and reducing tariffs on these crops will help motivate decision that will promote a better environment. When decision-makers seek to target interventions that improve the environment considering both the production and transportation stages of traded crops, a healthier international crop trade environment will not be a dream.

References

Agricultural Management Information System Statistics (AMIS), 2019. AMIS Market Database. Accessed 10 Jun 2019.

Animal and Plant Quarantine Agency (APQA), 2019. Statistics on Quarantine of Animals and Livestock Products. Available at: https://eminwon.qia.go.kr/statistics. Accessed 5 Jun 2019.

Bajgain, R., 2018. Long Term Dynamic of Cropland Use in Iowa State – Corn and Soybean Rotation. *The Journal of ACTA Scientific Agriculture*, 2(10): 20-27.

Ballingall, J. and N. Winchester, 2008. Miles and More: A Quantitative Assessment of the 'Food Miles' Movement.

Ballingall, J. and N. Winchester, 2010. Food Miles: Starving the Poor?. *The Journal of the World Economy*, 33(10): 1201-1217. DOI: 10.1111/j.1467-9701.2010.01270.x.

Bergqvist, R., Turesson, M., and A. Weddmark, 2015. Sulphur Emission Control Areas and Transport Strategies - The Case of Sweden and The Forest Industry. *The Journal of European Transport Research Review*, 7(10).

Bernatz, G., 2009. Apples, Bananas, and Oranges: Using GIS to Determine Distance Travelled, Energy Use, and Emissions from Imported Fruit. *The Journal of Resources Analysis*. 11:1-15.

Carlson, K., Gerber, J., Mueller, N., Herrero, M., MacDonald, G., Brauman, K., O'Connell, C., Johnson, J., Saatchi, S., and P. West, 2017. Greenhouse Gas Emissions Intensity of Global Croplands. *Nature Climate Change*, 7: 63-68.

Census of Agriculture (COA), 2014. 2012 corn production data from "Quick Stats" (US Dept of Agriculture, National Agricultural Statistics Service, Washington, DC).

Centre for Transport Strategies (CTS), 2014. Ukraine-Agricultural Trade, Transport, and Logistic Advisory Services Activity. World Bank.

Chaves, M. and M. Oliveira, 2004. Mechanisms Underlying Plant Resilience to Water Deficits: Prospects for Water-Saving Agriculture. *The Journal of Experimental Botany*, 55(407): 2365-2384.

Chin, T., Tat, H., and Z. Sulaiman, 2015. Green Supply Chain Management, Environmental Collaboration and Sustainability Performance. *Procedia CIRP*, 26(2015): 695-699.

Choi, J., Woo, B., and Y. Hwang, 2010. A Study on Conceptualization of Food Self-Sufficiency Rate and Reestablishing its Targe in Korea. The Ministry of Agriculture, Food and Rural Affairs (MAFRA) (in Korean).

Christensen, L.O., Galt, R.E., and A. Kendall, 2018. Life-cycle Greenhouse Gas Assessment of Community Supported Agriculture California's Central Valley. *The Journal of*

Renewable Agriculture and Food Systems, 33(5): 393-405. DOI: 10.1017/S1742170517000254.

Chukalla, A.D., Krol, M.S., and A.Y. Hoekstra, 2015. Green and Blue Water Footprint Reduction in Irrigated Agriculture: Effect of Irrigation Techniques, Irrigation Strategies and Mulching. *The Journal of Hydrology and Earth System Sciences*, 19(12), 4877-4891.

Coley, D., Howard, M., and W. Michael, 2009. Local Food, Food Miles and Carbon Emissions: A Comparison of Farm Shop and Mass Distribution Approaches. *The Journal of Food Policy*, 34(2): 150-155. DOI: 10.1016/j.foodpol.2008.11.001.

Conley, D.M. and A. George, 2008. Spatial Marketing Patterns for Corn under the Condition of Increasing Ethanol Production in the US. *International Food and Agribusiness Management Review*, 11(1030-2016-82737), 81-98.

Cristea, A., Hummels, D., Puzzello, L., and M. Avetisyan, 2013. Trade and the Greenhouse Gas Emissions from International Freight Transport. *The Journal of Environmental Economics and Management*, 65(1): 153-173. DOI: 10.1016/j.jeem.2012.06.002.

Dalin, C. and I. Rodríguez-Iturbe, 2016. Environmental Impacts of Food Trade via Resource Use and Greenhouse Gas Emissions. *Environmental Research Letters*, 11.

Dellink, R., Hwang, H., Lanzi, E., and J. Chateau, 2017. International

Trade Consequences of Climate Change. *OECD Trade and Environment Working Papers*, 2017/01, OECD Publishing, Paris. DOI: 10.1787/9f446180-en.

Denicoff, M.R., Prater, M.E., and P. Bahizi, 2014. Corn Transportation Profile.

Department of Infrastructure, Regional Development and Cities (DIRDC). 2009. Road and Rail Freight: Competitors or Complements?. Australian Government.

Ecoinvent, 2019. Life-Cycle Inventory of Transportation Modes Database.

Economic Research Service (ERS), 2018. Export quantity of US corn., Economic Research Service of the US Department of Agriculture (USDA).

Energy Information Administration of the US (EIA), 2018. Energy and The Environment Explained: Greenhouse Gases and The Climate. US Energy Information Administration.

Engelhaupt, E., 2008. Do Food Miles Matter?. *The Journal of Environmental Science & Technology*, 42(10).

Environmental Protection Agency of the US (EPA), 2017. Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), US Environmental Protection Agency.

Environment Friendly Agricultural Products Certification (EAPC), 2019. Eco-certification Statistics. Accessed 29 May 2019.

Envision Transportation, 2011. The transportation of grain. Center for Transportation Research (CTR)

Farmeers Weekly (FW), 2006. Farmers Weekly Food Miles Campaign - Join the Battle for Local Food. Available at: https://www.fwi.co.uk/arable.

Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., Johnston, M., Mueller, N., O'Connel, C., Ray, D., West, P., Balzer, C., Bennett, E., Carpenter, S., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., and D. Zaks, 2011. Solutions for a Cultivated Planet. *Nature*, 478: 337-342.

