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Effect of Climate Change on Crop Production Patterns with Implications to Transport Flows and Inland Waterways

Final Report

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16. Abstract

This project analyzed the demand for transportation capacity and changes in transportation flows on inland waterways due to shifts in crop production patterns induced by climate change. Shifts in the crop production mix have been observed in recent years in response to changing climate. The primary exhibited trend is that of a northward shift resulting, for example, in increased corn production in historically wheat-producing regions. Given differences in the typical destinations and volumes of corn and wheat shipments, such changes have the potential to alter the pattern, composition and seasonality of grain flows toward and along the Mississippi River. As a result, bulk cargo traffic patterns, transportation flows, and demand for transportation capacity and facilities in the Mississippi River basin may change dramatically in the near future. The project analyzed these changes using a U.S. agricultural sector model and an international grain transportation model. The former predicts shifts in production patterns due to climate change, while the latter analyzes the effect of predicted production shifts on transportation flows. The results will help planners in forecasting demand for Mississippi River transport facilities and capacity.

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EFFECT OF CLIMATE CHANGE ON CROP PRODUCTION PATTERNS WITH IMPLICATIONS TO TRANSPORT FLOWS AND INLAND WATERWAYS

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DISCLAIMER

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Executive Summary

U.S. grain production plays a crucial role in supplying global and local demand for food, feed, and biofuels. In the 2009/2010 crop year, the U.S. supply of corn, soybeans, and wheat accounted for about 39, 31, and 9 percent of the respective world supplies. A highly efficient, low-cost transportation system is a major factor determining U.S. competitiveness. Agriculture is a very large user of the transportation system accounting for 22 percent of all transported tonnage and 31 percent of all ton-miles generated via all modes in 2007.

Recent studies, including those by the Intergovernmental Panel on Climate Change (IPCC) indicate that the world's climate conditions are changing and are projected to continue to do so. Such changes are expected to substantially impact agriculture, with the most immediate reaction of agricultural producers being adaptation.

Several studies indicate that crop production will increase in high latitudes and decline in low latitudes. Research suggests that crop suitability zones may shift more than 100 miles northward.

Other studies suggest that climate change, in particular warming temperatures, may result in a drop in Great Lakes water levels and shorter duration of ice cover in the Great Lakes and the Upper Mississippi River basin.

Given these climate change-related phenomena plus differences in the typical destinations of grain shipments for different commodities, there will be likely changes in the pattern and seasonality of interregional grain transportation flows and corresponding demand for transportation capacity. Furthermore, climate change is also expected to cause droughts in many regions of the world, disrupting grain production and exports as was recently demonstrated by the drought in Ukraine, Russia and parts of Eastern Europe in 2010.

The objectives of this study are thus to investigate the effect of climate change on interregional grain transportation flows due to (1) climate-induced shifts in crop production patterns; (2) a decline in Great Lakes water levels; (3) an extension of the navigation season in the winter for the Great Lakes and the Upper Mississippi River; and (4) the impact of drought in foreign grain exporting regions competing with the Great Lakes ports. This study is built on the results of the previously funded UTCM project #08-15-14.

The main modeling approach of the study consists in (i) estimating northward shifts in the crop mix under different climate scenarios and (ii) calculating the implications for trade flows. This is achieved by linking together two modeling systems – Agricultural Sector Model (ASM) and International Grain Transportation Model (IGTM). The results of the changes in crop mix patterns on transportation flows are calculated first and used as a benchmark. The remaining scenarios [(2) through (4) above] are then analyzed in terms of changes relative to the benchmark.

Under the climate change-induced shifts in the crop production patterns, the Corn Belt is anticipated to ship less corn to the Pacific, Northeast, Rocky Mountain, Southeast, and South-Central regions plus the Pacific Northwest and Lower Mississippi ports, while the Great Lakes ports and Lake States are expected to receive higher corn shipments. Furthermore, the Corn Belt is expected to ship higher amounts of soybeans to the Southeast and the Northeast, plus the Great Lakes and Atlantic ports. The importance of Lower Mississippi ports and interior Mexico is projected to diminish, whereas the role of Pacific Northwest ports, Great Lakes ports, and Atlantic ports is projected to increase. Finally, demand for rail and truck for total grain shipments is expected to rise, while demand for barge mode is projected to drop.

The analysis of incremental changes in transportation flows due to an extension of the navigation season in the winter along the Upper Mississippi River indicates that the Corn Belt's grain shipments to the Lower Mississippi River ports would decline and this reduction could possibly be replaced by a substantial increase of corn shipments from the Lake States. Overall, Lower Mississippi River ports are likely to receive higher grain flows, while Pacific Northwest ports and Great Lakes ports would tend to receive lower grain shipments. The seasonality of overall grain transportation flows is likely to be affected with increasing flows in the winter and decreasing flows in the fall. Finally, the usage of truck and rail is expected to increase, while usage of barge is projected to drop.

The extension of the navigation season in the winter along the Great Lakes would result in a very small impact on corn flows. Soybean shipments from other regions to the Great Lakes ports are likely to increase, while the Lower Mississippi River, Pacific Northwest, and Atlantic ports would receive lower soybeans shipment from other regions. Corn flows are projected to decline in the fall but increase in winter. Soybeans shipments are expected to increase in the fall and summer seasons. The demand for modes of transportation would be unaffected for corn flows, with small changes projected for soybean shipments. Overall, higher demand is projected for truck, but demand for rail and barge would decrease.

An increase in the shipping cost caused by a fall in Great Lakes water levels would not affect seasonal movements of grain flows. However, as the shipping cost increases, Great Lakes ports are projected to receive fewer grain shipments from all excess supply regions, especially from the Corn Belt. At the same time, the Lower Mississippi River ports and Atlantic ports are expected to receive higher grain shipments. Overall, the higher the increases in shipping cost, the greater the demand for rail and barge and the lower the demand for truck.

A drought-related reduction of grain exports from regions competing with the Great Lakes ports would not substantially affect soybean flows or seasonality of overall grain transportation flows. However, higher shipments of corn are projected to the Great Lakes ports, Texas Gulf ports, and Lower Mississippi River ports. Furthermore, the demand for barge and rail is also projected to increase.

Several clear implications arise from the analysis.

- Although overall the future demand for barge mode may drop, the Upper Mississippi River is likely to receive higher grain transportation shipments under climate change scenarios due to the predicted increase in the grain supply from the middle to northern parts of Minnesota and North Dakota. Therefore, enlarging or improving conditions of locks and dams in that segment might be appropriate to speed up passage of barge tows and increase the barge efficiency, which could also increase the competitiveness of U.S. grain for export.
- Due to the projected increase in overall demand for rail, many components of the rail infrastructure may need to be upgraded and expanded along the routes that are projected to have new or higher levels of grain transportation flows. This includes routes from Minnesota and North Dakota to Pacific Northwest ports; New York to North Carolina; Colorado to Idaho;

Minnesota to New Mexico and Oklahoma; Nebraska to California; Pennsylvania to Virginia; South Dakota to Texas Gulf ports; and Michigan to Atlantic ports.

- To collect grain from rural farmlands in the northern region grain elevators, short line rail track beds and bridge structure could be expanded. To increase the speed of the shipments and their reliability, expanding mainline rail track and increasing the number of sidings should be considered.
- Transportation by trucks is also a mode that is projected to receive increasing grain transportation flows. Road infrastructure may need to be expanded and upgraded to accommodate the heavy future truck traffic from the areas where grain supply is expected to increase to nearby excess demand locations and ports. Examples include roads in rural areas along the Upper Mississippi River in Minnesota, Ohio River, Arkansas River, and the Lower Mississippi River in Kentucky leading toward nearby barge locations shipped to the Lower Mississippi ports; routes in northern parts of Ohio leading toward the Great Lakes ports at Toledo; and roads in Ohio, Pennsylvania, and New York leading toward Atlantic Ports at Norfolk, Virginia. Finally, due to a multifaceted system of grain supply chain, improving intermodal connectors such as truck routes connecting highways with ports and rail terminals might be suitable in those areas.

Introduction

U.S. grain production plays a crucial role in supplying global and local demand for food, feed, and biofuels. In the 2009/2010 crop year, the U.S. supply of corn, soybeans, and wheat accounted for about 39.0, 31.0, and 9.0 percent of the respective world supplies. The U.S. share of the international export market was about 52.0, 44.0, and 18.0 percent for corn, soybeans, and wheat, respectively (USDA-WAOB 2011).

A highly efficient, low-cost transportation system is a major factor determining U.S. competitiveness. Barges, railroads, and trucks bridge the gap between the U.S. grain producers, and domestic and foreign consumers. Not only is agriculture a very large user of the transportation system, accounting for 22 percent of all transported tonnage and 31 percent of all ton-miles generated via all modes in 2007, but grain is also the largest user of freight transportation in agriculture (Denicoff et al. 2010).

According to Marathon and Denicoff (2011), from 1978 to 2007, total U.S. grain shipments increased 92 percent with corn transportation accounting for 63 percent of all grain movements in 2007 followed by movements of soybeans and wheat (19 percent and 14 percent, respectively). During 2002–2007, inland grain transportation via truck and rail was the principal channel accounting for about 85 percent, while inland water transportation via barge represented 15 percent of grain tonnage. Although inland water transportation has a small share of all movements, it is a major route to export markets accounting for about 48 percent of all tonnage.

Adjustments in transport will occur in the future and climate change is one likely driving force. Recent studies, including those by the Intergovernmental Panel on Climate Change (IPCC) (2007a; 2007b) indicate that the world's climate conditions are changing and are projected to continue to do so. Such changes are expected to substantially impact agriculture (e.g., IPCC 2007b; Mendelsohn et al. 1994; Deschenes and Greenstone 2007; McCarl et al. 2008; Schlenker and Roberts 2009), with the most immediate reaction of agricultural producers being adaptation.

Several studies indicate that crop production will increase in high latitudes and decline in low latitudes (e.g., IPCC 2007b; 2007c; Adams et al. 1990; Reilly et al. 2003). Research suggests that crop suitability zones may shift more than 100 miles northward (Reilly et al. 2003). In the U.S., northward shifts in the crop production mix have already been observed; e.g., with more corn being planted in North Dakota among other changes[1] (Upper Great Plains Transportation Institute 2011). Such developments will increase regional volumes of grain production and the demand placed on the transport system since corn per-acre yields are about four times greater than wheat (USDA-NASS 2011).

Several studies suggest that climate change, in particular warming temperatures, may result in a drop in Great Lakes water levels (e.g., Millerd 2011; Easterling and Karl 2001; Chao 1999; Wittman 2008). Any increases in precipitation are not expected to be sufficient to overcome the increased evaporation and evapotranspiration (Chao 1999; Croley 1990; Easterling and Karl 2001; Hartmann 1990; Mortsch and

[1] In 1990, roughly 60 percent of the cropland in North Dakota was planted to wheat. In 2009, this number was 45 percent. Over the same period, corn acres have increased from 5 to 10 percent of cropland.

Quinn 1996). As a result, lower water levels may potentially cause reductions in vessel loads, increasing the number of trips and the cost of moving cargo across the Great Lakes.[2]

Shorter duration of ice cover due to warming climate is predicted in some studies to occur in the Great Lakes and the Upper Mississippi River basin. This development could lead to an extension of the navigation season (e.g., Millerd 2011; Kling and Wuebbles, 2005; Wittman 2008). Furthermore, climate change is also expected to cause droughts in many regions of the world (IPCC 2007b). For example, a recent drought (2010) in the grain producing countries such as Ukraine, Serbia, Moldova, and Kazakhstan reduced their grain exports to the world market. The drought conditions in these grain exporting countries are likely to repeat and are projected to increase their strength in the future (Dai 2010). Since exports from these regions compete with the U.S. grain exports shipped primarily through the Great Lakes (Fuller, et al. 2008), such a development may result in an increasing demand on shipping infrastructure.

Given these climate change-related phenomena plus differences in the typical destinations of grain shipments for different commodities, there will be likely changes in the pattern and seasonality of interregional grain transportation flows and corresponding demand for transportation capacity. Although several studies investigated the effect of climate change on transportation systems in general, to authors' knowledge no one comprehensively focused on the effect of climate change on the transportation of agricultural commodities — the largest user of the transportation systems.

The objectives of this study were to investigate the effect of climate change on interregional grain transportation flows due to (1) climate-induced shifts in crop production patterns; (2) a decline in Great Lakes water levels; (3) an extension of the navigation season in the winter for the Great Lakes and the Upper Mississippi River; and (4) the impact of drought in foreign grain exporting regions competing with the Great Lakes ports.

The remainder of the report is organized as follows. The second section provides review of the existing literature on adaptation patterns of the U.S. crop production to climate change and the effect of climate change on transportation systems. The third section describes the analytical approach including model components, data, and linkage procedures. The fourth section presents the empirical findings. The last section concludes by discussing climate change implications for the U.S. grain transportation systems.

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[2] All vessels carrying import or export cargo to or from the Great Lakes are limited in size by the dimensions of the St. Lawrence Seaway locks between Montreal and Lake Ontario. The Seaway locks can accommodate vessels up to 740 feet long and 78 feet wide. If a lake vessel has to reduce its draft by 3 feet, its cargo capacity is reduced by 15 percent (Millerd 2011). Moreover, according to the Lake Carriers' Association, a 1,000-foot-long vessel typically used for intra-lake transport loses 270 tons of capacity for each inch of draft loss. (Draft is the distance between the water line and the bottom of the vessel.) Ocean-going vessels, sized for passage through the St. Lawrence Seaway, are approximately 740 feet long and lose 100 tons of capacity for each inch of draft lost (Great Lakes Regional Assessment Team 2000).

Literature Review

This section concentrates on two aspects of the literature; namely, the climate change-related studies relevant to crop mix adaptation and studies on transportation systems.

Crop Mix Adaptation to Climate Change

There are a number of ways that land use can be affected by climate change. For example, climate change alters land values through changes in the productivity of crops, forests, pastures, and livestock. Land use can also be affected by climate change-induced alteration of spatial and temporal distribution and proliferation of pests and diseases (e.g., see the discussion in Reilly et al. 2002 and recent reviews in Aisabokhae et al. 2012).

A number of studies have examined how climate change influences the migration of crop mixes as an adaptation response. A general conclusion is that the crop production is expected to increase at high latitudes and decline at low latitudes due to corresponding projected changes in precipitation patterns (e.g., Adams et al. 1990; Reilly et al. 2003). This effect has also been observed in the results of Reilly et al. (2003) who construct the geographic centroid of production for maize (corn) and soybeans and plot their movements from 1870 (1930 for soybeans) through 1990. They found that both U.S. maize and soybean production shifted northward by about 120 miles during the analyzed period. An updated result is presented in Beach et al. (2009), who found soybean production trending northwest between 1970 and 2007, shifting northward by about 3.6 miles per year on average during this timeframe.

Many studies also conclude that climate change would affect crop yields and result in northward shifts in cultivated land (e.g., Adams et al. 1990; Reilly et al. 2002; Reilly et al. 2003). For example, Reilly et al. (2002) found substantial shifts in regional crop production, with Lake States, Mountain, and Pacific regions showing gains in production; with Southeast, Delta States, South Plains, and Appalachia regions generally losing production acres. More recently, McCarl (2011) estimates changes of crop acreage in the U.S. under 2030 climate scenarios with adaptation. He finds decreased acreage for cotton, soft white and hard red spring wheat, barley, hay, sugar cane, sugar beets, processed tomatoes, and processed oranges; but increased acreage for soybeans, hard red winter wheat, rice, potatoes, fresh tomatoes, and fresh citrus.

The Effect of Climate Change on the Transportation Systems

Climate Change and Transportation Infrastructure

Changing climate raises critical questions for the transportation sector in the U.S. Several studies analyze how transportation would be affected by changes in weather and climate extremes (e.g., Peterson et al. 2008; Koetse and Rietveld 2009; Humphrey 2008). Koetse and Rietveld's (2009) survey concludes that flooding of coastal roads, railways, transit systems, and runways due to rising sea levels coupled with storm surges may be some of the most bothersome factors. They reviewed previous studies and found that countries at higher latitudes would become more suitable for food production, while countries at lower latitudes (including a majority of developing countries) would become less suitable. This would likely result in an increase in grain trade flows from developed to developing countries.

Savonis, Burkett, and Potter (2008) studied climate change implications for the Gulf Coast, and found that seven of the ten largest commercial ports (by tons of traffic) may be inundated over the next 50 to 100 years due to sea level rise (up to 48in/122 cm), with 27 percent of major roads, 9 percent of rail lines, and 72 percent of ports being at risk. They also found that combined effects of increases in mean and extreme high temperatures are likely to affect the construction, maintenance, and operations of the transportation infrastructure and vehicles.

Climate-Induced Changes in Great Lakes Water Levels and the Transportation Systems

Several studies found that watersheds supplying water to the Great Lakes are likely to experience drier conditions, resulting in lower water levels in the lakes (e.g., Hartmann 1990; Chao 1999; Easterling and Karl 2001; Angel and Kunkel 2010). For example, using four global circulation models (GCMs) for the 1995 IPCC assessment, Chao (1999) found a reduction of annual water level in the Great Lakes relative to the baselines for all GCMs. By 2050, the water level is expected to decrease by 0.1 to 1.8 meters (0.3 to 5.9ft). Using 565 model simulations from 23 GCMs used in the 2007 IPCC assessment, Angel and Kunkel (2010) found a large range of uncertainty regarding future changes in the Great Lakes water levels, but a majority of the projections indicate a decrease in water levels over time. For example, under the A1B scenario, they found the median decline in water levels in all lakes to range from 0.10 to 0.25 meters (0.3 to 0.8ft) by 2050–2064 relative to the 1970–1999 averages.

This projected decline in the Great Lakes water level potentially reduces shipping capacity and increases the cost of shipping agricultural and other commodities via this artery (e.g., Marchand et al. 1988; Millerd 2005; 2011; Wittman 2008). Marchand et al. (1988) found the increase in overall annual shipping costs in the Great Lakes – St. Lawrence River system in Canada. Under the scenario involving changes in lake water level and no change in economic conditions, they project a 3.66 percent increase in the annual shipping costs of grain by 2035 relative to the baseline of 1951–1980. Similarly, Millerd (2005) found that the annual average cost of shipping grains from the Upper lakes to the St. Lawrence River will increase by about 11 percent in 2050 compared to the baseline of 1990–1989. For all commodities and routes, average annual shipping costs are projected to increase 13 percent by 2050 from the baseline. Millerd (2011) also projects an increase in the U.S. vessel operating costs for grains and agricultural products ranging 4.2–5.0 percent by 2030, 8.0–9.3 percent by 2050, and 21.71–22.62 percent in the doubling CO_2 scenario, respectively.

Climate-Induced Extension of Navigation Season and the Transportation Systems

Many studies find that warming temperatures are likely to result in more ice-free ports, improved access to ports, and longer shipping seasons (e.g., Marchand et al. 1988; Great Lakes Regional Assessment Team 2000; Kling and Wuebbles 2005). This could offset some of the resulting adverse economic effects from increased shipping costs as reviewed in the previous section (Millerd 2011; Humphrey 2008).

Marchand et al. (1988) found that by 2035 under a doubling of CO_2, ice cover in the Great Lakes will be a problem for less than one month per year. Foster, Meyer, and Wilkinson (2008) collected ice cover data from 1976–2006 and found a negative relationship between the average ice cover duration (the number of days of ice cover) and winter temperature on Lake Itasca, Minnesota, which is the origin of the Upper Mississippi River. During the period of analysis, the ice cover on the Lake had decreased from 177 to 128 days. This finding has been supported by 2010 Traffic Report prepared by the St. Lawrence Seaway Management Corporation and the St. Lawrence Seaway Development Corporation, which shows the average days of navigation on both the Montreal–Lake Ontario section and Welland Canal section have increased from 272 days during 1991–1995 to 282 days during 2006–2010.