Food and Agriculture Organization of the United Nations (FAO), 1999. Implications of Economic Policy for Food Security: a Training Manual. Available at: http://www.fao.org/docrep.

Food and Agriculture Organization of the United Nations (FAO), 2017. The Future of Food and Agriculture - Trends and Challenges.

Food and Agriculture Organization of the United Nations (FAO), 2019. Forest Certification, Basic Knowledge.

Food and Agriculture Organization of the United Nations, Statistics (FAOSTAT), 2019. Food and Agriculture Data. Available at: http://www.fao.org/faostat..

Fortenbery, T. and H. Park, 2008. The Effect of Ehtanol Production on the U.S. National Corn Price. *Research in Agricultural & Applied Economics*. DOI: 10.22004/ag.econ.92200.

Fries, N. and S. Hellweg, 2014. LCA of Land-based Freight Transportation: Facilitating Practical Application and including Accidents in LCIA. *The International Journal of Life Cycle Assessment*, 2014(19): 546-557. DOI: 10.1007/s11367-013-0657-2.

Future Directions International (FDI), 2014. China's Increasing Food Imports: The Impact on Global Markets. *Global Food and Water Crises SWA Articles*.

Godar, J., Suavet, C., Gardner, T., Dawkins, E., and P. Meyfroidt, 2015. Balancing Detail and Scale in Assessing Transparency to Improve the Governance of Agricultural Commodity Supply Chains. *Environmental Research Letters*, 11(2016) 035015. DOI: 10.1088/1748-9326/11/3/035015.

Goff, S.C., 2016. Fair Trade: Global Problems and Individual Responsibilities. *The Journal of Critical Review of International Social and Political Philosophy*, 21(4).

Google Maps, 2018. www.google.com/maps. Accessed Jan 2018.

Hill, H., 2008. Food Miles: Background and Marketing. National Center for Appropriate Technology (NCAT).

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., and B.D. Richter, 2012. Global Monthly Water Scarcity: Blue Water

Footprints Versus Blue Water Availability. *The Journal of Public Library of Science One*, 7(2), e32688.

Hong, J., 2011. Environmental Business Management and Korea Ecolabeling Program. Special Issues Global Green Growth Policy (GGGP), 37. 2011. 01. 18. (in Korean).

Hopkinson, J., 2018. Overview of U.S. - South Korea Agricultural Trade. Congressional Research Service (CRS).

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: IPCC Fourth Assessment Report (AR4).

International Maritime Organization (IMO), 2019. Sulphur 2020 - Cutting Sulphur Oxide Emissions, Vol. 2019, International Maritime Organization (IMO).

International Organization for Standardization (ISO), 1997. ISO 14040: Environmental Management - Life Cycle Assessment - Principlies and Framework.

International Organization for Standardization (ISO), 2000. ISO 14042: Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment.

International Organization for Standardization (ISO), 2006. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

International Organization for Standardization (ISO), 2018. ISO 14024:

Environmental Labels and Declarations - Type I Environmental Labeling - Principles and Procedures. Second Edition.

Jung, H., Sung, J., and H. Lee, 2018. Current Status and Issues of Eco-friendly Agricultural Products Market in Korea. The Korea Rural Economic Institute (KREI).

Kalluri, S., 2016. Comparative Life Cycle Assessment of Road and Multimodal Transportation Options - A Case Study of Copperwood Project. Dissertations, Master's Thesis and Master's Reports, Michigan Technological University, MI, USA.

Kampa, M. and E. Castanas, 2008. Human Health Effects of Air Pollution. *The Journal of Environmental Pollution*, 151(2): 362-367. DOI: 10.1016/j.envpol.2007.06.012.

Kastner, T., Erb, K., and H. Haberl, 2014. Rapid Growth in Agricultural Trade: Effects on Global Area Efficiency and the Role of Management. *Environmental Research Letters*, 9(2014) 034015. DOI: 10.1088/1748-9326/9/3/034015.

Kerridge, B., Hornbuckle, J., Christen, E., and R. Faulkner, 2008. Soil Spatial Variability Effects on Irrigation Efficiency.

Kim, C., Kim, S., Jung, C., and K. Suh, 2018. Analysis of Environmental Impacts and Alternative Scenarios of Transportation Stages on Food Miles for Major Imported Crops. *The Journal of Korean Society of Agricultural Engineers*, 60(3): 51-61. DOI: 10.5389/KSAE.2018.60.3.051 (in Korean).

Kim, H., 2017. A Study on the Development Plan for Agriculture, Rural Area, and Food Industry. The Ministry of Agriculture, Food and Rural Affairs (MAFRA) (in Korean).

Kim, J. et al., 2012. A Study on the Development Plan of Agriculture, Rural Fishing and Food Industry. The Korea Rural Economic Institute (KREI).

Kim, S., 2017. Life-Cycle Environmental Implications of Eco-Labelling for Rice Farming Systems. Master's Thesis. Seoul National University, Seoul.

Kim, T., 2012. Management of Food Mileage and Realization of Low Carbon Society. Korea Rural Economic Institute (KREI).

Kissinger, M., 2012. International Trade Related Food Miles-The Case of Canada. *The Journal of Food Policy*, 37(2): 171-178. doi:10.1016/j.foodpol.2012.01.002.

Knoema, 2019. World Exports and Imports of Agricultural Products. Available at: https://knoema.com.

Knudsen, M., Yu-Hui, Q., Yan, L., and N. Halberg, 2010. Environmental Assessment of Organic Soybean (Glycine max.) Imported from China to Denmark: a Case Study. *The Journal of Cleaner Production*, 18(2010): 1431-1439. DOI: 10.1016/j.jclepro.2010.05.022.

Korea Agro-Fisheries & Food Trade Corporation (aT), 2017. 2016 Processed Food Subdivision Market Status.

Korea Customs Service (KCS), 2019. Trade Statistics Database-Total Export & Import.

Korea Feed Association (KFA), 2018. Registered Group. Available at: http://www.kofeed.org/mem/factory. Accessed Jan 2018.

Korea Flour Mills Industrial Association (KOFMIA), 2018. Registered Group. Available at: http://www.kofmia.org/member. Accessed Jan 2018.

Korean Statistical Information Service (KOSIS), 2018. Status of Agricultural land area. Available at: http://kosis.kr/statHtml.

Korean Statistical Information Service (KOSIS), 2019. Agricultural Production: Wheat. Available at: https://kosis.kr.

Kosior, J., Prentice, B., and E. Vido, 2002. A Mixed Logistics Strategy for Grain: The Competitiveness of Containers Versus Bulk. The Transport Institute of Agriculture and Agri-Food Canada.

Krueger, S., 2018. How Much Nitrogen Does Your Corn Need?. Farmer's Business Network (FBN). Available at: https://emergence.fbn.com/agronomy. Accessed 1 Feb 2019.

Lang T., 1999. The Complexities of Globalization: The UK as a Case Study of Tensions within the Food System and the Challenge to Food Policy. *The Journal of Agriculture and Human Values*, 16: 169-185. DOI:10.1023/A:1007542605470.

Lewis, M. and A. Mitchell, 2014. Food Miles: Environmental Protection or Veiled Protectionism?. *Michigan Journal of International Law*, 35(3): 580-620.

Maston, P., Parton, W., Power, A., and M. Swift, 1997. Agricultural Intensification and Ecosystem Properties. *Science*, 277(5325): 504-509. DOI: 10.1126/science.277.5325.504.

Meisterling, K., Samaras, C., and V. Schweizer, 2009. Decisions to Reduce Greenhouse Gases from Agriculture and Product Transport: LCA Case Study of Organic and Conventional Wheat. *The Journal of Cleaner Production*, 17(2): 222-230. DOI: 10.1016/j.jclepro.2008.04.009.

Merchan, A.L., Belboom, S., and A. Leonard, 2017. Life Cycle Assessment of Freight Transport in Belgium. BIVEC/GIBET Transport Research Days 2017, Proceedings of the BIVEC-GIBET Transport Research Days 2017.

Millstone, E., and T. Lang, 2013. The Atlas of Food with a New Introduction.

Miteva, D., Loucks, C., and S. Pattanayak, 2015. Social and Environmental Impacts of Forest Management Certification in Indonesia. *The Journal of PLoS ONE*, 10(7): e0129675.

National Agricultural Statistics Servics (NASS) of the USDA, 2019. Crop Production Database.

National Corn Growers Association (NCGA), 2008. World of Corn 2007.

National Corn Growers Association (NCGA), 2018. World of Corn 2017.

National Oceanic and Atmospheric Administration (NOAA), 2019. State of the Climate Reports by the National Centers for Environmental Information.

Oak Ridge National Laboratory (ORNL), 2018. Inter-County Distance Matrix. Available at: https://cta.ornl.gov/transnet/SkimTree.htm Accessed 15 Nov 2018.

Opara, L.U. and F. Mazaud, 2001. Food Traceability from Field to Plate. The Journal of Outlook on Agriculture, 30(4): 239-247.

Opara, L.U., 2003. Traceability in Agriculture and Food Supply Chain: A Review of Basic Concepts, Technological Implications, and Future Prospects. The Journal of Food, Agriculture & Environment, 1(1): 101-106.

Park, D., and J. Seung, 2013. Policies to Increase self-Sufficieany of Crops. Korea Rural Economic Institute (KREI) (in Korean).

Park, S., 2013. Transport infrastructure problems as grain production increases in Brazil. Korea Trade-Investment Promotion Agency (KOTRA). (in Korean).

Pavlović, D. and B. Radoš, 2016. The Impact of Transport on International Trade Development. *The Journal of Acta Economica Et Turistica*, 2(1): 13-28.

Paxton, A., 1994. The Food Miles Report: the Dangers of Long Distance Food Transport. London: Sustainable Agriculture, Food and Environment Alliance (SAFE).

Pelton, R., 2019. Spatial Greenhouse Gas Emissions from US County Corn Production. *The International Journal of Life Cycle Assessment*. DOI: 10.1007/s11367-018-1506-0.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and R. Seidel, 2005. Environmental, Energetic, and Economic Compaisons of Organic and Conventional Farming Systems. *The Journal of BioScience*, 55(7): 573-582.

Pirog, R., Pelt, T., Enshayan, K., and E. Cook, 2001. Food, Fuel, and Freeways: An Iowa Perspective on How Far Food Travels, Fuel Usage, and Greenhouse Gas Emissions. Leopold Center for Sustainable Agriculture.

Pretty, J.N., Ball, A.S., Lang, T., and J.I. Morison, 2005. Farm Costs and Food Miles: An Assessment of the Full Cost of the UK Weekly Food Basket. *The Journal of Food Policy*, 30(1): 1-19.

Rosegrant, M.W., Ringler, C., and T. Zhu, 2009. Water for Agriculture: Maintaining Food Security under Growing Scarcity. *Annual Review of Environment and Resources*, 34: 205-222.

Searates, 2019. Find the Best Freight Quote. Available at: https://www.searates.com Accessed 3 Oct 2018.

Shin, Y., Son, M., and D. Park, 2018. Korean Agriculture in the World by Statistics. Korea Rural Economic Institute (KREI) (in Korean).

Ślusarczyk, B., 2010. Transport Importance in Global Trade, ALS. Advanced Logistic Systems. Theory and Practice, 2010(4).

Smith, A., Watkiss, P., Tweddle, G., McKinnon, A., Browne, M., Hunt, A., Treleven, C., Nash, C., and S. Cross, 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final Report produced for UK Department for Environment, Food and Rural Affairs (DEFRA). Report Number ED50254, Issue 7. Didcot, Oxfordshire, AEA Technology.

Smith, T.M., Goodkind, A.L., Kim, T., Pelton, R.E., Suh, K., and J. Schmitt, 2017. Subnational Mobility and Consumption-Based Environmental Accounting of US Corn in Animal Protein and Ethanol Supply Chains. *Proceedings of the National Academy of Sciences*, 114(38): E7891-E7899. DOI: 10.1073/pnas.1703793114.