Climate-Induced Drought Condition and Transportation Systems

IPCC (2007b) projects strengthening drought conditions in many regions of the world caused by climate change. In particular, more frequent or prolonged droughts are projected in grain exporting countries that compete with the Great Lakes grain ports, such as Ukraine, Serbia, Moldova, and Kazakhstan. These grain exporting countries have reduced the role that the U.S. and Canada play in selected European and North African countries that Great Lakes grain ports historically served (Fuller et al. 2008). Dai (2010) predicts that drought conditions in these foreign grain exporting countries are likely to strengthen over the period of 2030–2099. These projected drought conditions will likely affect grain production and grain exports of these foreign regions, which could have implications for the U.S. grain transportation.

Based on the above studies, climate change has a potential to affect crop production patterns, physical transportation infrastructures, inland waterways, lakes, shipping costs, and drought conditions, which could lead to changes in overall transportation flows of commodities. However, no one has directly focused on the effect of climate change on the transportation flows leading to changes in regional demands for transportation capacity and facilities in the near future.

MODEL COMPONENTS, DATA, AND PROCESS OVERVIEW

In order to examine changes in transportation flows due to shifts in crop production patterns under alternative climate scenarios, the extent of the northward shifts in the crop mix were estimated and then the implications for trade flows were evaluated. In order to achieve this, two modeling systems were used in sequence. The systems and the procedure for linking their inputs and outputs are described in this section.

AGRICULTURE SECTOR MODEL (ASM)

The first model simulates the location of crop production under climate change scenarios. It is based on the ASM model developed by McCarl and others (Baumes 1978; Burton 1982; Adams et al. 1986; Adams et al. 1990; Chang et al. 1992; Adams et al. 1996; McCarl and Schneider 2000; Schneider 2000; Adams et al. 2005; Schneider et al. 2007; Beach et al. 2009). This model has been used in a large number of climate change–related studies including Adams et al. (1999), Reilly et al. (2002), Reilly (2003), Beach et al. (2010), and McCarl (2011).

In brief, ASM is a price-endogenous, spatial equilibrium[3] mathematical programming model of the agricultural sector in the U.S. It includes all states in the conterminous U.S. broken into 63 subregions for agricultural production and 10 market regions, as shown in Table A1 in Appendix A. It also incorporates land transfers and other resource allocations within the U.S. agricultural sectors. ASM is a component of the forest and agricultural sector optimization model (FASOM) and, as such, is described in Adams et al. (2005); Beach et al. (2009); and Beach et al. (2010). The model framework is summarized in Appendix A. For the purposes of the present analysis, it needs to be run twice —with and without the effects of each climate change scenario.

INTERNATIONAL GRAIN TRANSPORTATION MODEL (IGTM)

Overview

The international grain transportation model was constructed in order to examine the transportation implications of the climate-induced changes in geographic crop mixes and production. The model used for the present analysis is the latest version of the model developed by Fuller and others (e.g., Fuller, Fellin, and Grant 1999; Fuller, Fellin, and Eriksen 2000; Fellin et al. 2008). The current version is based on the version described in Fellin et al. (2008) with the data updated by Vedenov et al. (2010) (UTCM Project #08-15-14 September 2010) to the 2007–2008 production year. The current data reflect recent changes in grain demand due to growth in the biofuel market along with the cost effects of higher energy prices. The original model and its modified versions have been used in many transportation studies (e.g., Fuller, Fellin, and Grant 1999; Fellin et al. 2001; Fuller, Fellin, and Eriksen 2000; Fuller et al. 2003; Fellin et al. 2008).

[3] This implies that production levels, production allocation across regions, and product prices are determined internally in the model as a result of optimal allocation of resources given input costs and aggregate demand.

IGTM depicts the world trade in corn and soybeans and contains a detailed representation of the internal transport system in the U.S. IGTM follows a price-endogenous, spatial equilibrium, mathematical programming framework. The theoretical underpinnings of the model can be found in Samuelson (1952), and Takayama and Judge (1971). IGTM simulates quarterly grain production, consumption, prices, and storage. It also predicts quarterly transportation flows by modes (truck, rail, barge, lake vessel, and ocean-going ship) from and to 303 U.S. regions going through 42 intermediate shipping points where modes can be changed. The model also depicts the world trade, which is modeled on a quarterly basis with 118 foreign exporting and importing countries/regions represented.

IGTM's basic geographic unit for the U.S. regions is a crop reporting district (CRD)[4]. The geographic scale of non-U.S. regions is at the country level. IGTM does not take into account transport flows within the regions (mainly accomplished by truck[5]), but rather is limited to the interregional trade. As a result, the role of truck mode in this study is generally smaller than in the real world. Appendix C provides the description of the model and its mathematical structure. The model data, sources, and data processing procedures are discussed in greater detail in Vedenov et al. (2010).

IGTM Validation

Since the analysis in this study focused on the long-term climate change impacts on the transportation systems, IGTM needs to be validated in order to determine whether the model can replicate the general pattern of grain transportation flows in the real world. This section offers a comparison of historical and model-projected transportation flows of the IGTM for the purpose of model validation. Available historical data used to compare with the model-projected flows were collected from various sources, including the U.S. Army Corps of Engineers, the USDA-AMS[6], the USDA-FAS[7], and previous transportation studies; in particular, recent studies by Marathon and Denicoff (2011) and Denicoff et al. (2010). Overall model-projected transportation flows for corn and soybeans were found to be in the range of historical transportation flows. (Tables 1 through 4).

Table 1 shows that the model-projected quantities of corn and soybeans transported to the U.S. export locations by mode of transportation are within their historic ranges during 2005–2007. Overall, barge plays an important role for the export of corn and soybeans, which is followed in importance by rail and truck, respectively.

For the domestic flows (Table 2), IGTM-simulated corn and soybean flows shipped via rail and barge modes were also found to be within the historic ranges except for corn shipped via barge where model-projected quantities are slightly lower than the historical quantities. As expected, model-projected shipments of corn and soybeans via truck were lower than their historic ranges estimated by Marathon and Denicoff (2011) since shipments within the CRDs are mainly accomplished by truck, and these intraregional flows are not modeled.

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[4] A state typically includes nine crop reporting districts, each incorporating 8-10 counties.

[5] In general, truck is more advantageous than rail and barge for short distances, while for middle to long distances its competitiveness drops compared to rail and barge.

[6] Agricultural Marketing Service of the U.S. Department of Agriculture

[7] Foreign Agricultural Service of the U.S. Department of Agriculture

Table 1. Historic and Model-Projected Quantities and Shares of Corn and Soybeans for Export by Modes of Transportation

Mode	Corn		Soybeans	
	Model-Projected Quantities	Range of Historic Quantities	Model-Projected Quantities	Range of Historic Quantities
Truck	5,639	1,600–6,429	2,019	1,654–3,998
	(9)	(3–10)	(7)	(5–12)
Rail	21,454	20,251–22,352	13,282	11,273–14,169
	(35)	(35–44)	(46)	(40–46)
Barge	34,409	28,778–34,689	13,395	15,030–15,242
	(56)	(50–57)	(47)	(46–53)
Total	61,501	50,629–63,470	28,696	28,118–32,824
	(100)	(100)	(100)	(100)

Notes: Numbers in parentheses are shares of corn and soybeans for export. Quantities are in 1,000 metric tons Ranges of historic data of corn and soybeans during 2005–2007 were collected from Marathon and Denicoff (2011).

Table 2. Historic and Model-Projected Quantities and Shares of Corn and Soybeans for Domestic Demand by Modes of Transportation

Mode	Corn		Soybeans	
	Model-Projected Quantities	Range of Historic Quantities	Model-Projected Quantities	Range of Historic Quantities
Truck	23,938	148,918–165,570	12,473	43,686–47,910
Rail	62,985	57,657–63,407	7,731	6,382–8,121
Barge	1,365	2,646–2,961	1,034	982–1,302
Total	88,289	209,536–227,106	21,238	43,686–47,375

Note: Quantities are in 1,000 metric tons. Ranges of historic data of corn and soybeans during 2005–2007 were collected from Marathon and Denicoff (2011).

Table 3. Historic and Model-Projected Quantities and Shares of Corn and Soybeans Exiting via U.S. Port Areas

Port Areas	Corn		Soybeans	
	Model-Projected Quantities	Range of Historic Quantities	Model-Projected Quantities	Range of Historic Quantities
Lower Mississippi	38,244	28,839–39,986	15,349	15,520–23,481
	(62.2)	(57.4–64.8)	(53.5)	(52.0–59.6)
Texas Gulf	1,616	689–3,071	51	108–2400
	(2.6)	(1.4–4.0)	(0.2)	(0.3–6.0)
Pacific Northwest	11,679	8,480–12,727	8,678	6,044–10,301
	(19.0)	(17.0–24.9)	(30.2)	(21.6–29.3)
Great Lakes	602	122–1,707	677	334–1,112
	(1.0)	(0.3–3.1)	(2.4)	(1.0–4.0)
Atlantic	707	469–769	1,143	565–1,389
	(1.1)	(1.0–1.4)	(4.0)	(1.8–3.4)
Overland	8,655	4,448–7,457	2,798	3,041–5,449
	(14.1)	(8.0–14.6)	(9.8)	(7.7–16.6)
Total	61,501	45,236–63,470	28,696	28,034–41,423
	(100)	(100)	(100)	(100)

Notes: Numbers in parentheses are shares of corn and soybeans for export. Quantities are in 1,000 metric tons. Ranges of historic data of corn and soybeans for 2006–2010 were collected from Marathon and Denicoff (2011) and Grain National Reports from the USDA-AMS (USDA-AMS 2007; 2008; 2009; 2010; 2011)

Table 4. Historic and Model-Projected Shares of Corn and Soybeans Exiting at the Lower Mississippi River Ports by Modes of Transportation

Modes	Corn		Soybeans	
	Model-Projected Share (%)	Historical Share (%)	Model-Projected Share (%)	Historical Share (%)
Barge	90	87–91	87	87–89
Truck & Rail	10	9–13	13	11–13
Total	100	100	100	100

Note: Ranges of historic data of corn and soybeans for 2005–2009 were collected from Marathon and Denicoff (2011) and USDA-AMS (2011).

Model-projected quantities of corn and soybeans exiting via U.S. port areas were generally in the range of their historic quantities (Table 3). The Lower Mississippi River ports and the Pacific Northwest ports are the major destinations for corn and soybean exports from the U.S. to the rest of the world.

Finally, model-projected shares of corn and soybeans exiting at the Lower Mississippi River ports classified by modes of transportation were also found to be within their historic ranges for 2005–2009 (Table 4). Projections were comparatively close to their historic ranges and showed that almost all corn and soybean were shipped via barge to these ports. Based on this evidence, researchers can reasonably conclude that the model is adequate for the analysis to be conducted for this study.

Developing Climate Change-Induced Crop Mix Shifts with ASM

ASM has been used on at least 10 occasions to look at the climate change implications, starting with Adams et al. (1988), Adams et al. (1990), and Reilly et al. (2002) and ranging through the most recent work by McCarl (2011). The same procedures were used in this project and are most explicitly detailed in McCarl (1999). The specific adjustments incorporated in the model for the purposes of present study are as follows.

- Crop yields were altered under the climate change scenarios based on the estimates developed by Beach et al. (2009). The latter were obtained from runs of the Environmental Policy Integrated Climate (EPIC) model[8] over four IPCC 2007 A1B scenarios.[9] The data used from these estimates were percent changes in irrigated and dryland yields plus irrigation water use.
- Levels of inputs such as fertilizer, energy, labor, and insecticides were varied with crop production changes. For example, if yields are higher more inputs are needed and *vice versa*. Farm level evidence suggests that the change in input use is less than proportional to the yield change. The estimated relationships vary by crop, but the change for most crops was on the order of a 0.4 percent change in input use for a 1.0 percent change in yield based on results in Adams et al. (1999).
- Climate change can have implications for livestock, principally through changes in appetite and the distribution of energy between maintenance and growth. Animal yields were modified based on the data in Adams et al. (1999).
- The amount of feedstuffs and other inputs change when livestock productivity changes. It is assumed that feedstuff use is strictly proportional to the volume of animal products produced. The use of the non-feed inputs changed by 0.5 percent for every 1.0 percent change in livestock yields.
- Climate change effects on water supply and, in turn, the amount of irrigation water available for agriculture was calculated using data from the water component of the U.S. national assessment (Gleick et al. 2000, as explained in McCarl 1999).

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[8] First developed by Williams et al. (1984)

[9] Namely those from the GFDL-CM 2.0 model; the GFDL-CM 2.1 model, the Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model (MRI-CGCM 2.2) and the Coupled Global Climate Model (CGCM 3.1).

- Climate change effects on grass growth and thus the effective supply of pasture and animals that can be supported on Western grazing lands was altered based on EPIC hay simulation results.
- Pesticide treatment cost was raised using the results from Chen and McCarl (2001).

Changes of corn and soybean yields under the climate change scenarios from several GCMs for the period of 2045–2055 are shown in Figures 1 and 2, respectively.[10] Dryland corn yield is expected to increase in almost all states in the Rocky Mountains, Pacific Southwest and Pacific Northwest under all GCM scenarios, while it is projected to decrease in almost all states in the southern parts of the Corn Belt. The MRI-CGCM 2.2 scenario provides the most optimistic projections for corn yield changes both on dry and irrigated land. For dryland, various degrees of yield increase are projected across the U.S. regions except for Utah, some regions of Texas, and Virginia. For irrigated land, small increases in corn yield are predicted. On the other hand, GFDL 2.1 presents the most pessimistic projections for changes in both dryland and irrigated corn yield. In particular, under this model irrigated corn yield is projected to decrease almost everywhere (Figure 1).

The MRI-CGCM 2.2 scenario results in the most optimistic projected change in soybean yield. On the other hand, GFDL 2.1 generates the most pessimistic projections. The variation in soybean yield changes across models is generally larger than that of corn yields. In particular, soybean yields are projected to drop by more than 20 percent in a large part of Corn Belt, Southwest, and South-Central regions under GFDL 2.0 and GFDL 2.1 models. On the other hand, various degrees of yield increases are projected under all GCM scenarios in almost the entire northern part of the U.S (Great Plains, Northern part of the Rocky Mountains, Lake States, and Northeast).

[10] Beach et al. (2009) present more details.

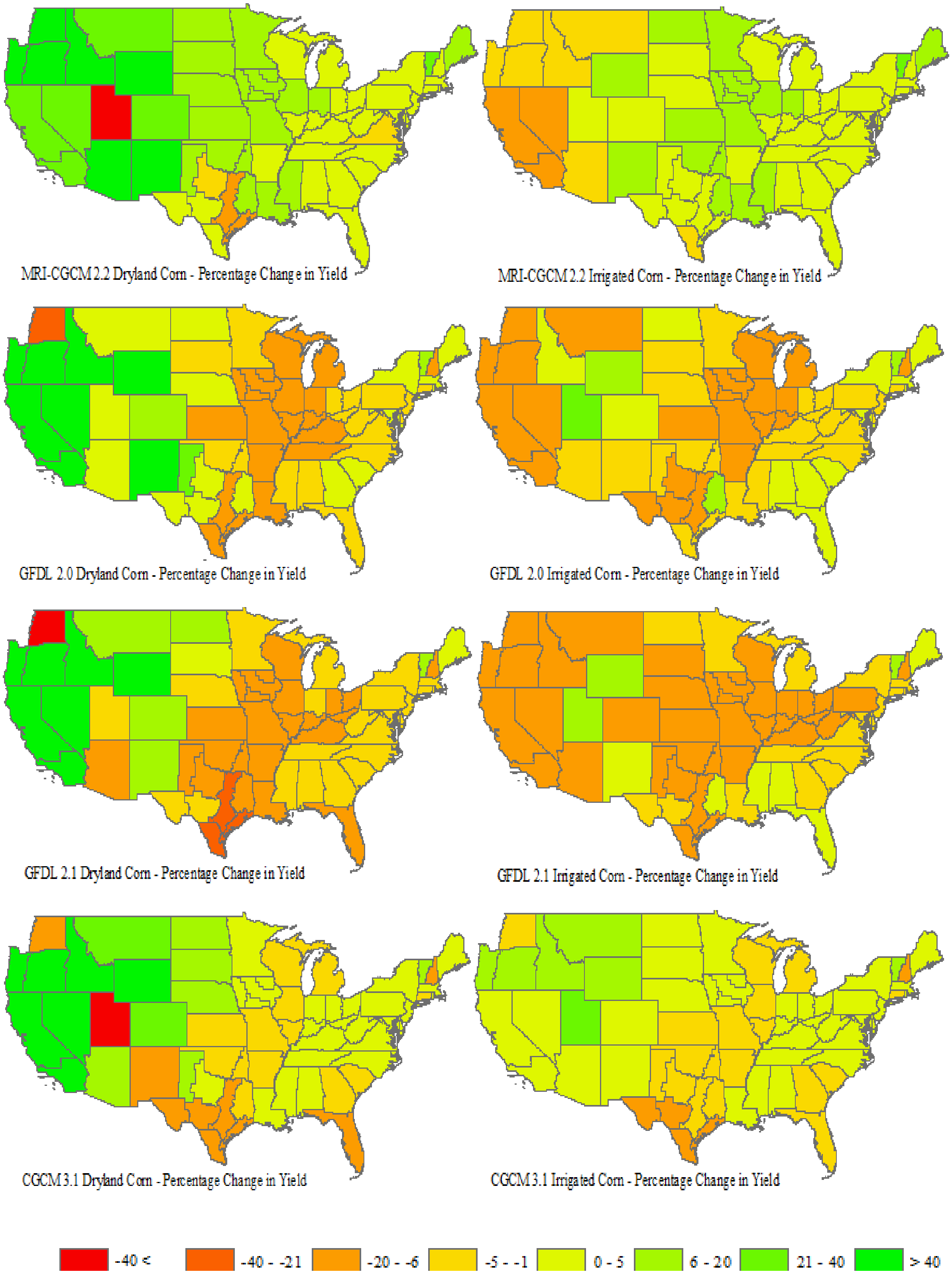

Figure 1. Percent change in dryland and irrigated corn yields under different GCM scenarios simulated for the period of 2045–2055.

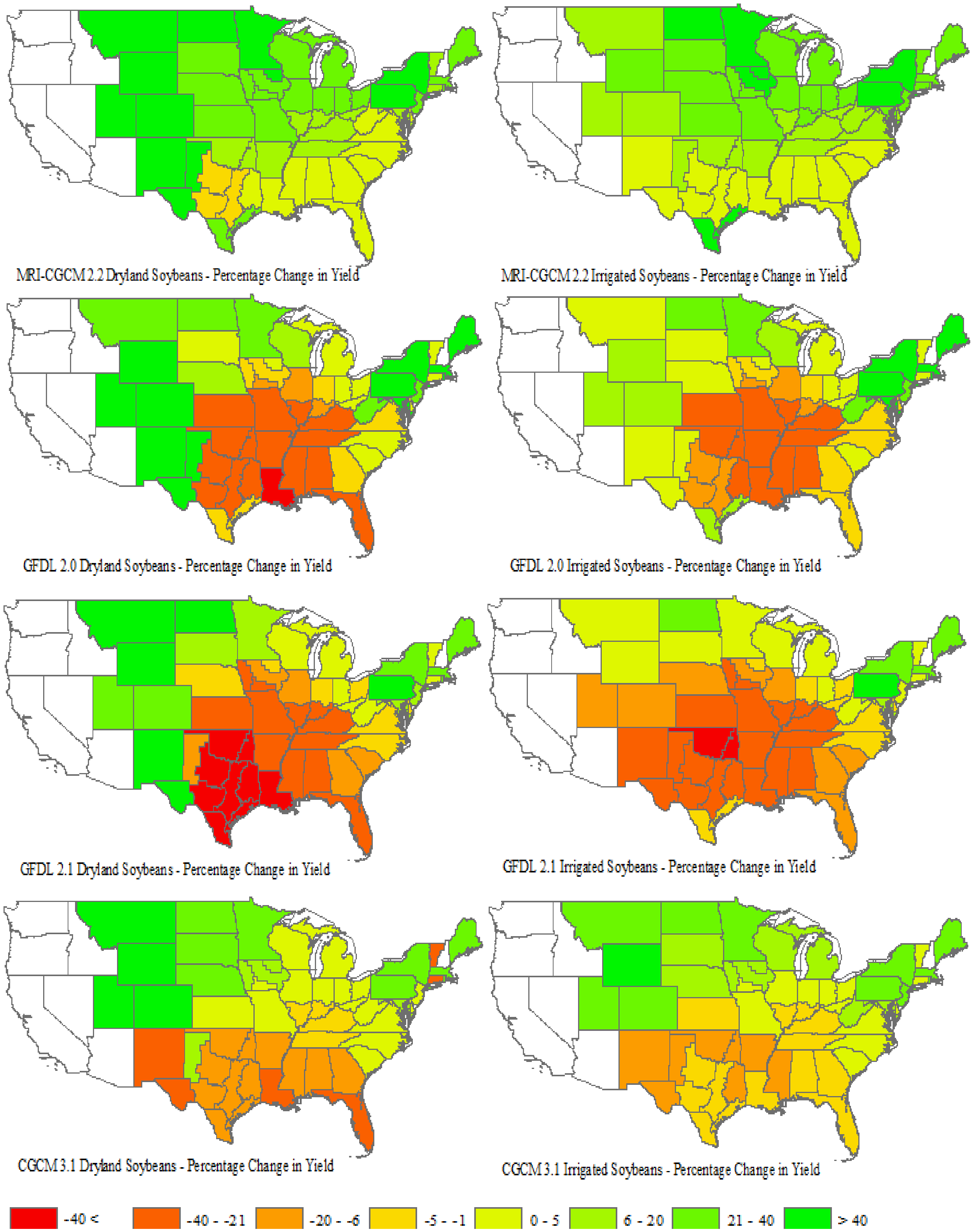

Figure 2. Percent change in dryland and irrigated soybean yields under different GCM scenarios simulated for the period of 2045–2055.

Linking the Models

In order to examine the transport implications of the climate change, the ASM was run for the baseline case and several climate change scenarios (the procedure is explained below). The resulting changes in grain production patterns were then incorporated into IGTM by appropriately shifting regional excess supplies. The linkage between the models is implemented as follows.

ASM represents production in 63 regions in the U.S. Although this is a fairly fine level of spatial detail for economic analysis, it is not sufficiently detailed for the grain transportation model in which 303 U.S. regions are analyzed. Therefore, downscaling is required in order to incorporate ASM results into IGTM.[11] To do this, a downscaling procedure developed by Atwood et al. (2000) and later employed in Pattanayak et al. (2005) was followed here. The procedure allocates the 63 region crop mix to the component counties in each region using a multi-objective programming downscaling model that minimizes the deviations between the crop mixes based on the ASM solution and those observed in the 1970–2007 data drawn from the Census of Agriculture, U.S. Bureau of Census, USDA-NRI[12], and USDA county crops data after accounting for crop migration due to climate change as discussed below.

The fundamental choice variable in the downscaling model is the acres of each crop allocated to each irrigation status in each county. This choice variable is constrained so it matches the land area shift in ASM, but minimally deviates from the observed data. More specifically, the following eight criteria were imposed.

- Total modeled acres farmed in a county do not exceed maximum observed.
- Total modeled acres farmed in a county are at least as high as the minimum observed.
- Total modeled irrigated acres in a county do not exceed maximum observed.
- Total modeled acres of an individual crop in each county does not exceed maximum observed.
- Total modeled acres of an individual crop in each county are at least as high as the minimum observed.
- Total acres allocated to each crop by irrigation status across all counties in an ASM region have to equal the totals that were in the ASM solution for the region.
- Total acres farmed in a county are constrained to minimally deviate from an interpolated county crop mix developed by interpolation between the periodic NRI and census data using agricultural statistics for the whole state following McCarl (1982).
- The ratio of total acres of an individual crop relative to the total acres of the same crop in all adjacent counties is required to equal the historical average ratio between the counties.

The downscaling model chooses the county land allocation that minimizes the sum of the deviations from all of the above criteria. This model was run for 14 crops in ASM.[13] The resulting crop mix and total

[11] Development of a CRD-level counterpart to the ASM crop mix would not be necessary if researchers could use CRD as the ASM spatial specification. However, not only would such a model be very large but developing/maintaining production budget, crop mix and resource data for such a scale would be a monumental undertaking.

[12] NRI = National Research Initiative.

[13] The 14 crops included barley, corn, cotton, forage production, oats, peanuts, potatoes, rice, rye, sorghum, soybeans, sugar beets, tomatoes, and wheat.

production numbers at the county level were then aggregated to the crop reporting district level and passed to IGTM.

However, the analysis could not rely purely on deviations from historical data, since climate change introduces the possibility of crop expansion into new production areas[14], as shown in Figure 3. The latter depicts the weighted central locations of national production of corn and soybeans, which moved about 100 and 138 miles northwest, respectively, during 1950–2010. To account for this possibility, the study applied a method based on econometric results developed by Adams et al. (1999), which allows one to identify a proportion of crop acreages in the immediately southern area that can shift to a given county. Such shifts were calculated and then incorporated into the historical Census, NRI and USDA data, as explained in Appendix B.

The results from the downscaling model were then employed to calculate the CRD level grain supplies using the climate change-adjusted yields and the CRD acreage data arising from each climate change scenario. The excess supply/demand was then calculated by subtracting the CRD-level grain demand[15] from the corresponding grain supply. The generated excess demands and supplies of grain in each CRD were used as inputs for IGTM.[16]

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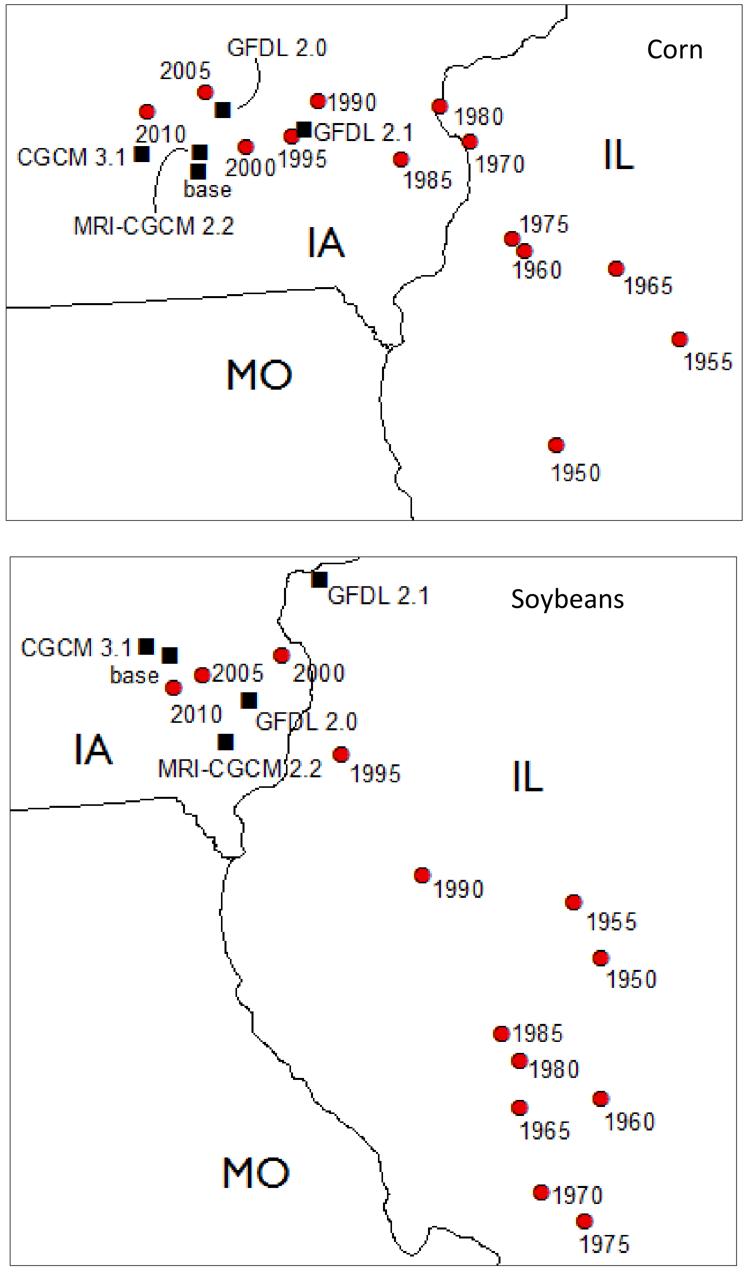
[14] The regionalizing downscaling of Atwood et al. (2000) disaggregated the solution of crop mixes and crop acreage from sector model to the county level by fixing crop mix and crop acreage solutions close to the county level historical crop mix, which cannot fully account for items which are expected to fall significantly outside the range of historical observation.

[15] Demand for grains in the IGTM was estimated using the 2007-2008 marketing year. Demand for corn is the summation of seed use, consumption for feed purposes, and consumption for food, alcohol, and industrial use, while demand for soybeans includes soybean crush and seed, feed, and residual use (see more details in Vedenov et al. (2010)).

[16] The difference between the production and supply of grains in this study is the beginning stock. That is, the summation of production and beginning stock of grains is the supply of grains. In the analysis of transportation flows it is necessary to take into account both production and beginning stock of the commodity.



Notes: Red circles are historical locations in 1950–2010; a black square marked “base” is the baseline scenario location in 2007/2008, the other black squares are locations under the climate change scenarios for various GCMs in 2050.

Figure 3. Production-weighted central locations of U.S. grain production.

MODEL RESULTS

This section reports results of ASM and IGTM runs. The magnitudes of the crop mix shifts are presented first, followed by the implications for transportation flows due to (1) climate-induced shifts in crop production patterns; (2) extension of the navigation season in the winter along the Great Lakes and the Upper Mississippi River; (3) decrease in the Great Lakes water levels; and (4) the impact of drought in grain exporting regions competing with the Great Lake ports.

CROP MIX SHIFT

The projected changes in the overall crop mix under different climate scenarios are summarized in Table 5. The results are generally consistent with the simulated change in crop yields as presented in the previous section. GFDL 2.1 projects a decrease in crop production due to the projected drop in crop yields, thus leading to the rise in crop prices. In contrast, MRI-CGCM 2.2 predicts the increase in overall crop production, which leads to the decrease in crop prices. Corn production is projected to increase only under MRI-CGCM 2.2, while soybean production is projected to increase in three out of four GCM scenarios. Total national cropland use increases with the expansion of irrigated land and contraction of dryland. Dryland corn production remains constant in all GCM scenarios, while for soybeans it tends to increase (except under GFDL 2.1). On irrigated land, both corn and soybeans are projected to increase (except under GFDL 2.1 for soybeans).

Table 5. Summary of Projected Agricultural Activities and Cropland Use

	Baseline	MRI-	GFDL 2.0	GFDL 2.1	CGCM 3.1
Agricultural Activities (index: base=100)					
Production of all crops	100.00	117.74	100.79	92.19	106.68
Production of corn	100.00	109.27	93.39	82.84	89.98
Production of soybeans	100.00	130.10	105.87	86.05	103.80
Price of all crops	100.00	94.58	105.72	106.11	100.00
Price of corn	100.00	90.93	103.71	108.01	94.61
Price of soybeans	100.00	92.07	100.00	101.19	97.16
Crop Land Use (in 10,000 acres)					
Corn, irrigated land	999.72	1,205.22	1,369.07	1,367.75	1,431.16
Corn, dryland	6,904.38	6,904.38	6,904.38	6,904.38	6,904.38
Corn, total land use	7,904.10	8,109.60	8,273.45	8,272.13	8,335.54
Soybeans, irrigated land	268.46	383.31	363.72	257.74	342.16
Soybeans, dryland	4,686.83	5,412.47	4,633.24	4,746.42	4,981.61
Soybeans, total land use	4,955.29	5,795.78	4,996.96	5,004.16	5,323.77
All crops, irrigated land	3,838.79	4,175.91	4,093.00	4,321.34	4,191.75
All crops, dryland	26,461.35	26,138.12	26,253.13	26,006.19	26,154.38
All crops, total land use	**30,300.14**	**30,314.02**	**30,346.13**	**30,327.53**	**30,346.13**

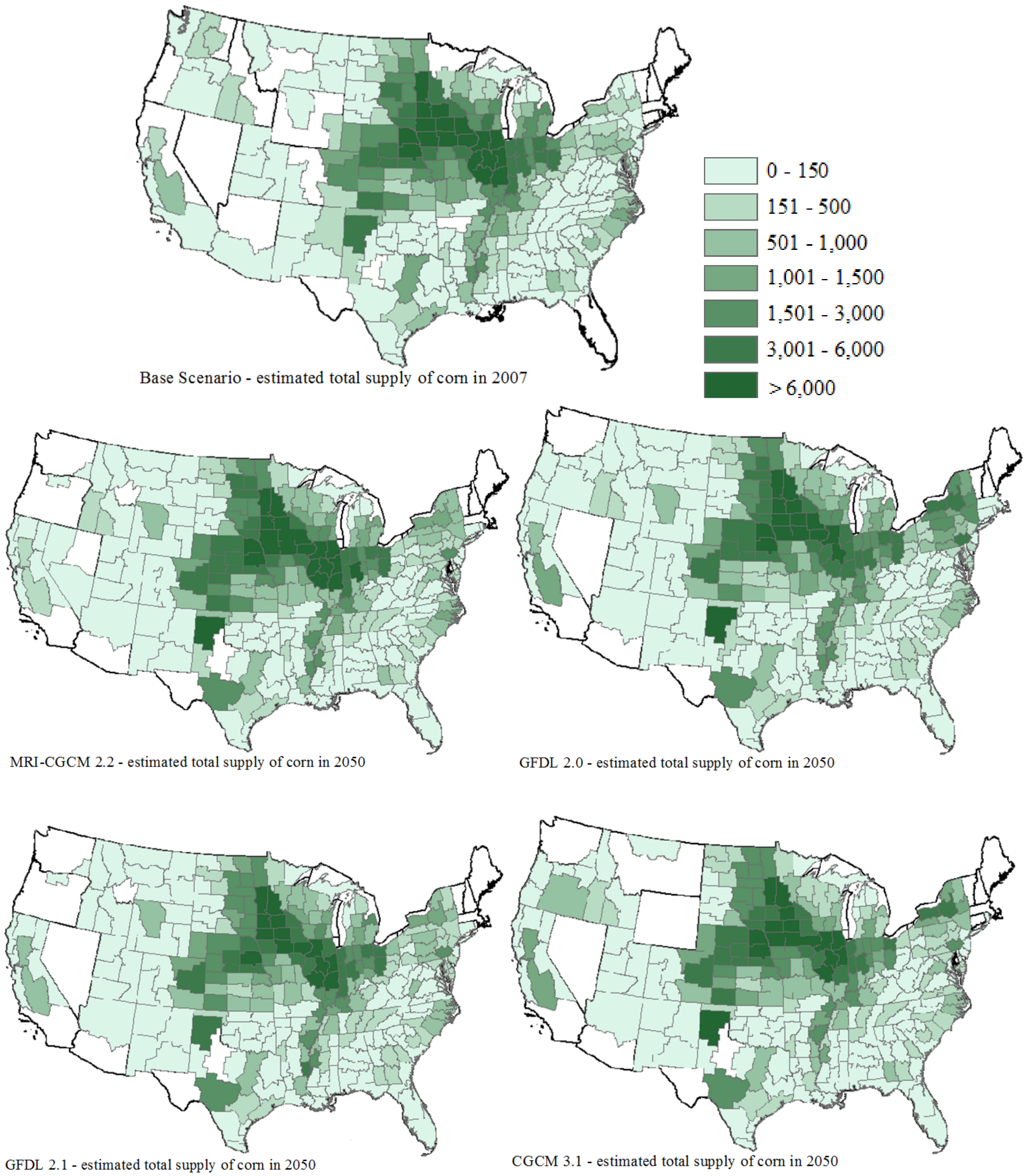
Supply Locations of Grains

The supply-weighted centroids of the overall U.S. grain supply under the baseline scenario and climate change scenarios in 2050 are shown in Figure 3. For corn, the climate change is likely to induce a further movement of the centroid of about 20 miles by 2050. For soybeans, the centroid is projected to shift northward about 18 miles by 2050.[17]

Estimated total supplies of corn and soybeans for the baseline and GCM scenarios simulated in 2050 are shown in Figure 4 and Figure 5, respectively. The principal results were as follows.

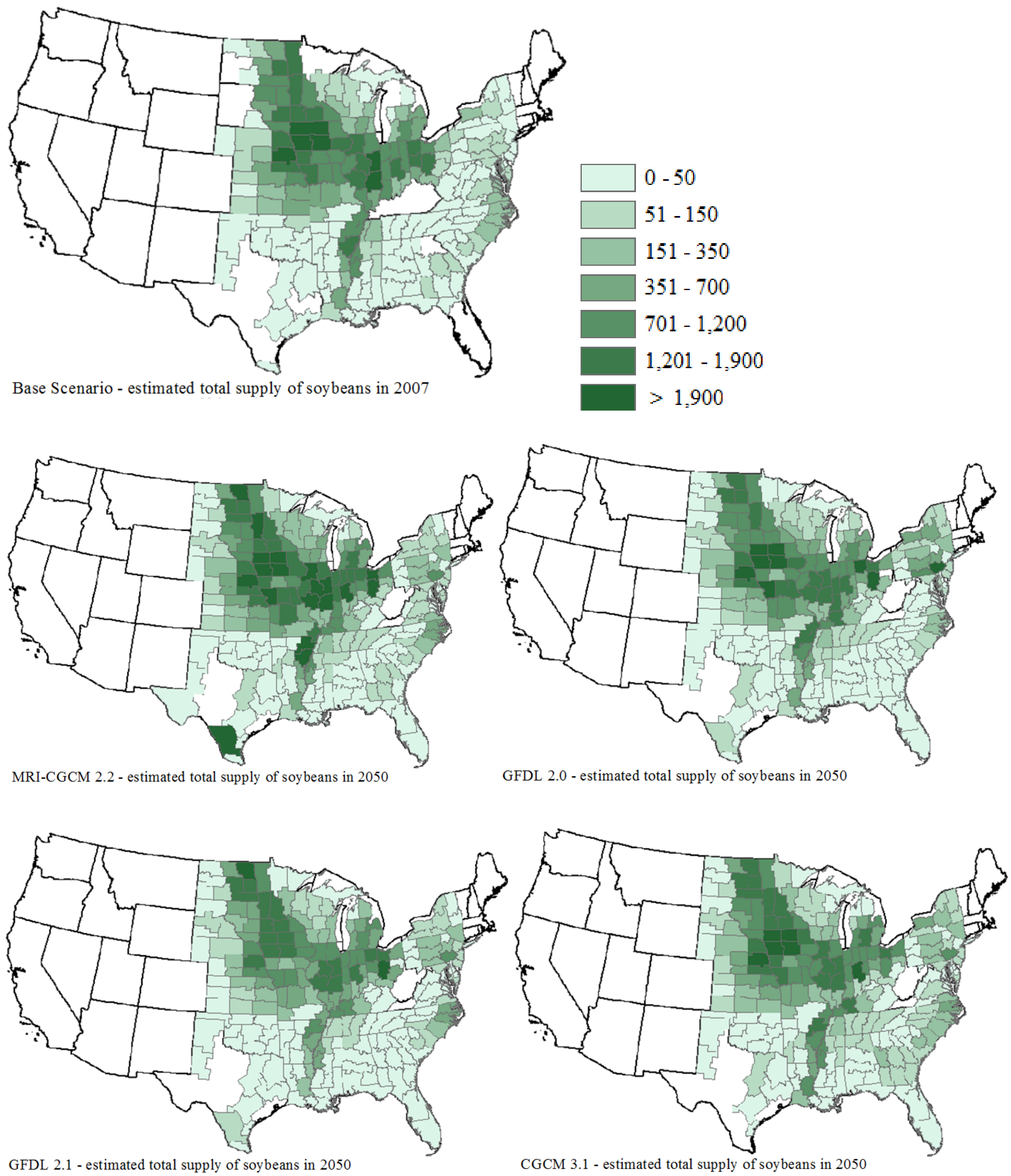
- Under the climate change scenarios, the overall supply of corn and soybeans increased in Northern regions, while it tended to decline in some areas in the Southern U.S. This finding is consistent with the projected increase in temperature across the U.S. regions under climate change scenarios (e.g., IPCC 2007a), which could damage crop production in the southern part of the country, while likely to be beneficial to crop production in the northern part of the country.
- For corn, the GCM scenarios provide mixed results. Nevertheless, corn supply was generally projected to increase in Colorado, Wyoming, North Dakota, South Dakota, upper Nebraska, Minnesota, Connecticut, New Jersey, New York, Pennsylvania, Rhode Island, and California, while decline in Arizona, New Mexico, and Kansas.
- For the traditional locations of corn production—especially the Corn Belt—three out of four GCM scenarios projected a decline in corn supply (except for Ohio). However, corn is likely to expand into new production areas including Connecticut, Rhode Island, Massachusetts, parts of Idaho, Oregon, Montana, northern part of Arkansas, Minnesota, Colorado, and California (Figure 4).
- For soybeans, the results under the MRI-CGCM scenario indicated an increase in supply across all U.S. regions, while other GCM scenarios provided mixed results. All GCMs predict an increase in soybean supply in Pennsylvania, New Jersey, North Dakota, Michigan, Indiana, and Texas. On the other hand, supply of soybeans was projected to fall in Maryland, West Virginia, South Dakota, Virginia, Florida, Mississippi, and Oklahoma. Moreover, soybean supply in the Corn Belt, a traditional supply location, was predicted to fall under GFDL 2.1 and CGCM 3.1, but rise under MRI-CGCM 3.1 and GFDL 2.0. Finally, the supply of soybeans was likely to expand in Kentucky, Northern Minnesota, Georgia, and the western parts of South and North Dakota (Figure 5).