Sparger, A. and M. Nick, 2015. Transportation of U.S. Grains. United States Department of Agriculture (USDA).

Spielman, K., 2001. Food Supply Chains and Food-Miles: An Analysis for Selected Conventional, Non-Local Organic and Other-Alternative Foods Sold in Miuuoula, Montana. Master's Thesis, The University of Montana, Missoula, MT.

Statistics Korea (KOSTAT), 2018. the Result of Rice Production in 2018 (in Korean).

Stocton, M. and D. Broadhead, 2018. The Corn/Soybean Rotation and Profitability. Agricultural Economics of University of Nebraska, Lincoln: Cornhusker Economics.

Suh, K., Suh, S., and T. Smith, 2011. Implications of Corn Prices on Water Footprints of Bioethanol. *The Journal of Bioresource Technology*, 102(2011): 4747-4754.

The Van Trump Report (TVTR), 2015. Brazil Soybean Production by State.

US Department of Agriculture (USDA), 2014. World Agricultural Outlook Board (WAOB). Available at: https://www.usda.gov.

US Department of Agriculture (USDA), 2016. World Agricultural Outlook Board (WAOB). Available at: https://www.usda.gov.

US Department of Agriculture (USDA), 2019a. World Agricultural Supply and Demand Estimates (WASDE) report. Available at: https://www.usda.gov/oce/commodity/wasde.

US Department of Agriculture (USDA), 2019b. Crop Production 2018 Summary.

US Department of Agriculture (USDA), 2019c. Foregin Agricultural Service, Grain: World Markets and Trade. Available at: https://www.fas.usda.gov/data.

UStrade. 2018. Export value of US corn, USA Trade Census of the US Department of Commerce (USDC).

Vörösmarty, C.J., Green, P., Salisbury, J., and R.B. Lammers, 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, 289(5477): 284-288. DOI: 10.1126/science.289.5477.284.

Wadhwa, M. and Bakshi M.P.S., 2016. Application of Waste-Derived Proteins in the Animal Feed Industry. *The Journal of Protein Byproducts*, 2016: 161-192.

Wakeland, W., Cholette, S., and Kumar V. 2012. Food Transportation Issues and Reducing Carbon Footprint. *Green Technologies in Food Production and Processing*, Food Engineering Series, Springer. DOI:10.1007/978-1-4614-1587-9_9.

Wallander, S., Claassen, R., and C. Nickerson, 2011. The Ethanol Decade: An Expansion of U.S. Corn Production, 2000-09. US Department of Agriculture (USDA).

Weber, C.L. and H.S. Matthews, 2008. Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *The Journal of Environmental Science and Technology*, 42: 3508-3513.

Westhoff, P., 2010. The Economics of Food: How Feeding and Fueling The Planet Affects Food Prices. New Jersey, NJ: FT Press.

Wynen, E. and D. Vanzetti. 2008. No Through Road: The Limitations of Food Miles. Asian Development Bank (ADB) Institute.

Yang, Y. and R. Heigungs, 2017. A Generalized Computational

Structure for Regional Life-cycle Assessment. *The International Journal of Life Cycle Assessment*, 22: 213-221. DOI: 10.1007/s11367-016-1155-0.

Yoon, B., Jeong, R., Lee, G., Woo, H., and J. Park, 2010. The Study on Food Mileage Relating to Nations' Dietary Life. The Ministry of Environment (in Korean).

Abstract in Korean

국제 곡물 공급망 분석을 통한 수입곡물의 환경영향평가

김 찬 우
국제농업기술학과
서울대학교 대학원

국제 곡물교역량이 2001년에 2억 9,600만 ton에서 2016년에 78% 증가한 5억 2,600만 ton으로 지난 15년간 지속적으로 증가해왔다. 교역규모(trade value)도 같은 기간 동안 1,040억 USD에서 3,560억 USD로 242% 증대되었으며, 곡물의 교역량과 규모는 계속해서 증가할 것으로 예상되고 있다. 지역적인 불균등한 인구분포와 곡물의 생산과잉과 부족의 차이는 곡물의 국제적 교역량을 증가시켜왔다. 예를 들어, 곡물의 주요수출국인 미국의 곡물 수출량은 2001년부터 2016년까지 지난 15년 동안 1억 1,000만 ton에서 1억 4,500만 ton으로 32% 증가한 반면, 중국은 많은 양의 곡물을 다른 국가에 의존하면서 수입량이 2,600만 ton에서 1억 1,100만 ton으로 321% 상승하였다.

이러한 곡물 무역은 단지 생산과잉과 부족으로 인한 차이를 채우기

위해 발생하는 것은 아니다. 운송과 저장기술의 발달은 더 많은 양의 곡물이 보다 먼 거리를 이동할 수 있게 하면서 곡물을 향한 접근성을 더욱 원활하게 하였고, 사람들의 다양한 식품에 대한 선호도 변화는 곡물의 가용성을 높이면서 곡물무역의 확대에 기여하였다. 또한 곡물의 많은 품목은 기후를 포함한 여러 조건으로 인해 생산이 가능한 국가가 있으나, 그렇지 못한 국가도 있기 때문에 무역이 필연적으로 발생한다. 우리나라의 경우 매년 커피소비량이 200만 ton에 달하지만, 커피생산량은 소비량의 약 1%에 불과하다. 국제적인 곡물교역이 활발해지면서, 한 국가의 제한적인 곡물생산은 더 이상 사람들의 선호도를 한정하지 않는다.