[17] It is worth mentioning that the distances of corn and soybean movements in this study were lower than what were found in their historical movements, as illustrated in Figure 3. This happens because this study fixes all factors affecting corn and soybean production such as technological progress to their current level in the base year, and allows only the effect of the northward shift of crop production patterns and the change in grain yields.



Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.

Figure 4. Estimated total supply of corn for the baseline scenario and under different GCM scenarios.



Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.

Figure 5. Estimated total supply of soybeans for the baseline scenario and under different GCM scenarios.

Demand Destinations for Grains

Figure 6 shows estimated CRD-level demand for corn and soybeans in the 2007/2008 marketing year. The Corn Belt has the largest share of domestic grain demand, accounting for 37 and 59 percent of corn and soybeans, respectively. More than half of the Corn Belt's demand comes from Iowa and Illinois. Great Plains, Lake States, South-Central region, and the Southeast are also major destinations for corn and soybeans. States with the highest demand for corn are Iowa, Nebraska, Illinois, Minnesota, Indiana, Texas, North Carolina, Kansas, Wisconsin, and South Dakota. Iowa, Illinois, Minnesota, Indiana, Ohio, Missouri, Nebraska, Georgia, North Carolina, and Kansas have the highest domestic demand for soybeans.

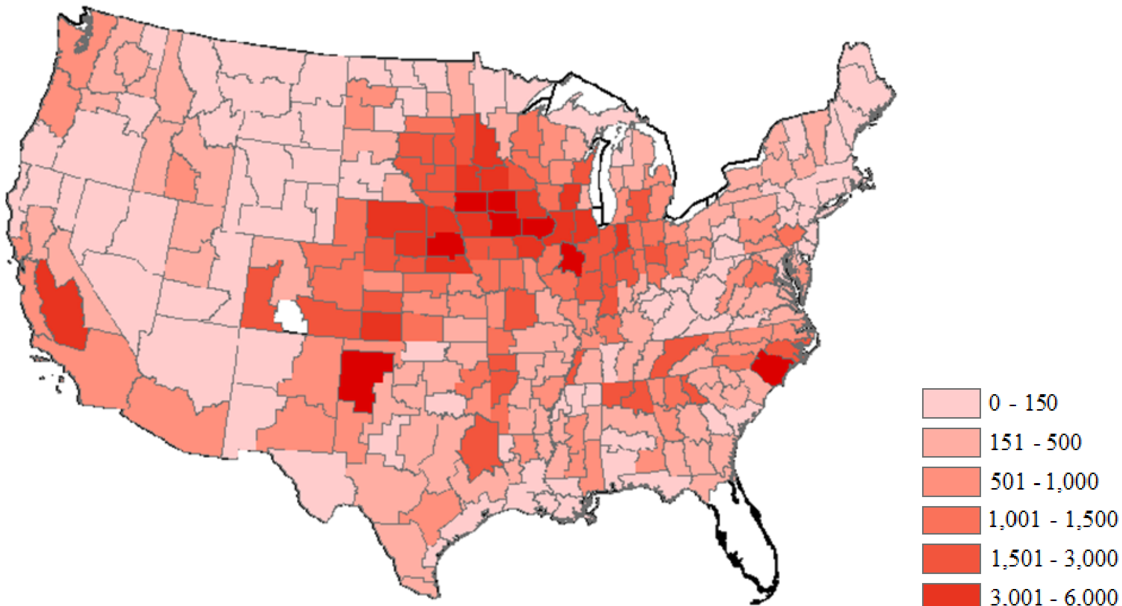
Excess Supply and Demand Locations for Grains

The identified excess supply and demand regions for corn and soybeans are shown in Figures 7 and 8, respectively. The results were used as an input to the IGTM. An interesting observation was that while some regions produced large volumes of corn and/or soybeans (as shown in Figures 4 and 5), after taking into account their own demand (cf. Figure 6), these regions become excess demand locations (see for example, CRD 40 in Illinois, CRD 60 in Iowa, and CRD 11 in Texas for corn; CRDs 20, 40, 70, and 80 in Iowa; and CRDs 30, 40, and 50 in Illinois for soybeans in the baseline scenario).

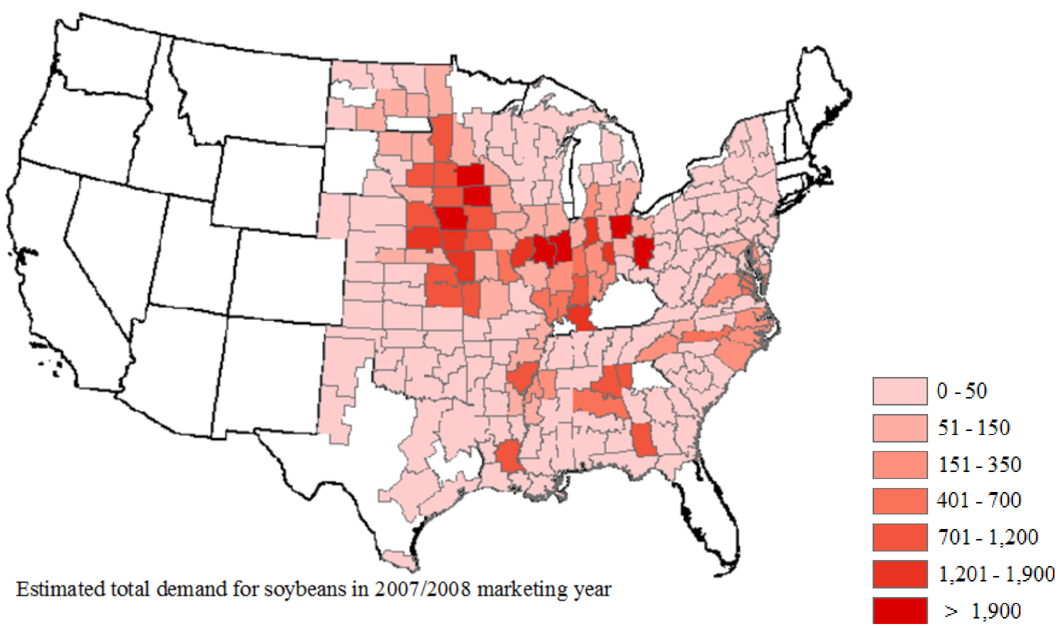
In all GCM scenarios, climate-induced shifts in geographic crop production patterns increase excess supply of corn in the Rocky Mountain region (mainly northern parts of Colorado and Wyoming) and the Northeast (mainly New York and Pennsylvania), while it reduces excess supply of corn in the Southeast (Georgia and Virginia). Three GCM scenarios project increases in the excess supply of corn in the Lake States (mainly in the central to northern part of Minnesota), South-Central region (mainly in Arkansas and Louisiana), and Pacific Southwest (mainly in the northern part of California). At the same time, declines in excess supply of corn are projected in the Great Plains (except North and South Dakota), Corn Belt (except Ohio), and Southwest regions.

For soybeans, three GCM scenarios projected an increase in excess supply in many U.S. regions. In the Northeast (mainly in Maryland, New Jersey, and Pennsylvania), the excess supply was forecasted to increase by all four GCMs. Three GCM scenarios resulted in supply increases in the Great Plains (mainly in North Dakota and Nebraska), Lake States (mainly in Michigan), and South-Central regions (mainly in Alabama, Kentucky, and Louisiana). Conversely, the Southeast and Corn Belt regions were the only two regions for which more than one GGM scenario resulted in reduced excess supply of soybeans.

Further, under the climate change scenarios some excess demand regions, especially those in the northern portion of the U.S., become excess supply regions (e.g., CRD 20 in Colorado; CRDs 20, 30, 50, and 60 in Minnesota; and CRD 20 in Nebraska for corn; CRD 70 in Indiana, CRDs 10 and 20 in Maryland; CRD 70 in Michigan; CRD 50 in Ohio; and CRDs 20 and 30 in Pennsylvania for soybeans). Conversely, some excess supply regions, especially areas in the south and central regions of the U.S., become excess demand locations (e.g., CRD 90 in Iowa; CRD 60 in Kansas; CRD 30 in Maryland; CRDs 70, 80, and 90 in Michigan; CRD 20 in Missouri, CRDs 40 and 70 in Ohio; CRD 40 in Oklahoma; and CRDs 30 and 50 in South Carolina for corn; CRDs 80 and 90 in Illinois; CRD 80 in Indiana; CRD 90 in Texas; and CRD 70 in Virginia for soybeans).



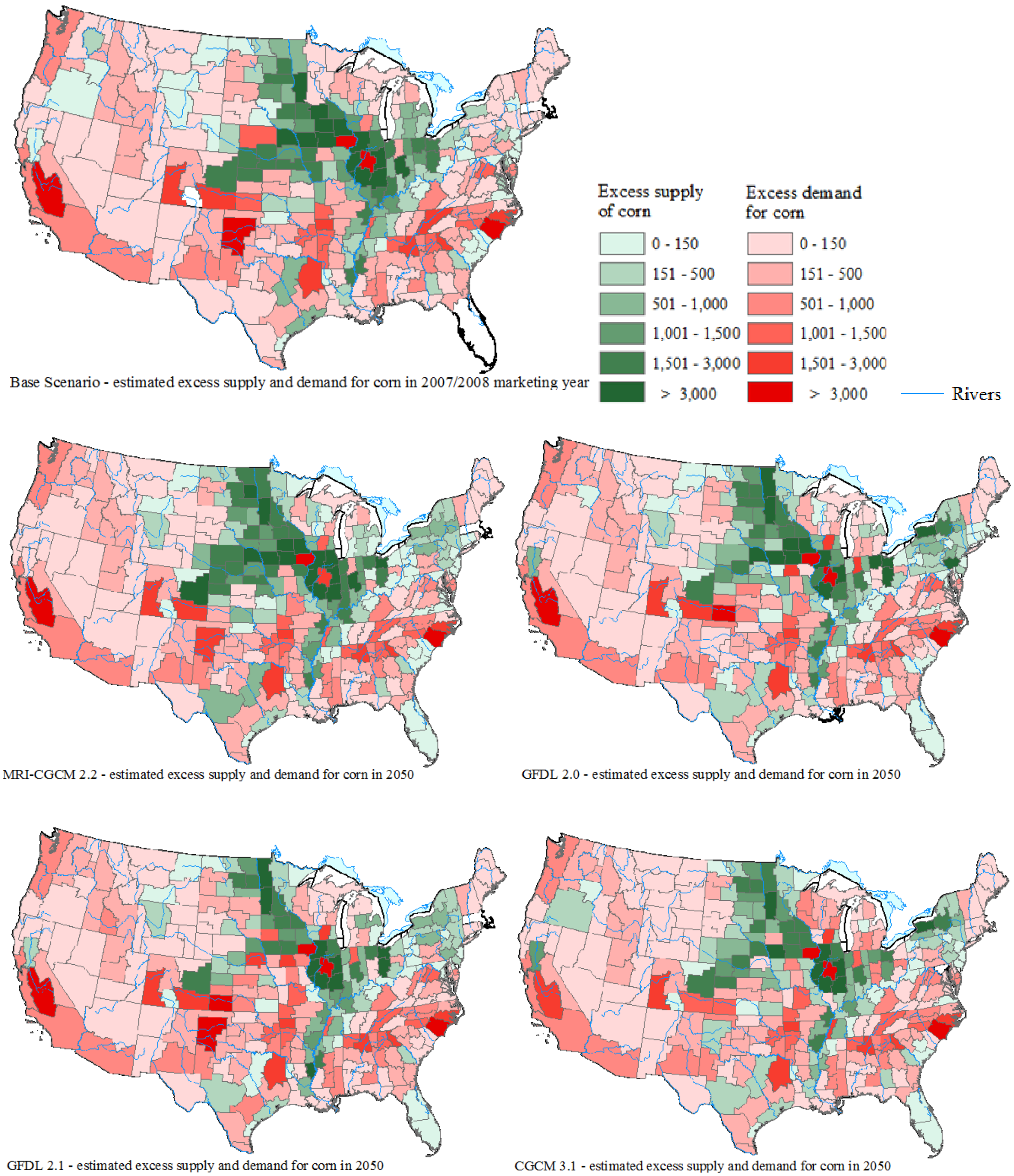
Estimated total demand for corn in 2007/2008 marketing year



Estimated total demand for soybeans in 2007/2008 marketing year

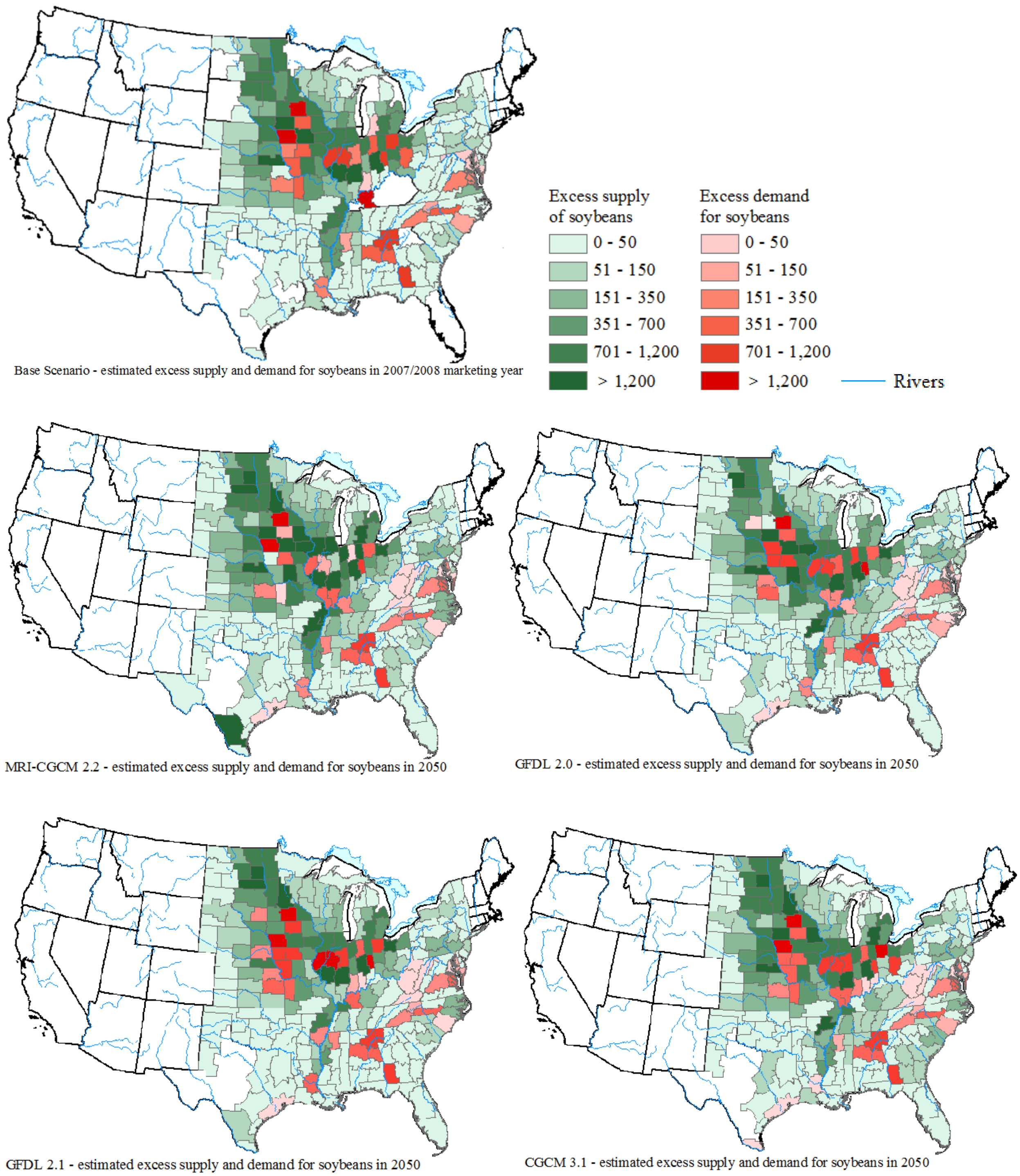
Note: Quantities are in 1,000 metric tons.

Figure 6. Estimated total demand for corn and soybeans for the 2007/2008 marketing year.



Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.

Figure 7. Excess supply and demand for corn for the baseline scenario and under different GCM scenarios.



Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.

Figure 8. Excess supply and demand for soybeans for the baseline scenario and under different GCM scenarios.

TRANSPORTATION FLOWS AND DEMAND FOR MODES OF TRANSPORTATION

Changes in Transportation Flows due to Climate-Induced Shifts in Crop Production Patterns

Climate change alters the volume of grain produced in each region and the geographic distribution of the excess supply and demand regions. This section examines how these outcomes affect interregional grain transportation flows. Tables 6 and 7 summarize the simulated interregional transportation flows of corn and soybeans under all four GCM scenarios, respectively. The U.S. regions and exporting channels included in the flow summary are shown in Figure 9.

Corn Flows

Under all GCM scenarios, the Corn Belt—the largest producer of corn in the U.S. and the source to 57 percent of all U.S. interregional corn shipments in the baseline model—is projected to ship less corn in 2050 (Table 6). In particular, all scenarios showed declines in the Corn Belt's shipments to the Pacific[18], Northeast, Rocky Mountain, Southeast, and the Lower Mississippi River ports. Moreover, under three GCM scenarios the Corn Belt's corn shipments to the South-Central region and Pacific Northwest ports were reduced. In the baseline model, of the total Corn Belt shipments, 34 percent goes to Lower Mississippi River ports, about 20 percent to the Southeast, and about 15 percent to the South-Central region. Therefore, the Corn Belt's important interregional corn flows are projected to be altered by the climate change. At the same time, the GCM scenarios were not in unanimous agreement on other changes to the interregional corn flows from the Corn Belt. However, three GCM scenarios suggested the Corn Belt would increase flows to Great Lakes ports, Lake States, and back to its own (Corn Belt) region, with internal flows comprising about 14 percent of all Corn Belt shipments.

The Great Plains—a source to about 20 percent of all interregional corn flows in the baseline model—is projected to increase overall corn shipments in three out of four scenarios. All GCM scenarios suggested increased shipments to the Pacific region and Canada. Three GCM scenarios showed increased shipments to Pacific Northwest ports comprising about 33 percent of the region's corn shipments. These flows largely originated from increased corn supplies in North and South Dakota. All GCM scenarios concur on declining corn shipments to the Southwest and within the Great Plains region itself. Three GCM scenarios indicated declining interior shipments to Mexico and to the Rocky Mountains. Note that in the baseline model, the corn shipments to interior Mexico and the Southwest represented about 22 and 21 percent of the Great Plains corn shipments in the base model, respectively; with shipments within the region itself, to the Rocky Mountains, and Pacific accounting only for 10, 9, and 4 percent, respectively.

[18] Due to the low volume of grain shipments from the Pacific Southwest and Pacific Northwest to all excess demand locations and to save space, the two regions were merged and named the "Pacific" region.

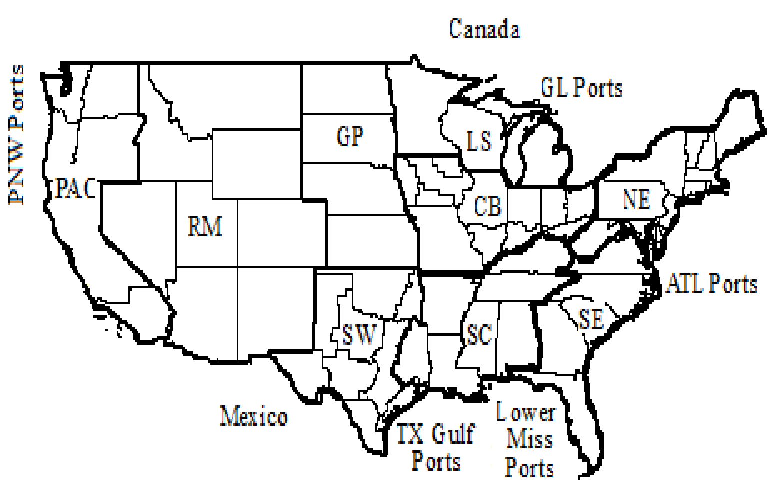
Table 6. Interregional Transportation Flows of Corn in the Baseline Scenario and under Different GCM Scenarios

Source	Destination	Baseline	MRI–CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	12,188	11,931	20,680	17,921	18,100
	Great Plains	2,629	396	5,882	4,289	1,297
	Lake States	43	86	243	—	2,955
	Pacific	5,257	5,255	—	—	998
	Northeast	2,114	1,460	525	494	1,173
	Rocky MT	1,481	1,077	9	884	631
	Southeast	16,777	14,768	8,920	12,430	9,872
	South-Central	12,382	15,249	9,843	8,565	10,051
	Southwest	2,597	2,679	2,191	3,709	2,094
	Lower Miss Ports	29,114	26,165	6,730	12,861	14,840
	PNW Ports	193	1,057	—	—	—
	Great Lakes Ports	602	1,729	2,946	2,501	497
	Atlantic Ports	—	—	—	724	—
	Interior, Mexico	—	—	—	1,031	—
	All Regions	**85,377**	**81,852**	**57,969**	**65,409**	**62,508**
Great Plains	Corn Belt	—	44	—	—	589
	Great Plains	2,831	1,273	2,009	1,508	2,160
	Pacific	1,305	2,651	5,275	1,451	3,689
	Rocky MT	2,598	2,838	1,803	346	1,877
	South-Central	—	469	—	—	—
	Southwest	6,284	3,464	1,272	3,132	2,115
	Texas Gulf Ports	—	—	2,437	—	1,735
	PNW Ports	9,746	11,608	13,954	7,386	14,343
	Interior, Mexico	6,347	7,071	5,513	2,370	4,859
	Interior, Canada	226	931	1,460	1,405	1,445
	All Regions	**29,338**	**30,348**	**33,723**	**17,599**	**32,812**
Lake States	Corn Belt	1,111	120	—	1,618	—
	Great Plains	227	213	—	2,420	125
	Lake States	2,285	3,654	4,432	3,316	4,658
	Pacific	1,521	1,480	1,586	5,798	1,296
	Northeast	619	—	—	—	—
	Rocky MT	1,457	1,026	1,843	2,241	1,358
	Southeast	1,232	386	—	1,779	—
	South-Central	684	696	1,064	—	1,045
	Southwest	—	—	943	2,555	—
	Lower Miss Ports	4,238	2,847	6,433	1,366	4,460
	PNW Ports	1,400	5,283	6,156	6,830	4,461
	Great Lakes Ports	—	72	56	—	68
	Atlantic Ports	543	50	—	71	—
	Interior, Mexico	—	—	—	171	—
	Interior, Canada	1,692	657	—	—	—
	All Regions	**17,009**	**16,484**	**22,513**	**28,165**	**17,471**

Table 6. Interregional Transportation Flows of Corn in the Baseline Scenario and under Different GCM Scenarios (Continued)

Source	Destination	Baseline	MRI–CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Rocky MT	Pacific	—	—	23	—	—
	Rocky MT	1,893	3,207	3,646	3,508	3,076
	All Regions	**1,893**	**3,207**	**3,668**	**3,508**	**3,076**
Pacific	Pacific	88	—	698	482	1,367
	Rocky MT	196	—	1	—	157
	PNW Ports	339	—	—	—	452
	All Regions	**623**	**—**	**699**	**482**	**1,977**
Northeast	Northeast	1,006	2,447	1,772	2,438	2,595
	Southeast	208	2,518	9,774	3,320	7,164
	Atlantic Ports	—	5	4,441	790	5
	Interior, Canada	389	786	820	775	801
	All Regions	**1,603**	**5,757**	**16,806**	**7,323**	**10,565**
Southeast	Northeast	96	—	—	—	—
	Southeast	797	782	289	267	667
	South-Central	—	—	—	—	8
	Atlantic Ports	164	126	—	—	78
	All Regions	**1,057**	**908**	**289**	**267**	**753**
South-Central	Southeast	160	162	752	656	413
	South-Central	5,818	5,629	7,950	9,225	7,711
	Southwest	—	—	—	394	—
	Lower Miss Ports	4,892	4,124	4,340	7,079	2,159
	All Regions	**10,870**	**9,915**	**13,042**	**17,354**	**10,283**
Southwest	Southwest	404	894	815	702	1,064
	Texas Gulf Ports	1,616	904	385	387	612
	All Regions	**2,020**	**1,798**	**1,200**	**1,089**	**1,676**
All Regions	**All Regions**	**149,791**	**150,269**	**149,911**	**141,196**	**141,124**

Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050. Source: Authors' calculation.



Notes: CB–Corn Belt; GP–Great Plains; LS–Lake States; RM–Rocky Mountain; PAC–Pacific; NE–Northeast; SE–Southeast; SC–South-Central; SW–Southwest; PNW Ports–Pacific Northwest Ports; TX Gulf Ports–Texas Gulf Ports; Lower Miss Ports–Lower Mississippi River Ports; GL Ports–Great Lakes Ports; and ATL Ports–Atlantic Ports

Figure 9. U.S. regions and exporting channels.

The Lake States rank third among the corn shipping regions, sourcing approximately 11 percent of all interregional corn flows in the baseline model. Results from three of the four GCM scenarios project expanded corn shipments, with all scenarios projecting increased shipments within the region itself and to the Pacific Northwest ports. In particular, the expanded shipments within the region (Lake States) are projected to increase 45 to 100 percent, while the flows to the Pacific Northwest ports are projected to increase between 200 and 400 percent relative to the baseline projections. Most of the latter shipments are projected to originate in Minnesota. Furthermore, three of the four GCM scenarios project expanded shipments to the South-Central region and the Great Lakes ports. All GCM scenarios show declining shipments to the Northeast, Atlantic ports, and interior Canada; and three of the four GCM scenarios project declines in shipments to the Corn Belt, Great Plains, and the Southeast.

The South-Central region—the source of approximately 7 percent of the U.S. interregional corn shipments—is projected to increase corn shipments in two of the GCM scenarios. The primary corn shipment by the South-Central states in the baseline scenario (54 percent) is to the region itself, and three of the GCM scenarios project this flow to increase. The second-ranked flow (45 percent) is to the Lower Mississippi River ports and three of the GCM scenarios project this flow to decrease.

Several additional regions have interesting changes in shipments as a result of climate change. For example, the Northeast region is projected to ship only 1.6 million metric tons of corn in the base model, but this increases to 5.7 to 16.8 million metric tons by 2050 depending on the climate change scenario. These expanded shipments are to the region itself, Southeast, Atlantic ports, and interior locations in Canada. The expanded flows from the Northeast affect corn shipments by the Corn Belt, Lake States, and Great Plains. The Rocky Mountain region is also projected to increase shipments, with virtually all shipments staying within the region itself.

The analysis offers strong evidence that climate change will affect quantities transported over selected transport corridors. The importance of the Lower Mississippi River ports—the port area with the largest U.S. corn exports—is projected to diminish, whereas the role of Pacific Northwest ports is expected to increase. For example, the flow of corn from the Corn Belt to Lower Mississippi River ports decreases in all cases, falling by an estimated 10 to 67 percent. Similarly, all GCM scenarios show Corn Belt flows to the Southeast declining from the baseline's 16.8 million metric tons by an estimated 12 to 50 percent. Corn flows from the Great Plains to Pacific Northwest ports are projected to increase by as much as 47 percent.

Climate-induced shifts in crop production patterns are also projected to generate new transportation flows for corn. Examples of such new flows include those from Illinois to Michigan; Minnesota to New Mexico and Oklahoma; Colorado to Idaho; New York to Maine, North Carolina, and Vermont; Pennsylvania to Delaware and Atlantic ports; and South Dakota to California. The increase in the excess supplies of corn in the northern regions of the U.S. and the decrease in excess supplies of corn in the middle to lower sections of Corn Belt and the Great Plains (Nebraska and Kansas) may be the primary reason behind these outcomes.

Soybean Flows

Table 7 summarizes projected flows of soybeans under different GCM scenarios. Changes in soybean shipments from the Corn Belt—the largest producer of soybeans in the baseline model—vary across GCM scenarios. However, all scenarios predict increasing soybean flows from the Corn Belt to the

Southeast and the Northeast, plus the Great Lakes and Atlantic ports. Moreover, three GCM scenarios demonstrate increasing Corn Belt shipments to Lakes States, but reduced soybean shipments to the South-Central region.

The Great Plains ranks second among the soybean shipping regions, sourcing about 25 percent of all interregional soybean flows in the baseline model. Three of the four GCM scenarios predict expanded overall soybean shipments from the Great Plains. All GCM scenarios indicate increased shipments to the Pacific region and three GCM scenarios show increased shipments to the Pacific Northwest ports due to the expected increase in excess soybean supplies in North Dakota and the northern portion of Nebraska. On the other hand, the Plains states are projected to ship lower quantities of soybeans to the South-Central region (in all GCM scenarios), and the Lower Mississippi River ports (in three out of four GCM scenarios).

The Lake States—a source to about 17 percent of all interregional soybean flows in the baseline model—is predicted to ship greater quantities of soybeans in three out of four GCM scenarios. Soybean flows from Lake States to Atlantic ports are expected to increase under all GCM scenarios, with flows projected to increase between 40 and 200 percent relative to the baseline shipments. Most of these increased soybean shipments will be originating in Michigan. Moreover, three out of four GCM scenarios project the shipments from the Lake States to the Corn Belt and the Great Lakes ports to increase. While primary soybean shipments by the Lake States in the baseline model is to the Lower Mississippi River ports (25 percent) and within the region itself (23 percent), three out of four GCM scenarios predict these flows to decline. Finally, all GCM scenarios project the Lake States to reduce soybean shipments to the Southeast.

The South-Central region—accounting for approximately 10 percent of all interregional soybean flows in the baseline model—is projected to increase soybean shipments under three of the four GCM scenarios. Similarly, three of the four scenarios show increasing soybean shipments to the Lower Mississippi River ports and within the region itself. In the baseline model these flows represent 55 and 14 percent, respectively, of the South-Central's soybean shipments.

Additional regions have interesting changes in soybean shipments as a result of projected climate change. The Northeast region is expected to ship increased quantities of soybeans within the region itself, and ship greater amounts of soybeans to the Southeast region and Atlantic ports. The Southeast region is projected to ship greater quantities of soybeans to its own excess demand regions and also ship additional soybeans to the Atlantic ports (except under GFDL 2.0). The Southwest is projected to export higher volumes of soybeans to Texas Gulf ports (except under CGCM 3.1) and Mexico.

Table 7. Interregional Transportation Flows of Soybeans in the Baseline Scenario and under Different GCM Scenarios

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	9,016	6,278	8,447	10,915	10,879
	Great Plains	—	—	271	—	—
	Lake States	443	1,255	1,929	—	1,238
	Northeast	—	2	1	1	2
	Southeast	56	915	313	206	99
	South-Central	2,558	1,972	2,587	1,356	874
	Lower Miss Ports	9,192	14,816	10,674	6,066	6,290
	Great Lakes Ports	579	1,586	1,356	1,709	506
	Atlantic Ports	182	—	463	226	—
	Interior, Mexico	—	438	—	—	—
	All Regions	**22,026**	**27,262**	**26,041**	**20,479**	**19,888**
Great Plains	Corn Belt	1,008	37	1,233	401	2,115
	Great Plains	397	253	698	1,443	354
	Pacific	18	26	37	30	31
	South-Central	495	351	150	—	261
	Southwest	—	35	—	235	—
	Lower Miss Ports	1,069	2,114	24	—	907
	PNW Ports	6,856	7,407	7,836	6,053	8,300
	Interior, Mexico	2,596	2,424	2,626	1,892	2,606
	All Regions	**12,439**	**12,647**	**12,604**	**10,054**	**14,574**
Lake States	Corn Belt	836	941	597	2,475	1,357
	Great Plains	—	—	—	102	—
	Lake States	1,899	1,811	1,711	2,502	1,450
	Southeast	835	299	670	740	456
	South-Central	—	—	—	213	—
	Lower Miss Ports	2,122	1,993	1,422	995	2,452
	PNW Ports	1,804	2,651	669	831	2,002
	Great Lakes Ports	98	280	117	—	543
	Atlantic Ports	731	2,176	1,007	1,569	1,235
	Interior, Mexico	—	—	—	183	—
	All Regions	**8,325**	**10,151**	**6,193**	**9,610**	**9,495**
Northeast	Northeast	62	313	356	385	277
	Southeast	780	780	1,324	965	870
	Atlantic Ports	5	7	65	16	8
	Interior, Canada	156	114	338	94	280
	All Regions	**1,003**	**1,215**	**2,083**	**1,459**	**1,435**

Table 7. Interregional Transportation Flows of Soybeans in the Baseline Scenario and under Different GCM Scenarios (Continued)

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Southeast	Northeast	18	—	—	5	7
	Southeast	554	1,010	252	652	1,020
	Atlantic Ports	225	387	120	328	328
	All Regions	**796**	**1,397**	**372**	**985**	**1,355**
South-Central	Southeast	1,545	1,581	1,571	1,283	1,513
	South-Central	732	682	845	1,582	747
	Southwest	—	1	2	1	1
	Lower Miss Ports	2,832	4,414	4,528	1,073	4,570
	Texas Gulf Ports	10	—	12	—	—
	All Regions	**5,119**	**6,678**	**6,958**	**3,939**	**6,831**
Southwest	South-Central	3	—	17	—	—
	Southwest	—	—	—	45	1
	Lower Miss Ports	134	1,236	59	17	69
	Texas Gulf Ports	41	869	87	139	6
	Interior, Mexico	45	139	91	340	81
	All Regions	**223**	**2,244**	**254**	**541**	**157**
All Regions	**All Regions**	**49,931**	**61,593**	**54,505**	**47,069**	**53,736**

Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050. Source: Authors' calculation.

Similar to corn, the above findings show strong evidence that climate change will affect soybean shipments over selected transport corridors. For example, the flow of soybeans from the Corn Belt to the Lower Mississippi River ports may be reduced by up to 34 percent. The analysis further suggests important declines (as much as 66 percent) by 2050 in the Corn Belt's shipments to the South-Central region. Furthermore, soybean flows from the Great Plains to Pacific Northwest ports are projected to increase by as much as 21 percent. The analysis also shows that port areas with historically small export volumes will become more important. These include the Great Lakes ports, the Atlantic ports, and interior locations shipping overland to Mexico.

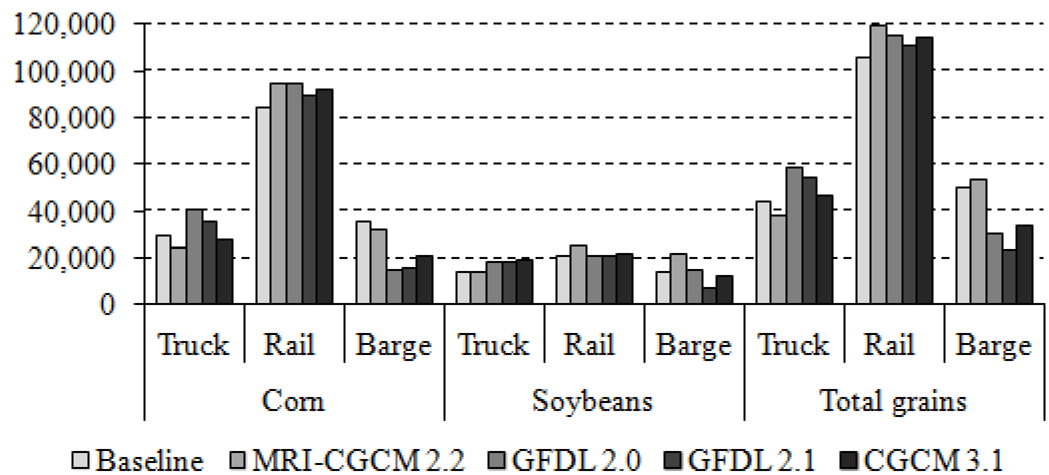
Similar to corn, the climate change is projected to generate new and expanded soybean flows. For example, Kentucky is projected to ship soybeans to Alabama, Georgia, North Carolina, and Lower Mississippi River ports; whereas Maryland would ship soybeans to Atlantic ports and to its own excess demand region. Illinois is expected to receive greater amounts of soybeans from within the state itself, while North Carolina will receive additional shipments from New York. North Dakota, Ohio, and Michigan are projected to increase soybean shipments to the Pacific Northwest ports, the Great Lake ports at Toledo (Ohio), and the Atlantic port at Norfolk (Virginia), respectively.