국제적인 곡물교역량의 증가와 함께 곡물무역이 세계화되고 운송거리가 증가하면서 곡물의 교역과정에서 발생하는 부정적인 환경영향이 커지고 있다. 국제적인 곡물무역의 교역과정에서 온실가스, 미세먼지를 포함한 많은 환경오염물질이 발생하며, 앞으로도 곡물의 국제교역량이 지속적으로 상승하리라 전망되면서 이에 따른 환경영향도 계속해서 증가할 것으로 예상되고 있다. 곡물교역이 환경에 미치는 영향에 대한 사람들의 관심이 지속적으로 높아지면서, 곡물교역의 환경영향은 국제적 농업 정책의 환경 및 지속가능성 목표를 달성하기 위한 주요 대상이 되고 있다. 우리나라의 경우에도 국내 수입곡물의 대표적 수출국이 우리나라와 원거리에 위치한 미국, 호주, 브라질 등으로 나타나면서, 먼 거리를 이동하는 수입곡물의 환경영향을 향한 관심이 커지고 있다.

곡물교역의 환경영향을 향한 관심이 높아지면서 “푸드마일” 기반의 운송과정을 중심으로 한 환경영향이 주로 분석되고 있다. 푸드마일은 농산물 수출입에 대한 운송과정의 푸드마일을 고려하여 온실가스 발생량을 분석하는 등 다양한 방면에서 운송의 환경지표로서 활용되고 있다. The Farmers’ Weekly 매거진에서는 2006년 “Local food is miles better"이라는 슬로건과 함께 농식품의 푸드마일을 감축시키기 위한 campaign을 진행하기도 하였다. 푸드마일은 일반적으로 농식품이 생산지에서 소비지에 도달하기까지 이동한 총 운송거리로 정의되며, 이러한 푸드마일에 따른 환경영향의 문제를 줄이기 위한 방안으로 많은 사람들이 소비지에서 인접한 곳에서 생산된 농산물의 구입을 장려하고 있다. 하지만 대다수의 푸드마일 관련 연구들은 교역을 위한 운송과정에서 발생하는 환경영향만을 제한적으로 다루고 있어, 실제 교역을 위한 곡물의 생산과정에서 발생하는 생산지역별 환경영향을 고려한 연구는 부족한 실정이다.

생산과정의 환경영향이 운송과정에 비해 상대적으로 큰 비중을 차지하지만, 곡물의 생산과정에서 생산지역별 환경영향을 포함하기는 어렵다. 곡물은 생산단계에서 많은 양의 전기, 비료, 농업용수 등의 에너지를 필요로 하기 때문에, 이에 따른 환경영향은 온실가스 증대, 수자원 저하와 같이 광범위한 오염을 유발하는 것으로 인식되고 있다. 미국식품의 전과정에서 발생되는 온실가스는 생산과정에서 83%를 차지하는 반면, 운송과정에서의 발생량은 전체 발생량의 11%에 해당한다. 또한 덴마크에서 수입하는 중국산 대두의 생산과정에서 발생되는 환경영향은 전체 교역과정에서의 환경영향 중 55%를 차지한다.

또한 곡물생산과정의 기후와 투입물의 차이로 인해 배출되는 환경오염물질에 많은 차이가 존재하므로, 생산지역별 편차를 고려한 연구가 필요하다. 이러한 곡물 생산의 환경영향은 지리적 차이로 인해 국가별로도 큰 차이가 있으며, 한 국가 안에서도 지역별로 많은 차이를 보인다. 지역별 생산과정의 환경영향이 포함될 경우 실제 수출입 곡물의 환경영향은 크게 달라질 수 있다. 예를 들어, 생산과정의 환경영향이 상대적으로 높은 지역에서 생산된 수입곡물을 환경영향이 적은 지역에서 생산된 곡물로 대체한다면 교역곡물의 환경영향을 저감할 수 있다. 따

라서 보다 더 친환경적으로 생산된 수출입 곡물의 선택은 필연적인 곡물무역에서 발생하는 환경영향을 줄일 수 있는 방안이 될 것이라 생각되며, 이를 위해 푸드마일과 함께 생산지역별 생산과정의 환경영향을 포함한 평가가 요구된다.

하지만 국제곡물교역과 관련한 많은 정보가 있음에도 불구하고, 교역곡물을 공급하는 생산지에 대한 정보가 없어 곡물의 실제 생산지를 파악하기가 어렵다. 이에 환경적인 관점에서 교역곡물의 영향을 평가한 많은 연구들은 생산지역별 영농과정에서 발생하는 환경영향을 반영하지 못했다. 반면, Smith et al. (2017)은 구매비용과 운송비용의 최적화를 기반으로 한 옥수수의 이동경로 분석을 통해 미국에서 소비되는 옥수수의 생산지를 추정하고 생산지역별 영농과정의 환경영향을 평가하였다. 이러한 생산지의 추정방법을 교역곡물에 적용한다면 교역을 위해 수출항구에 공급되는 곡물의 생산단계와 운송단계를 포함한 환경영향을 평가할 수 있을 것으로 생각되며, 곡물의 공급지역별 환경영향의 차이를 고려하여 보다 친환경적인 곡물의 수입을 통해 환경영향 개선 잠재력을 평가할 수 있으리라 예상된다.

따라서 본 연구는 주요곡물에 대한 수입의존도가 90% 이상으로 높은 우리나라의 수입곡물을 대상으로 생산지로부터 소비지까지의 공급망을 분석하고 생산과정과 운송과정을 모두 포함한 환경영향을 평가해 보고자 하였다. 이를 위해 주요수입곡물의 운송경로 최적화를 통한 운송단계별 최소한의 푸드마일에 따른 환경영향을 온실가스를 포함한 다양한 환경영향 범주에 대해 분석해 보고, 푸드마일이 가장 높은 곡물인 옥수수에 대하여 대표적 수출국의 생산지에서 수출항구까지의 운송비용을 최소로 할 수 있는 항구별 공급망에 따른 환경영향을 평가하였다. 수출항에 공급된 옥수수의 생산지역별 영농과정의 환경영향 차이를 고려하여 환경영향을 최소화하기 위한 수출항의 선택이 곡물교역의 환경영향

에 어떠한 변화를 주는지 살펴보았으며, 환경영향이 적은 곡물의 수입을 위한 한국의 정책적 수단에 대해 논의하였다.