Demand for Modes of Transportation

Figure 10 shows the shift in transportation mode usage for corn, soybeans, and both grains combined under the baseline and the four climate change scenarios. Considering both domestic and export shipments, railroads transport the largest share (in terms of tons) of the interregional grain movements (both corn and soybeans) between excess supply and demand locations. The railroads are also expected to have an increasing role under the four climate change scenarios as compared to the truck and barge modes. Three of the four GCM scenarios suggest an increasing demand for trucking of corn, soybeans, and total shipments. Conversely, barges are expected to transport fewer grain shipments (under three of the four GCM scenarios). Demand for barge transportation of corn declines under all GCM scenarios because of reduced excess supplies in proximity of the Mississippi River in the Corn Belt and south Minnesota. However, barge shipments of soybeans remain relatively stable.

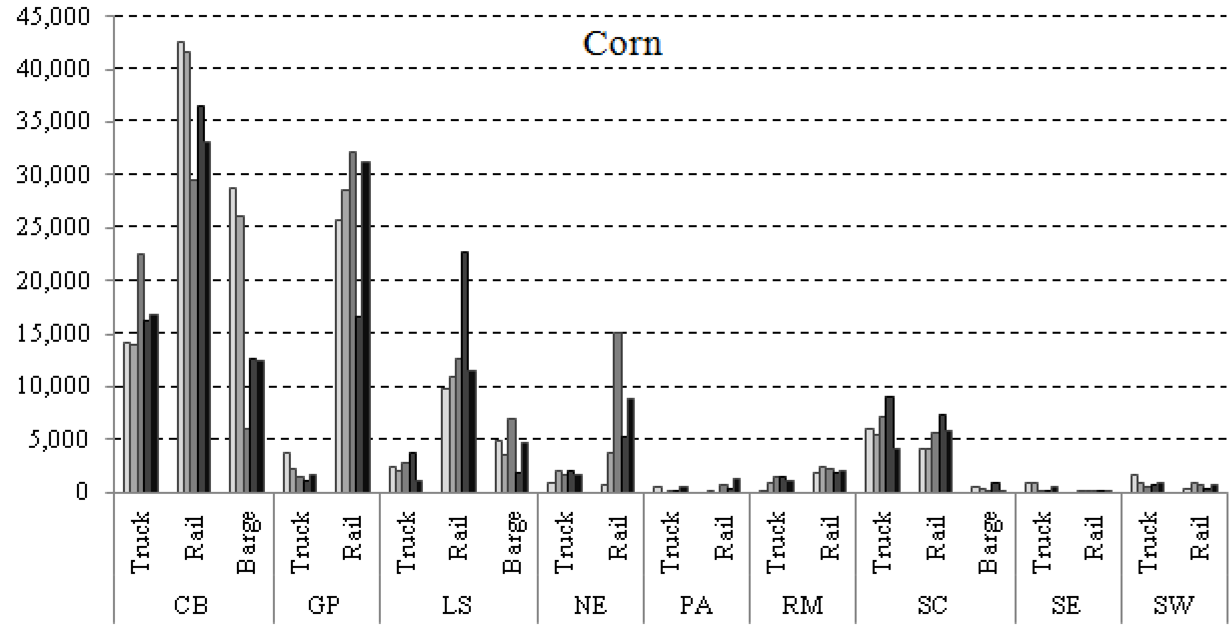
A more detailed breakdown of transportation mode demand by region is shown in Figures 11(a) for corn and 11(b) for soybeans. The projected demand for the truck mode for corn tends to increase in the Corn Belt (except under MRI-CGCM 2.2), Northeast, and Rocky Mountains and decline in the Great Plains, Southeast, and Southwest. For soybeans, the increase is expected in the Great Plains (except under MRI-CGCM 2.2), South-Central, and Northeast; whereas a decline is projected for the Southwest.

The demand for the rail mode is projected to increase in almost all regions for both corn and soybeans under a majority of GCMs, except Corn Belt for corn and South-Central region for soybeans. A majority of GCMs predict a reduction in demand for barge mode for corn in all regions, while the results are mixed for soybeans. The South-Central region is the only region where more than two GCM scenarios project an increase in barge transportation demand for soybeans.

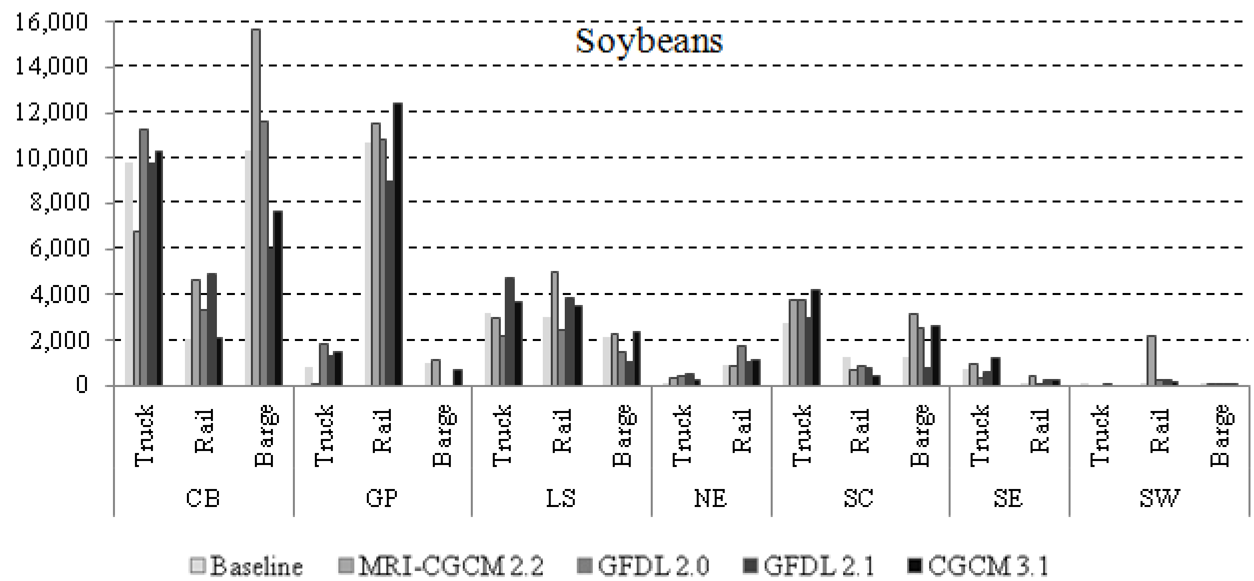


Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.

Figure 10. Grain shipments by modes of transportation under the baseline and GCM scenarios.



(a)



(b)

Notes: Quantities are in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. The projections under different GCM scenarios are for 2050.CB–Corn Belt; GP–Great Plains; LS–Lake States; NE–Northeast; PAC–Pacific; RM–Rocky Mountain; SC–South-Central; SE–Southeast; SW–Southwest.

Figure 11. Corn and soybean shipments by regions and modes of transportation under the baseline and GCM scenarios.

Changes in Transportation Flows Due to an Extension of the Navigation Season

Rising temperatures are projected to reduce the duration of ice cover in the Upper Mississippi River and the Great Lakes during the winter season, with an extension of the navigation season being the most direct effect. In order to account for the possibility of the extended shipping season, the IGTM was modified to allow grain shipments during the winter season along the Upper Mississippi River above St. Louis (MO) and the Great Lakes. In the analysis presented in the previous subsection, these arteries were blocked to transportation in winter season due to ice cover.

An Extension of the Navigation Season along the Upper Mississippi River

Extended navigation in the winter along the Upper Mississippi River is likely to affect interregional transportation flows as well as seasonal movements of grain flows and demand for modes of transportation. This section presents the results of the modified simulations and compares those to the results established in the previous subsection.

Corn Flows

Table 8 summarizes the additional effect of extended navigation season relative to the results reported in Table 6. Three of the four GCM scenarios show the Corn Belt's corn shipments to the Southwest region, Lower Mississippi River ports, and Great Lakes ports to decline. On the other hand, all GCM scenarios suggest increased flows back to the region itself and to the Rocky Mountains, with the shipments to the latter going up from 9 to about 1,100 thousand metric tons[19] in at least one scenario. Finally, three out of four GCM scenarios indicate increased shipments to the Southeast.

All GCM scenarios suggest that the Great Plains region is likely to ship larger amounts of corn to the Pacific (mainly from South Dakota) and within the region itself. The increases range from 2.52 to 30.44 percent and from 0.13 to 112.33 percent, respectively. Three GCM scenarios indicate lower amount of corn flows to the Pacific Northwest ports (mainly from South Dakota) and Mexico. The magnitude of the effect ranges from 0.05 to 17.73 percent and from 0.21 to 17.37 percent, respectively.

All GCM scenarios predict that the reduction of corn shipments from the Corn Belt to the Lower Mississippi River ports would be replaced by a substantial increase of corn shipments from the Lake States (mainly Minnesota), with the flows projected to increase between 20.91 and 150.28 percent. This will be compensated by reduced shipments to other regions (Rocky Mountains, Pacific, and Pacific Northwest ports) and within the region itself. Finally, in three GCM scenarios, the Northeast and South-Central regions are expected to ship lower amounts of corn to Southeast and Lower Mississippi River ports, respectively.

Overall, all GCM scenarios indicate that the Corn Belt is likely to import corn from other excess supply regions, including from within the region itself. In three GCM scenarios, all excess supply regions are likely to export higher levels of corn to the Lower Mississippi River ports and Northeast region. On the other hand, a majority of the GCM scenarios project lower levels of corn shipments to the Lake States, Texas Gulf ports, Pacific Northwest ports, and Great Lakes ports. The results are mixed for the Atlantic ports and Great Plains and are mostly unchanged for the remaining regions.

[19] Formally, this accounts for about an 11,000 percent increase as reported in Table 8. However, the seemingly large magnitude is due to very low baseline shipments in Table 6.

Soybean Flows

The effects of an extended navigation season on shipments of soybeans are shown in Table 9, which reports percent changes in transportation flows relative to the results in Table 7.

At least three GCM scenarios project an increase in soybean shipments from the Corn Belt to the Southeast and Lower Mississippi River ports, with the effect ranging from 0.16 to 14.14 percent and from 1.81 to 21.00 percent, respectively. The Corn Belt is expected to ship fewer soybeans within the region itself and to the Great Lakes ports.

For the Great Plains, a majority of the GCM scenarios suggest increased flows back to the region itself with the effect ranging from 0.02 to 81.42 percent. At the same time, the Great Plains region is expected to ship fewer soybeans to the Lower Mississippi River ports (up to 100 percent reduction) and Pacific Northwest ports (0.02 to 2.75 percent reduction).

A majority of GCM scenarios project expanded soybean shipments from the Lake States to the Southeast (an increase of up to 300 percent) and Lower Mississippi River ports (a 10.55–12.64 percent increase). At the same time, the Pacific Northwest and Atlantic ports are expected to receive lower soybean shipments from the Lake States, with most of the reductions coming from Minnesota and Michigan, respectively.

Several additional regions have interesting changes in shipment patterns due to an extended navigation season. For example, the South-Central and Southwest regions are projected to ship more soybeans within the region itself (an increase of up to 71.70 percent) and to Mexico (an increase of up to 159.71 percent). Overall, all excess supply regions are likely to export lower levels of soybeans to the Corn Belt, Texas Gulf ports (except for under MRI-CGCM 2.2), Pacific Northwest ports, and Great Lakes ports; while only the Lower Mississippi River ports are expected to receive higher soybean shipments.

Seasonality of Grain Flows

The extension of the navigation season along the Upper Mississippi River is also likely to affect the seasonal patterns of overall corn and soybean transportation flows. Table 10 presents changes in seasonal grain transportation flows under different GCM scenarios. Overall, transportation flows of corn and soybeans are projected to increase in the winter, with the effect ranging from 2.36 to 17.95 percent and from 5.60 to 56.28 percent, respectively. On the other hand, a majority of the GCM scenarios indicate lower corn and soybean shipments in fall (1.19–5.93 percent reduction for corn, and 1.42–19.87 percent reduction for soybeans) and spring (37.01–87.97 percent reduction for corn, and 10.20–38.94 percent reduction for soybeans). In the summer, the corn shipments are likely to increase by 20.72 to 61.94 percent, while findings for the soybeans are mixed.

Table 8. Percent Change in Interregional Transportation Flows of Corn under Different GCM Scenarios due to an Extension of the Navigation Season along the Upper Mississippi River

Source	Destination	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	12.46	1.76	2.56	0.62
	Pacific	−13.78	—	—	0.20
	Rocky MT	103.25	11,022.22	0.03	123.93
	Southeast	12.83	−3.14	2.28	0.54
	South-Central	−11.48	1.87	−2.74	1.13
	Southwest	−20.49	−4.15	9.41	−0.19
	Lower Miss Ports	2.15	−9.08	−6.70	−9.15
	PNW Ports	−100.00	—	—	—
	Great Lakes Ports	−45.29	7.94	−0.02	−14.29
	Interior, Mexico	858.00*	—	8.24	—
Great Plains	Great Plains	112.33	13.69	0.13	7.59
	Pacific	30.44	2.52	7.86	2.55
	Southwest	29.16	14.94	−1.37	−0.02
	Texas Gulf Ports	—	−23.92	—	−5.99
	PNW Ports	−17.73	−0.05	−1.67	−0.17
	Interior, Mexico	−17.37	−0.44	−0.21	−0.45
	Interior, Canada	62.30	0.01	0.03	−0.05
Lake States	Lake States	−18.86	0.23	−0.63	−7.45
	Pacific	−19.46	−8.58	−2.00	−8.18
	Rocky MT	−76.22	−59.58	−2.28	−64.36
	Lower Miss Ports	150.28	20.91	105.93	36.05
	PNW Ports	−27.75	−0.10	−0.20	0.38
Northeast	Northeast	50.18	0.28	−0.08	−0.19
	Southeast	−43.96	−0.24	0.63	−0.42
Southeast	Atlantic Ports	372.22	—	—	0.23
South-Central	South-Central	17.16	−1.04	0.70	7.99
	Lower Miss Ports	−8.90	1.04	−1.89	−30.66
All Regions	Corn Belt	14.95	2.27	0.04	0.35
	Great Plains	61.05	0.24	−0.04	−0.33
	Lake States	−18.98	0.04	−0.63	−0.50
	Northeast	45.33	0.26	−0.07	0.27
	South-Central	−3.84	0.54	−0.96	3.84
	Lower Miss Ports	13.50	4.44	2.12	−1.92
	Texas Gulf Ports	7.85	−20.66	−0.11	−4.18
	PNW Ports	−25.52	−0.06	−0.96	−0.03
	Great Lakes Ports	−43.45	7.43	−0.02	−12.59
	Atlantic Ports	685.08	−1.04	−6.88	0.23

Notes: Percent changes are relative to the results in Table 6, with the exception of the entries marked (*). The latter are in 1,000 metric tons because the corresponding results in Table 6 are zero.

Table 9. Percent Change in Interregional Transportation Flows of Soybeans under Different GCM Scenarios due to an Extension of the Navigation Season along the Upper Mississippi River

Source	Destination	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	33.51	−0.70	−0.99	−0.67
	Lake States	−88.92	1.40	—	−100.00
	Southeast	−42.95	5.75	0.16	14.14
	South-Central	68.61	−3.94	—	−0.01
	Lower Miss Ports	6.84	2.14	1.81	21.00
	Great Lakes Ports	−60.40	−1.33	−0.18	−3.56
	Atlantic Ports	295.00*	−4.10	0.88	–
Great Plains	Great Plains	81.42	8.88	0.02	−0.23
	Lower Miss Ports	−12.39	−100.00	−24.00*	4.41
	PNW Ports	−2.75	−0.97	−0.02	−0.67
Lake States	Lake States	87.80	−1.99	−0.20	87.45
	Pacific	747.00*	—	—	—
	Southeast	300.33	2.39	0.03	0.17
	Lower Miss Ports	12.64	12.03	10.55	−10.80
	PNW Ports	−64.32	−0.03	−21.30	−44.86
	Great Lakes Ports	120.00	−100.00	—	−11.97
	Atlantic Ports	−80.42	−0.20	−0.05	0.08
South-Central	Southeast	−14.23	−2.16	—	−0.73
	South-Central	71.70	−16.57	—	14.06
	Lower Miss Ports	21.52	1.77	−0.03	−2.07
Southwest	Lower Miss Ports	−21.93	−1.71	−100.00	−1.48
	Texas Gulf Ports	35.67	−0.91	−0.01	−0.88
	Interior, Mexico	159.71	0.14	13.53	0.14
All Regions	Corn Belt	30.97	−0.12	−0.05	−0.11
	South-Central	66.45	−7.70	—	4.94
	Lower Miss Ports	6.86	2.72	2.42	7.00
	Texas Gulf Ports	35.67	−8.08	−0.01	−0.88
	PNW Ports	−18.95	−0.89	−2.59	−9.26
	Great Lakes Ports	−33.33	−9.16	−0.18	−7.90
	Atlantic Ports	−48.60	−1.27	0.02	0.06

Notes: Percent changes are relative to the results in Table 7, with the exception of the entries marked (*). The latter are in 1,000 metric tons because the corresponding results in Table 7 are zero.

Table 10. Effect of Extended Navigation Season along the Upper Mississippi River and Great Lakes on Seasonal Grain Transportation Flows under Different GCM Scenarios

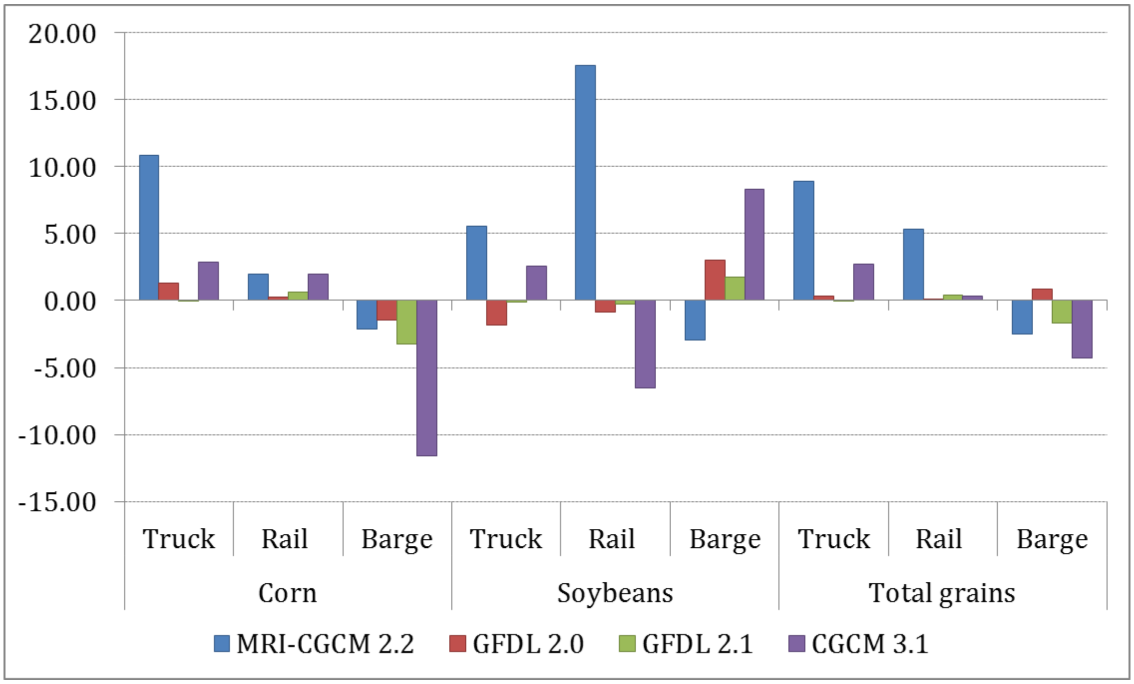
Crop	Season	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
		Projected seasonal grain transportation flows under crop mix shift only (in 1,000 metric tons)			
Corn	Fall	84,290	84,931	80,154	74,668
	Winter	57,726	56,752	57,842	59,193
	Spring	4,297	7,187	2,041	6,029
	Summer	3,956	1,041	1,159	1,234
Soybeans	Fall	33,807	33,470	30,983	34,324
	Winter	19,292	13,408	9,193	10,758
	Spring	5,536	4,215	6,196	6,568
	Summer	2,959	3,413	697	2,085
		Additional effect of extended navigation season (percent change)			
		along the Upper Mississippi River			
Corn	Fall	–5.93	–3.74	–1.19	–4.26
	Winter	2.36	17.95	2.41	12.84
	Spring	116.75	–87.97	–37.01	–75.31
	Summer	61.94	–13.22	27.13	20.72
Soybeans	Fall	–19.87	–3.42	0.32	–1.42
	Winter	56.28	23.98	5.60	34.28
	Spring	–8.94	–26.90	–10.20	–38.94
	Summer	32.82	–28.95	9.99	–27.42
		along the Great Lakes			
Corn	Fall	–0.78	–4.39	–2.69	–3.07
	Winter	–0.39	9.57	4.06	2.63
	Spring	20.68	–23.65	–9.35	12.20
	Summer	0.00	0.00	0.00	0.00
Soybeans	Fall	0.58	0.29	0.13	–0.15
	Winter	–1.39	–0.26	1.8	0.1
	Spring	1.56	–2.73	–6.74	0.67
	Summer	–0.04	–4.62	30.52	–0.05

Demand for Modes of Transportation

Figure 12 shows changes in usage of transportation modes for corn, soybeans, and both grains combined under different GCM scenarios due to an extension of the navigation season along the Upper Mississippi River. Considering both domestic and export shipments, the demand for barge is expected to drop between 1.46 and 11.62 percent for corn shipments, while it is projected to increase between 1.73 and 8.29 percent for soybean shipments. However for total shipments (corn and soybeans), three out of four GCM scenarios suggest a decreasing demand for barge (1.70–4.28 percent). All GCM scenarios indicate higher usage of rail for corn shipments (increase of 0.27–1.98 percent); while three of the four GCM scenarios suggest lower usage of rail for soybean shipments (decrease of 0.30–6.56 percent). Overall, demand for rail is expected to increase between 0.06 and 5.30 percent. Finally, three of the four GCM scenarios predict that overall demand for truck would largely increase for corn shipments with mixed findings for soybean shipments.

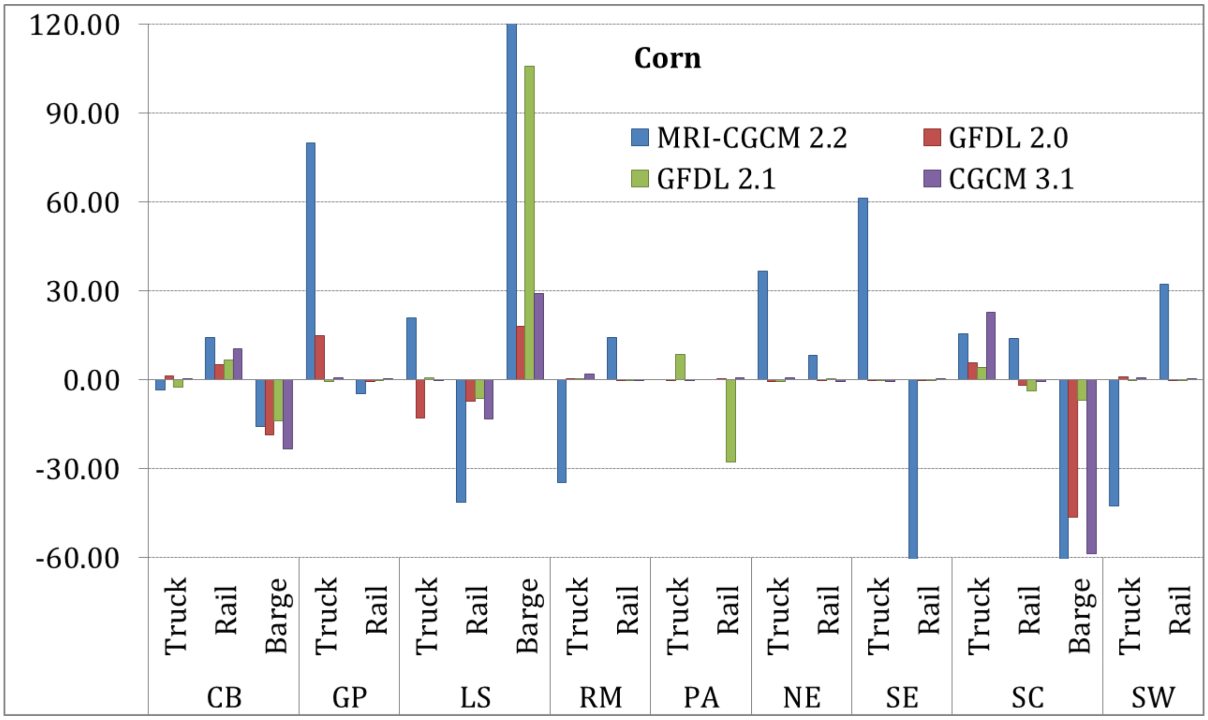
When broken by regions, the demand for barge for corn shipments tends to increase, mostly from the Lake States (between 18 and 120 percent), while it is likely to decline in the Corn Belt and South-Central by 14–23 percent and 7–60 percent, respectively (Figure 13a). The demand for rail is expected to increase mostly from the Corn Belt (5–14 percent), and drop mainly in the Lake States (6–41 percent) and the Southeast (up to 100 percent).

For the soybeans (Figure 13b), demand for barge is expected to increase in the Corn Belt, Great Plains, and Lake States, and drop mainly in the Southwest (by 7–62 percent). The usage of rail is projected to increase in the Southwest (by 1–87 percent). Lastly, demand for truck is expected to increase mainly in the Great Plains and drop in the Corn Belt and Southwest regions (by 4–18 percent and by 0–99 percent, respectively).

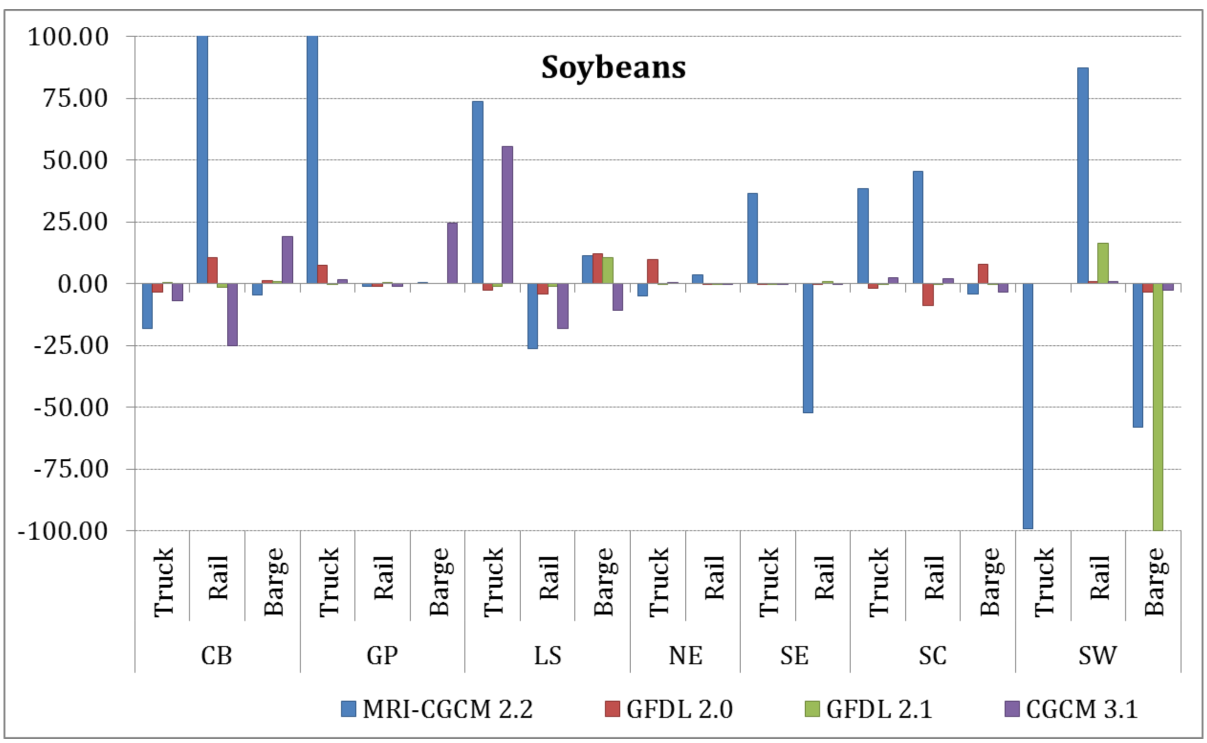


Note: The changes are relative to the results in Figure 10.

Figure 12. Percent change in corn, soybean, and total grain shipments by modes of transportation due to possible extension of the navigation season along the Upper Mississippi River.



(a) Corn



(b) Soybeans

Note: Changes are relative to the results in Figure 11.

Figure 13. Percent change in (a) corn and (b) soybeans shipments by regions and mode of transportation due to possible extension of the navigation season along the Upper Mississippi River.

An Extension of the Navigation Season along the Great Lakes

The extension of the navigation in the winter along the Great Lakes is found to primarily affect interregional transportation flows of soybeans, with a very small effect on corn flows. It also affects seasonal movements of grain flows and demand for modes of transportation.

Overall, the incremental effects relative to the results of the previous section (crop mix shift) are rather small. This is expected, since small quantities of grains are shipped via Great Lakes ports plus Great Lakes ports have less competitive transportation costs compared to major ports. Notable findings are summarized in Tables 10 and 11.

Corn and Soybean Flows

Corn transportation flows were found to remain mostly unchanged and are not reported here. However, the total annual transportation flows of soybeans would be affected to some extent.

A majority of GCM scenarios suggest lower soybean shipments from the Corn Belt to South-Central region (by 0.01–4.21 percent), Lower Mississippi River ports (by 0.38–1.87 percent), and Atlantic ports (up to 88.94 percent); while all GCM scenarios indicate an increase of soybean shipments from the Corn Belt to Great Lakes ports ranging from 0.40 to 41.89 percent. The Lake States region is expected to ship more soybeans to the Great Lakes ports (up to 225.71 percent), but less to the Atlantic ports (by 12.61–48.66 percent). Next, all GCM scenarios predict higher soybean shipments from the South-Central to Southeast region (up to 7 percent), but lower shipments to the Lower Mississippi River ports (0.03–18.92 percent). Overall, only Great Lakes ports are likely to receive higher soybean shipments from other excess supply regions (ranging from 21.77 to 57.71 percent); whereas the Lower Mississippi River, Pacific Northwest, and Atlantic ports would tend to receive lower soybean flows from other regions (Table 11).

Seasonality of Grain Flows

Although total annual transportation flows of corn are likely to be unchanged, an extension of the navigation season along the Great Lakes is likely to affect the overall seasonality of corn flows. All GCM scenarios indicate reduced total corn transportation flows in the fall season (by 0.78–4.39 percent), while three of the four GCM scenarios project higher corn shipments in the winter season (by 2.63–9.57 percent). The results are mixed for the spring and there is no change of corn flows in the summer (Table 10). On the other hand, soybean shipments are expected to shift to fall and summer seasons, with mixed results for winter and spring seasons.

Table 11. Percent Change in Interregional Transportation Flows of Soybeans under Different GCM Scenarios due to an Extension of the Navigation Season along the Great Lakes

Source	Destination	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	3.52	–1.69	–3.46	—
	Great Plains	—	40.22	—	—
	South-Central	–0.01	–4.21	–0.01	—
	Lower Miss Ports	–1.87	–0.28	3.48	–0.38
	Great Lakes Ports	3.72	41.89	21.77	0.40
	Atlantic Ports	—	–76.03	–88.94	—
Great Plains	Great Plains	0.02	–15.76	0.02	0.01
	South-Central	0.03	73.33	—	—
Lake States	Corn Belt	–23.59	23.79	15.27	—
	South-Central	—	—	–96.24	—
	Great Lakes Ports	225.71	0.01	—	111.23
	Atlantic Ports	–16.04	–12.61	2.61	–48.66
South-Central	Southeast	0.25	7.00	—	0.73
	South-Central	—	–13.02	12.90	—
	Lower Miss Ports	–0.03	–2.42	–18.92	–0.24
All Regions	South-Central	—	–3.03	–0.01	—
	Lower Miss Ports	–1.13	–0.84	0.06	–0.24
	PNW Ports	–0.73	–0.01	–3.09	–0.02
	Great Lakes Ports	37.03	38.56	21.77	57.71
	Atlantic Ports	–12.76	–25.26	–7.39	–36.16

Note: Percent changes are relative to the results in Table 7.

Demand for Modes of Transportation

Consistent with the results on grain flows, there does not appear to be any change in demand for modes of transportation for corn shipments due to an extension of the navigation season along the Great Lakes. Therefore, the corresponding results are not reported here. However, the demand for modes of transportation for soybean shipments is likely to change. Most interesting results are shown in Table 12. Corn Belt and Lake States are the only two regions that are significantly affected by an extension of the navigation season along the Great Lakes. The usage of truck for soybean shipments in both regions is expected to increase as compared to the results shown in Figures 10 and 11. Three of the four GCM scenarios suggest lower demand for barge in the Corn Belt for soybean shipments. Changes in the projected demand for rail are mixed in both regions. Considering all U.S. regions, demand for truck is projected to increase between 1.81 and 3.84 percent; while demand for rail and barge is expected to drop between 0.97 and 2.57 and between 0.47 and 1.92 percent, respectively.

Table 12. Percent Change in Soybean Shipments by Region and by Modes of Transportation under Different GCM Scenarios due to an Extension of the Navigation Season along the Great Lakes

Regions	Mode	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Truck	0.14	4.44	2.14	0.03
	Rail	6.80	–17.43	–4.22	1.16
	Barge	–1.77	–0.26	3.45	–0.36
Lake States	Truck	23.60	—	0.02	27.89
	Rail	–9.85	0.04	0.07	–12.37
	Barge	0.10	—	–0.30	0.01
All Regions	Truck	3.84	1.81	2.22	3.05
	Rail	–1.28	–1.75	–0.97	–2.57
	Barge	–1.92	–0.64	0.03	–0.47

Note: Percent changes are relative to the results in Figures 10 and 11.

Changes in Transportation Flows toward and along the Great Lakes due to a Possible Reduction in Lake Water Levels

As discussed earlier, several studies predict that climate change would likely lead to a reduction of Great Lakes water levels, thus potentially increasing the cost to ship agricultural and other commodities and, in turn, affecting grain transportation flows. This section discusses the incremental effect of increases in shipping cost caused by a fall in Great Lakes water levels. Following the results of Millerd (2011), the scenario analysis was performed by increasing the shipping cost by five, 10, and 20 percent relative to the shipping cost under the baseline scenario.

Transportation Flows

The incremental effect of lower water levels in the Great Lakes primarily manifests in the interregional grain transportation flows, while the seasonal movements are only slightly affected. Interesting findings of simulated changes in interregional transportation flows are shown in Table 13 and Table 14 for corn and soybeans, respectively.[20]

Corn Flows

Under all GCM scenarios and all scenarios of increases in shipping cost, the Corn Belt is projected to ship more corn to the South-Central, Lower Mississippi River ports, and Atlantic ports (Table 13). The higher the increase in shipping cost, the larger the corn shipments from the Corn Belt to those regions. On the other hand, corn flows from the Corn Belt to the Great Lakes ports are projected to drop substantially (up to 100 percent), with most of these expanded corn shipments originating in Ohio. Corn flows from the Lake States to the Lower Mississippi River ports are also projected to increase by up to 28.33 percent. Overall, as the shipping cost increases, Great Lakes ports are projected to receive fewer corn shipments from all excess supply regions, especially from the Corn Belt. At the same time, the

[20] The results are reported as deviations from benchmarks established in Tables 6 and 7, respectively.

South-Central region, Lower Mississippi River ports, and Atlantic ports are expected to receive higher corn shipments.

Soybean Flows

Table 14 shows that increases in shipping cost due to a fall in Great Lakes water levels are expected to decrease soybean shipments from the Corn Belt and Lake States to Great Lakes ports in all GCM scenarios under all scenarios of increases in shipping cost. The flows are projected to decrease between 4 and 100 percent and between 13 and 100 percent, respectively, with most of the reductions in soybean shipments originating in Ohio and Wisconsin. On the other hand, soybean flows from the Corn Belt to the Lower Mississippi River ports and Atlantic ports and from the Lake States to Atlantic ports are projected to increase. Results are mixed for soybean shipments from the Corn Belt to the region itself and from the Lake States to the Corn Belt depending on the GCM scenario and percent increase in shipping cost. Overall, similar to corn, as the shipping cost increases, Great Lakes ports are expected to receive lower soybean shipments from all regions, while the Lower Mississippi River ports and the Atlantic ports are likely to receive higher soybean shipments from all regions.

Demand for Modes of Transportation

In terms of demand for modes of transportation, both corn and soybean flows show similar patterns. Under most GCM scenarios (except for GFDL 2.0 for soybeans), the demand for truck tends to drop by 0.01–5.77 percent; primarily due to a reduction in corn shipments via truck — especially from the Corn Belt to Great Lakes ports. On the other hand, under a majority of GCM scenarios, the demand for rail is projected to increase by 0.52–4.09 percent due to increases of shipments from the Corn Belt to South-Central and Atlantic ports. The demand for barge is projected to increase in all GCM scenarios by 0.03–2.90 percent due to increases of corn shipments via barge from the Corn Belt and Lake States to the Lower Mississippi River ports. As expected, the higher the increases in shipping cost, the greater the demand for rail and barge and the lower the demand for truck (Figure 14).

After breaking modes of transportation down by regions, the Corn Belt and Lake States turn out to be the only two regions that are significantly affected by a fall in Great Lakes water levels. A majority of GCM scenarios suggest a drop in the demand for truck in both regions (0.02–11.29 percent for the Corn Belt and up to 3.20 percent for Lake States) and overall U.S. regions (0.01–5.77 percent) relative to the benchmark results in Figure 11. The projected changes in usage of rail for corn shipments are mixed. However, as the shipping cost increases, demand for rail in the Corn Belt is likely to increase, while demand for rail in the Lake States is likely to decrease. Considering all U.S. regions, three of the four GCM scenarios project an increase in demand for rail. For soybean shipments, demand for rail in the Corn Belt is projected to increase, whereas results are mixed in the Lake States. However, overall demand for rail is predicted to increase in three GCM scenarios. Finally, a majority of GCM scenarios suggest higher demand for barge (Figure 15).