주요수입곡물의 푸드마일을 최소화할 수 있는 운송경로를 구성하기 위하여 가장 가까운 지점에서부터 곡물이 수입되어 국내에서 가장 가까운 소비지로 운송한다는 가정 하에 최소한의 거리를 적용하였다. 이를 위한 곡물의 주산지는 주요수출국 내에서 해당 곡물의 생산 비중을 높게 차지하고 있는 지역 중 주요 수출항에서 가장 근접하게 위치한 곳으로 지정하였다. 운송경로는 주요수입곡물의 주산지로부터 국내 소비지까지로 구성하였으며, 소비지는 곡물의 용도에 따라 제분공장, 사료공장, 도매시장으로 분류하였다. 세부적인 운송과정은 곡물별 주산지에서 수출항까지의 육로운송, 수출항에서 수입항까지의 해상운송, 수입항에서 소비지까지의 육로운송으로 나누어 단계별 경로를 구성하였다.

푸드마일 산정을 위한 주요수입곡물은 농림축산식품부에서 제공하는 국내 곡물별 자급률 자료를 바탕으로, 2017년 기준 총 수요의 90% 이상을 수입에 의존한 밀(99.1%), 옥수수(99.2%), 대두(93.0%)로 설정하였다. 분석연도는 가용할 수 있는 데이터 중 최신연도인 2017년과 최근 15년 사이에 곡물수입량이 가장 많았던 2015년을 기준으로 하였다. 주요수입곡물의 수입량과 주요수출국은 관세청의 수출입무역포털을 통해 구득하였으며, 주요수출국은 수입곡물별 상위 3곳의 수출국으로 선정하였다. 밀의 주요수출국은 미국, 호주, 우크라이나이며 옥수수는 미국, 브라질, 우크라이나, 대두는 미국, 브라질, 중국으로 조사되었다. 주요수출국 내의 육로운송, 수출항에서 수입항까지의 해상운송, 수입 이후 국내에서의 육로운송거리는 각각 Goolgle maps, Searates, Naver 지도의 최단경로 분석 기능을 활용하였다.

푸드마일에 따른 운송단계별 운송과정의 환경영향을 평가하기 위해서는 단계별로 서로 다른 운송수단의 환경영향이 고려되어야 한다. 이에

전과정평가(Life-Cycle Assessment, LCA)기법을 활용하여 각 운송단계에서 사용하는 운송수단별 환경영향을 분석하였다. LCA는 제품의 생산에서 폐기까지 전과정의 투입물과 산출물을 고려하여 잠재적인 환경영향을 정량적으로 평가하는 효과적인 방법이다. 본 연구는 LCA를 통해 운송단계별 운송수단의 단위푸드마일(ton・km)당 환경영향 발생량을 평가하였다. 운송수단의 환경영향범주는 LCIA TRACI에서 제시하고 있는 다양한 환경영향범주들 가운데, 기후변화에 많은 영향을 미치는 온실가스와 최근 국내외로 크게 이슈가 되고 있는 대기오염물질인 초미세먼지($PM_{2.5}$)를 대상으로 선정하였다.

운송과정의 환경영향과 함께 생산지역별 영농과정의 환경영향을 포함한 평가를 위하여 곡물의 공급망 분석을 통해 카운티 단위의 생산지를 추정하였다. 평가를 위한 곡물은 주요수입곡물 가운데, 2017년 기준 푸드마일이 가장 높았던 미국 옥수수를 대상으로 하였다. 공급망은 최적화(Optimization) 기법을 활용하여 미국의 옥수수 생산 카운티에서 옥수수의 수출항구까지, 두 지점간의 운송비용을 최소로 할 수 있도록 모의하였다.

옥수수의 카운티별 생산량은 US Department of Agriculture (USDA)에서 5년마다 출간하는 The Census of Agriculture (COA) reports의 카운티별 옥수수 생산자료를 사용하였다. 분석 연도는 가용할 수 있는 데이터 중 가장 최신 연도인 2012년을 기준으로 하였다. 미국의 수출항구별 옥수수 수출량은 Economic Research Service (ERS) of USDA에서 제시하는 2012년의 총 수출량 자료와 US trade census에서 제공하는 32곳의 옥수수 수출항별 수출규모(USD) 값을 이용하여 추산하였다. 카운티에서 수출항까지의 운송비용은 임피던스(Impedance) 값을 사용하였으며, 임피던스 함수(Impedance factor)로는 the Oak Ridge National Laboratory (ORNL)의 inter-county distance matrix 데이터셋을 이용하

였다. 모의결과에서 각 수출항별로 생산지가 연결되므로 다시 ORNL 데이터셋을 이용하여 두 지점간의 운송수단을 결정하여야 한다. 이에 각 운송경로별 임피던스 함수를 비교하여 더 효율적인 수단을 주도적인 운송수단으로 결정하였다.

모의된 모델을 통해 각 수출항에 공급된 옥수수의 생산지를 추정하고, 생산지별 생산과정의 환경영향 차이를 고려하여 각 항구에 공급된 옥수수를 생산하기 위해 얼마나 많은 양의 환경영향이 발생되었는지 분석하고 항구별 차이를 비교하였다. 또한 우리나라에서 수입하는 옥수수가 수출되는 8곳의 항구 중에서 환경영향을 최소로 할 수 있는 수출항을 선택하였고, 이러한 선택에 따른 수입곡물의 환경영향 개선 잠재력을 평가하였다. 이를 위한 운송단계는 각각의 생산카운티에서 수출항구로 이동하는 육로운송과 수출항구에서 우리나라 수입항까지의 해상운송으로 분류하였다.

생산과정의 환경영향은 Smith et al. (2017)의 연구결과 중 옥수수의 생산과정에서 발생하는 온실가스와 관개용수량을 카운티 단위로 분석하여 제시한 값을 인용하였다. Smith et al. (2017)은 옥수수의 생산지역별로 사용하는 질소비료의 종류, 사용량, 직·간접 N_2O 배출량, 관개용수량의 차이를 고려하여 생산지별 단위무게당 옥수수 생산과정에서의 온실가스 발생량과 관개용수 소비량의 차이를 나타내었다. 운송과정의 환경영향을 평가하기 위한 운송수단별 환경영향 분석에는 LCA software인 GaBi를 사용하였고 전과정 목록은 Ecoinvent의 데이터셋을 활용하였다. 육로운송의 운송수단은 trcuk, rail, barge (waterway)로 선정하였고, 해상운송의 경우에는 농산물 운송에 주로 이용되는 bulk-commodity carrier (BCC, oceangoing)로 선정하였다.

주요수입곡물의 푸드마일은 2015년과 2017년에 각각 1,890억 ton·km와 1,470억 ton·km로 분석되었다. 이를 곡물별로 살펴보면, 수입

밀의 푸드마일은 2015년에 360억 ton·km, 2017년에 400억 ton·km로 분석되었으며, 옥수수는 다른 곡물에 비해 수입량이 많은 만큼 두 연도의 푸드마일도 각각 1,300억 ton·km, 900억 ton·km로 밀, 대두와 큰 차이를 보였다. 이러한 옥수수의 푸드마일은 2015년 주요수입곡물의 전체 푸드마일의 70%에 해당하였으며, 2017년에는 60%에 해당하였다. 대두의 경우 주요수출국에서의 수입량은 2015년과 2017년에 각각 130만 ton과 110만 ton이었으며, 이에 따른 푸드마일은 각각 220억 ton·km, 171억 ton·km이다.

푸드마일에 따른 운송과정의 환경영향을 평가하기 위해 운송수단별 단위푸드마일당 온실가스와 초미세먼지를 분석한 결과, 운송수단별로 두 범주 사이에 서로 다른 경향을 보였으며, 한 범주 안에서도 발생량에 큰 차이가 있다. 온실가스의 경우 발생량의 크기가 truck (1.29e-01 kg CO_2e/ton·km), rail (1.51e-02 kg CO_2e/ton·km), BCC (3.24e-03 kg CO_2e/ton·km)의 순으로 truck의 발생량이 가장 컸던 반면, 초미세먼지의 경우 rail (9.47e-04 kg PM2.5e/ton·km), truck (4.35e-04 kg PM2.5e/ton·km), BCC (2.03e-04 kg PM2.5e/ton·km)의 순으로 rail에서의 배출량이 가장 높게 나타났다.

주요수입곡물의 푸드마일을 운송단계별로 살펴보면 2015년과 2017년 모두 해상운송에서 가장 높은 것으로 평가되었다. 하지만 푸드마일에 따른 온실가스 발생량은 두 연도에서 모두 주요수출국 내의 주산지에서 수출항까지 이동하는 육로운송단계에서 전체 발생량 중 50% 이상이 발생되는 것으로 분석되었다. 반면, 초미세먼지는 온실가스와는 달리 해상운송단계에서 더욱 중점적으로(60-70%) 발생하는 경향을 보였다. 초미세먼지 지수의 운송수단에 따른 편차는 온실가스의 경우처럼 크지 않기 때문에, 초미세먼지는 수입곡물의 품목과 수출국에 관계없이 푸드마일이 높은 해상운송단계에서 가장 많은 양이 발생되는 것으로 판단된

다. 이러한 범주별 환경영향의 차이는 온실가스와 초미세먼지에서 뿐만 아니라 다른 영향범주에서도 나타날 수 있으므로, 향후에는 보다 확대된 환경영향범주들에 대한 평가가 수행될 필요가 있다.

생산단계의 환경영향을 포함한 평가를 위하여 미국 옥수수의 운송비용을 최소화할 수 있도록 시뮬레이션 된 이동경로 분석 모델을 통해 생산지를 추정하였다. 시뮬레이션 모델은 미국 내 191곳의 옥수수 생산카운티별 생산량과 32곳의 항구별 수출량을 바탕으로 각 항구에 공급된 수출옥수수의 생산지를 연결한다. 본 모델에서 연결된 생산카운티의 영농과정과 투입물의 차이를 고려하여 각 항구에 공급된 옥수수를 생산하는 과정에서 발생된 온실가스 배출량과 관개용수 소비량을 평가하였으며, 그 결과는 다음과 같다.

전체 수출항구에 공급된 옥수수의 단위무게당 생산과정에서 발생한 평균적인 온실가스는 0.363 kg CO_2e로 평가되었다. 이를 항구별로 살펴보면 생산과정의 온실가스 발생량은 적게는 0.187 kg CO_2e/kg에서 많게는 0.549 kg CO_2e/kg으로 큰 차이가 존재한다. 관개용수량의 경우, 항구별로 공급된 옥수수의 생산과정에서 많게는 0.873m^3/kg까지 소모한 것으로 나타나지만, 전체 항구의 평균소비량은 0.135 m^3/kg으로 분석되었다. 최대소비량과 평균소비량의 상당한 차이는 생산과정에서 관개용수를 전혀 혹은 거의 사용하지 않는 지역의 옥수수가 공급된 Portland (Maine), Dallas-Fort Worth (Texas)를 포함한 6개의 항구에 영향을 받은 것으로 판단되었다. 이러한 결과는 옥수수의 생산지역별 지리적 차이를 고려한 실제 항구별 단위무게당 온실가스 발생량 혹은 관개용수량의 관점에서 환경영향이 적은 항구를 통해 유통되는 옥수수를 선택할 시 실제 수출항과 비교하여 더 낮은 환경영향의 옥수수를 수출 혹은 수입할 수 있는 가능성을 보여준다.

따라서 항구별 환경영향의 차이를 고려한 수출항구의 선택이 수입옥

수수의 환경영향에 어떠한 영향을 주는지 분석하였으며, 이를 위해 우리나라를 대상으로 옥수수를 수출하는 8곳의 항구 중에서 생산과정의 온실가스 발생량과 관개용수량을 최소로 할 수 있는 항구를 각각 선택하였다. 또한 선택된 항구가 한국으로의 수출량을 모두 수용하지 못 할 경우, 그 다음으로 환경영향이 적은 수출항구의 수용량에 맞춰 옥수수를 할당하였다. 온실가스의 경우 생산과정에서 뿐만 아니라 운송과정에서도 발생되기 때문에, 생산과 운송단계에서의 발생량 변화를 각각 살펴보았다. 관개용수량은 운송과정에서 소모되는 양이 없으므로, 생산과정에서의 변화만을 평가하였다.

온실가스의 관점에서 생산과정의 발생량이 가장 적고 한국의 수입량을 모두 수용할 수 있는 Portland (Oregon) 항구를 통해 옥수수를 유통할 경우, 생산과정에서 약 1,100만 kg CO_2e(약 7%)의 온실가스를 저감할 수 있는 것으로 예상되었다. 운송과정에서는 기존 8곳의 항구와 비교하여 푸드마일은 18%(10억 ton·km) 감소함에도 불구하고, 온실가스 발생량은 1.5% 상승하게 된다. 이는 수출항의 선택을 통해 해상운송단계의 푸드마일은 감소하게 되나, 미국 내 육로운송단계의 푸드마일이 증가하면서 육로운송수단을 이용하는 거리가 확대됨에 따라 온실가스의 측면에서 더 부정적인 영향을 미치기 때문이다. 결과적으로, 수출항의 선택을 통해 생산과 운송과정을 포함하여 총 1,000만 kg CO_2e의 온실가스 배출량이 저감되는 것으로 기대할 수 있다. 감축된 온실가스의 가치를 탄소배출권 시장에서 2019년 1월 거래된 온실가스의 가격(25원/kg)을 적용하여 금액으로 환산하면 2.5억 원에 달한다.

온실가스 발생량을 최소로 할 수 있는 수출항의 선택을 통해 운송과정의 온실가스 발생량이 다소 증가하는 것으로 분석되었음에도 불구하고 우리가 수출입 곡물의 선택을 지향해야 하는 이유는 온실가스 발생량은 향후 운송연료의 대체, 운송수단의 효율 상승을 포함한 운송기술

의 지속적인 발달을 통해 감축될 수 있으리라 예상되기 때문이다. 또한 국제해사기구(International Maritime Organization, IMO)에서 2020년 시행예정인 운송부문의 온실가스 감축전략을 위한 황산화물(SOx) 배출 규제(연료 내 황 함유량 0.5% 이하)를 통해 운송과정의 온실가스 발생량을 더욱 감소할 수 있을 것으로 전망된다. 실제로 황 함유량이 0.5 wt.%로 적은 경유 기반의 벌크선과 LNG 기반의 벌크선을 활용할 경우, 기존 중유 기반의 벌크선(황 함유량 1.0 wt.%)에 비해 저감할 수 있는 온실가스 배출량은 각각 21%(0.003 kg CO_2e/ton·km)와 41%(0.006 kg CO_2e/ton·km) 달할 것으로 보인다.

관개용수량 관점에서는 관개용수의 소모가 가장 적은 New York City 항구에서 한국의 수입량을 모두 수용하지 못한다. 이에 항구별로 관개용수량의 소모가 적은 순서대로 각 항구의 수용량에 맞추어 옥수수의 공급량을 할당하였다. 이러한 과정을 통해 선택된 수출항은 New York City, Norfolk, San Francisco, Portland로, 수출항구의 선택으로 저감할 수 있는 관개용수량은 기존 소비량인 5,000만 m^3의 약 88%에 해당하는 4,400만 m^3으로 예상되었다.

본 연구에서는 국내 수입곡물의 생산단계와 운송단계를 포함한 환경영향을 평가하고, 실제 생산지를 고려한 종합적인 수입곡물의 환경영향 평가를 통해 보다 친환경적으로 생산된 곡물의 수입을 통한 환경영향 개선 잠재력을 평가하였다. 그 결과를 바탕으로 보다 친환경적으로 생산된 곡물의 수입을 장려하기 위해 에코라벨링(Eco-labeling)과 같은 친환경 인증제를 제안하고자 한다. 에코라벨링은 ISO 14024의 정의에 따라 제품의 생산, 유통, 소비 등 전과정의 환경영향을 평가하여 친환경제품임을 인증하는 라벨링을 의미한다.

우리나라의 경우에도 유기농법으로 재배된 농산물이나 저농약, 저비료 농산물을 인증하는 친환경농산물 라벨링이 활성화되어 있다. 특히

유기농산물의 시장규모는 2007년에 1,700억 원에서 2017년에 4,300억 원으로 10년간 153% 증대되었다. 이러한 시장규모의 증가는 친환경 농산물의 가격이 조금 더 비싸더라도 많은 사람들이 금액을 지불하고 구입하는 것으로 설명될 수 있다. 이와 같은 개념이 수입곡물에도 적용될 수 있으리라 생각되며, 공정무역의 경우처럼 생산물의 가격이 조금 더 혹은 많이 비싸더라도 생산자에게 적절한 노동의 대가를 지급하는 상품을 거래하겠다는 취지와 같이 환경에 초점을 맞춘 곡물무역으로 보다 친환경적으로 생산된 곡물을 수출 혹은 수입하는 노력을 자극할 수 있으리라 예상한다.

본 연구는 향후 곡물을 포함한 모든 농산물 교역에서 실제 생산지를 고려한 환경영향평가 연구와 보다 친환경적인 국제무역을 위한 의사결정 연구의 기반이 될 수 있으리라 사료된다. 본 연구의 접근법과 결과를 바탕으로 생산과 운송단계의 환경영향을 동시에 고려하여 친환경적으로 인증된 곡물을 수입하는 경우 곡물무역의 환경영향 개선에 기여할 수 있을 것으로 예상하며, 환경영향이 적은 곡물을 수출 혹은 수입하는 기업의 이미지를 제고하는 등 다양한 효과를 이끌어 낼 수 있을 것으로 전망한다. 또한 친환경 수입곡물에 대한 관세를 감축시키고 무역회사에 보조금을 지급하는 등의 방안을 통해 교역곡물의 생산단계와 운송단계에서 발생되는 부정적인 환경영향을 개선함과 더불어 곡물교역을 위한 더 나은 환경을 만들어 볼 수 있으리라 기대한다.

주요어 : 국제곡물교역, 푸드마일, 환경영향평가, 공급망 분석, 최적화

학 번 : 2017-21224