Table 13. Percent Change in Interregional Transportation Flows of Corn under Different GCM Scenarios due to Increases in Shipping Cost Caused by Reduced Water Levels in the Great Lakes

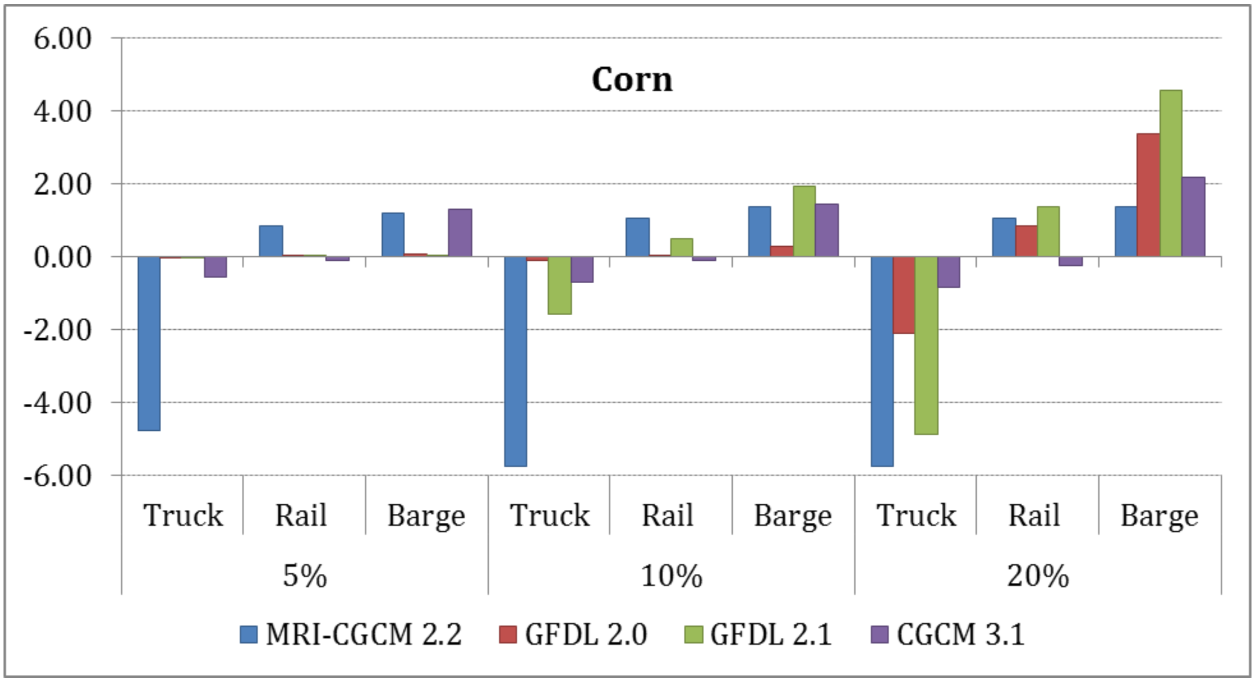
Source	Destination	% Increase in Shipping Cost	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	South-Central	5	5.76	—	—	—
		10	7.33	—	2.21	0.01
		20	7.34	0.06	4.44	0.01
	Lower Miss Ports	5	0.08	0.09	—	1.83
		10	0.29	0.06	0.86	2.06
		20	0.29	12.78	2.65	2.51
	Great Lakes Ports	5	−69.06	−0.27	—0.12	−55.13
		10	−86.58	−0.68	—13.63	−64.39
		20	−86.64	−37.92	—70.57	−100.00
	Atlantic Ports	5	252.00*	—	—	—
		10	253.00*	—	6.08	—
		20	253.00*	99.00	106.63	—
Lake States	Lower Miss Ports	5	12.54	—	0.02	0.02
		10	12.54	0.58	0.51	−0.16
		20	12.54	0.73	28.33	2.06
All Regions	South-Central	5	3.98	—	—	—
		10	5.07	—	1.02	—
		20	5.07	0.02	3.47	—
	Lower Miss Ports	5	1.15	0.03	—	1.27
		10	1.32	0.22	1.45	1.39
		20	1.32	5.19	3.19	2.16
	Great Lakes Ports	5	−66.26	−0.67	−0.12	−48.58
		10	−83.13	−2.30	−13.63	−56.74
		20	−83.13	−39.07	−70.57	−88.12
	Atlantic Ports	5	139.23	—	—	—
		10	139.23	0.01	1.52	0.23
		20	139.23	4.59	38.95	0.31

Notes: Percent changes are relative to the results in Table 6, with the exception of the entries marked (*). The latter are in 1,000 metric tons because the corresponding results in Table 6 are zero.

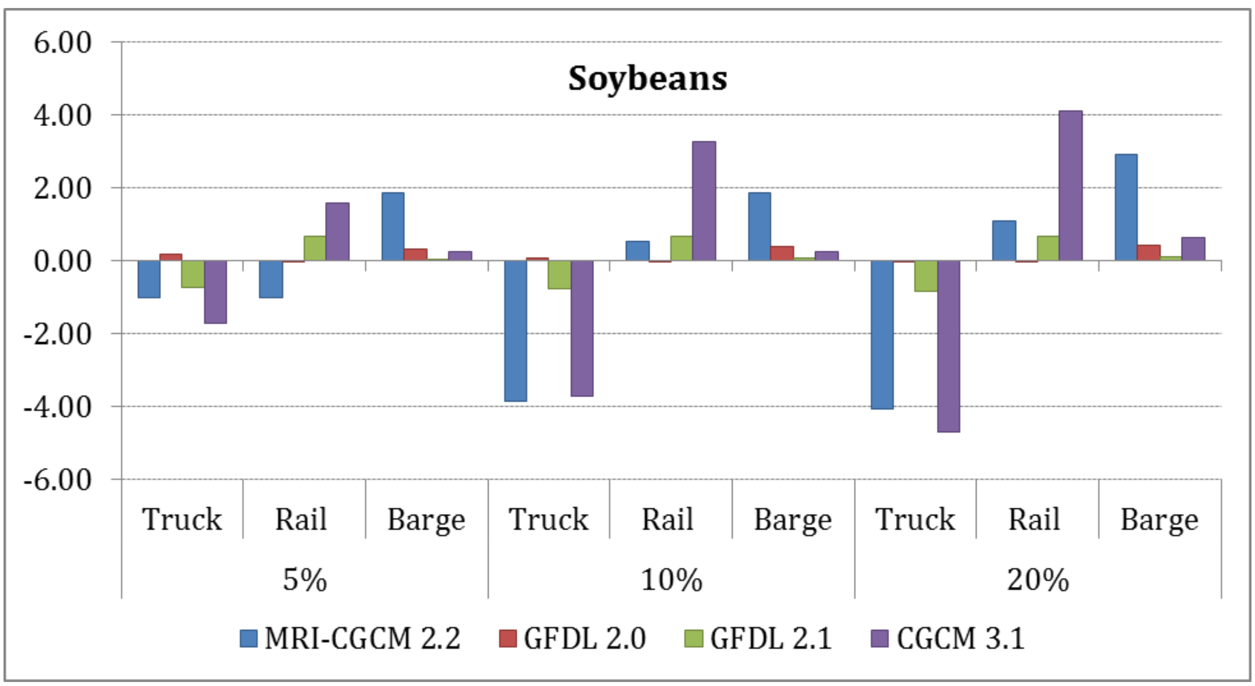
Table 14. Percent Change in Interregional Transportation Flows of Soybeans under Different GCM Scenarios due to Increases in Shipping Cost Caused by Reduced Water Levels in the Great Lakes

Source	Destination	% Increase in Shipping Cost	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	5%	–1.35	0.86	2.48	–0.12
		10%	3.74	0.73	3.22	–0.11
		20%	5.34	0.73	4.45	–0.14
	Lower Miss Ports	5%	2.71	0.44	0.02	0.20
		10%	2.72	1.11	0.03	0.20
		20%	3.34	1.17	0.07	0.24
	Great Lakes Ports	5%	–26.92	–9.22	–24.11	–3.36
		10%	–71.31	–9.59	–29.02	–56.72
		20%	–78.12	–11.14	–37.68	–100.00
	Atlantic Ports	5%	108.00*	10.37	59.73	—
		10%	481.00*	10.37	60.18	269.00*
		20%	481.00*	10.58	60.18	483.00*
Lake States	Corn Belt	5%	9.14	–12.23	–10.95	1.11
		10%	–24.76	–10.22	–14.14	1.11
		20%	–35.07	–10.22	–19.52	1.47
	Great Lakes Ports	5%	–13.21	–38.46	—	–64.09
		10%	–13.21	–100.00	—	–84.16
		20%	–100.00	–100.00	—	–87.66
	Atlantic Ports	5%	–2.48	3.67	17.08	23.08
		10%	11.26	3.67	22.05	31.82
		20%	11.53	3.77	24.92	26.40
All Regions	Lower Miss Ports	5%	1.64	0.48	0.03	0.20
		10%	1.65	0.91	0.05	0.20
		20%	3.32	0.96	0.11	0.56
	Great Lakes Ports	5%	–24.81	–11.54	–24.11	–34.76
		10%	–62.59	–16.77	–29.02	–70.86
		20%	–81.46	–18.19	–37.68	–93.52
	Atlantic Ports	5%	2.02	5.14	18.84	18.14
		10%	28.91	5.14	22.49	42.14
		20%	29.18	5.26	24.64	51.50

Notes: Percent changes are relative to the results in Table 7, with the exception of the entries marked (*). The latter are in 1,000 metric tons because the corresponding results in Table 7 are zero.



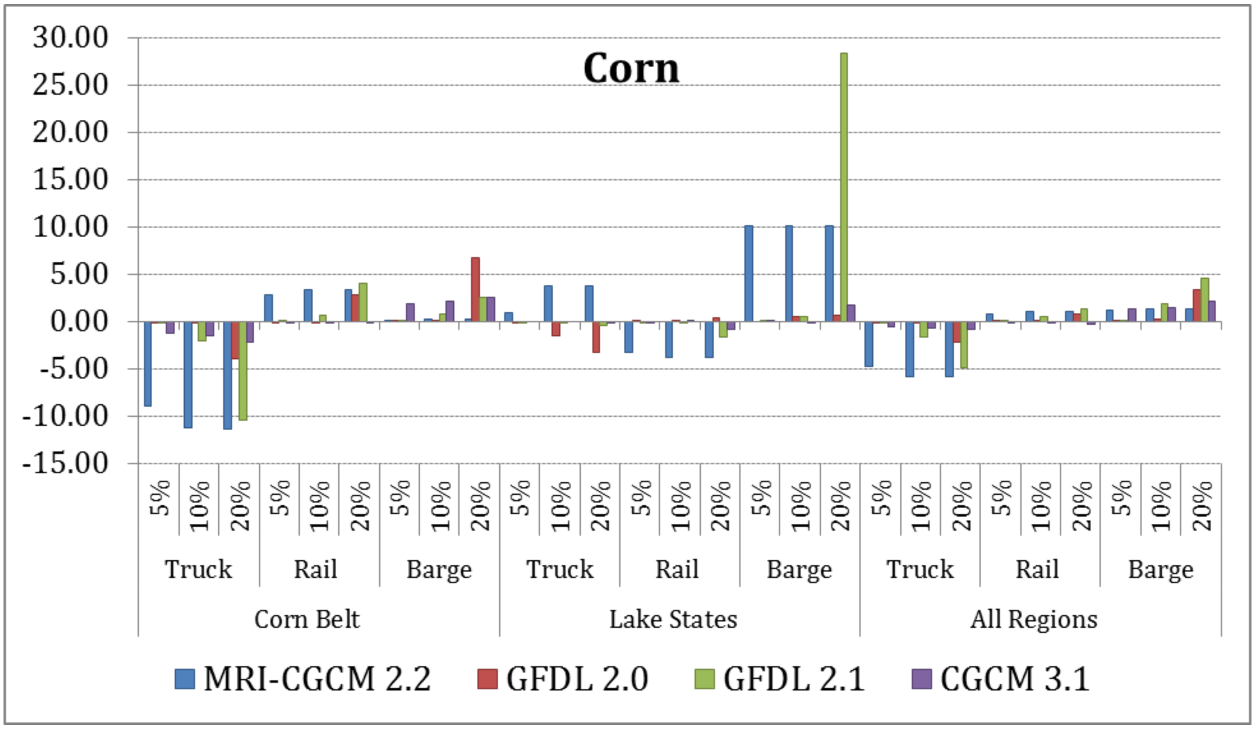
(a) Corn



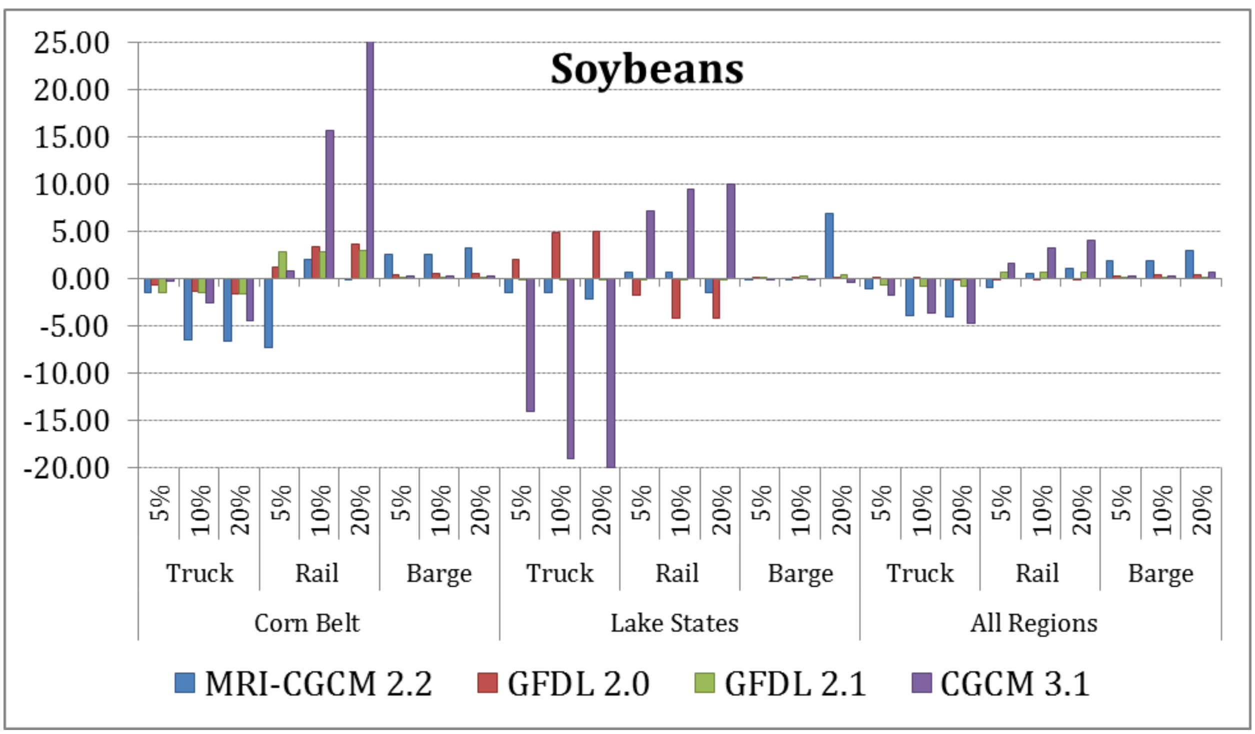
(b) Soybeans

Note: Changes are relative to the results in Figure 10.

Figure 14. Percent changes in (a) corn and (b) soybean shipments by modes of transportation under different GCM scenarios due to increases in shipping cost caused by a reduction in Great Lakes water levels.



(a) Corn



(b) Soybeans

Note: Changes are relative to the results in Figure 11.

Figure 15. Percent changes in (a) corn and (b) soybean shipments by regions and mode of transportation under different GCM scenarios due to increases in shipping cost caused by a reduction in Great Lakes water levels.

Changes in Transportation Flows due to Drought-Related Reduction of Grain Exports in Regions Competing with the Great Lakes Ports

As discussed earlier, one of the possible consequences of climate change is strengthening drought conditions in many regions of the world. Among the regions that could be affected by this phenomenon are grain-exporting countries (Ukraine, Serbia, Moldova, and Kazakhstan) that compete with the Great Lakes ports. Severe and/or prolonged drought conditions in these areas could reduce grain production and hence grain exports of these regions to the rest of the world.

This section analyzes the incremental effect such a reduction in grain exports may cause on grain transportation flows in the U.S. Since there are no reliable estimates of potential drought effects on grain production in the affected regions, the scenario analysis was performed by assuming that grain exports of these regions would decrease by 10, 30, and 50 percent relative to the baseline levels.

Transportation Flows

The reduction of grain exports in regions competing with Great Lakes ports appears likely to affect U.S. interregional transportation flows of corn, while leaving soybean flows and seasonality of grain transportation flows largely unchanged. Notable findings for simulated changes in the interregional grain transportation flows are presented in Table 15.

Texas Gulf ports, Great Lakes ports, and Lower Mississippi River ports are likely to receive higher corn shipments from all excess supply regions in all GCM scenarios and under all levels of reduction in corn exports from the regions competing with Great Lakes ports. Generally, the higher the export reduction, the larger the volume of corn shipments to these port areas. The magnitudes range from 0.11 to 12.70 percent for the Texas Gulf ports, from 0.04 to 6.10 percent for the Great Lakes ports, and from 0.27 to 3.15 percent for the Lower Mississippi River ports. Corn Belt (mainly Ohio) and Great Plains (mainly South Dakota) are the major excess supply regions that send additional corn shipments to the Great Lakes ports and Texas Gulf ports, respectively. Lower Mississippi River ports are likely to receive higher corn shipments from the Corn Belt, Lake States, and South-Central regions. In addition, under a majority of GCM scenarios, the Corn Belt and Lake States tend to ship less corn to the Southwest region. Finally, the Rocky Mountain region is likely to receive fewer corn shipments from the Great Plains.

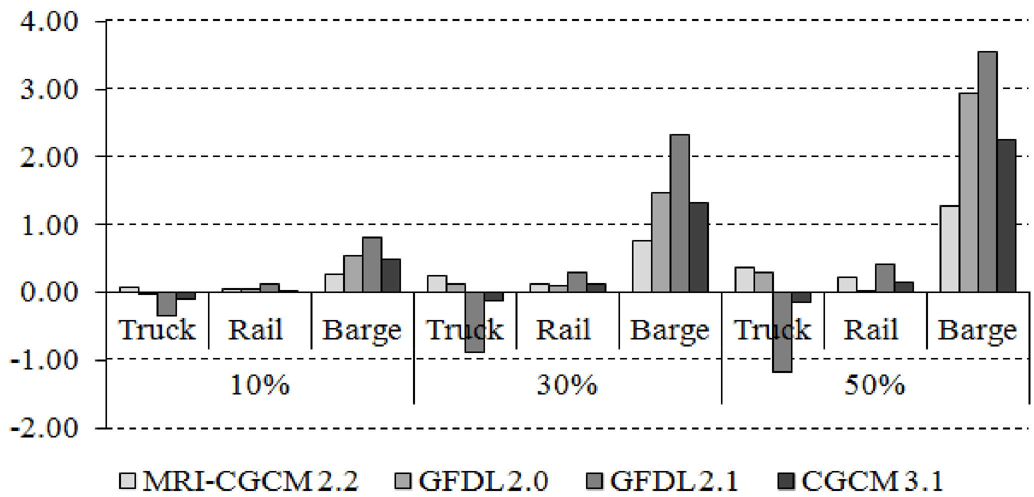
Demand for Modes of Transportation

The demand for modes of transportation for soybean shipments is projected to be mostly unchanged, while a small impact on demand for modes of transportation for corn would be observed (Figure 16). In all GCM scenarios and all levels of corn export reduction, the demand for barge increases between 0.27 to 3.57 percent, especially for shipments from the Corn Belt, Lake States, and South-Central regions to the Lower Mississippi ports. Demand for rail is also projected to increase, although by a very small amount (less than 1 percent). Generally, the higher the reduction in corn exports from the regions competing with Great Lakes ports, the greater the demand for barge and rail. Mixed results are obtained for truck.

Table 15. Percent Change in Interregional Transportation Flows of Corn under Different GCM Scenarios due to Drought-Related Reduction of Corn Exports from Regions Competing with the Great Lakes Ports

Source	Destination	% Reduction in Corn Exports	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Southwest	10%	–0.04	–0.37	0.86	–0.04
		30%	–0.07	–1.32	2.70	–0.14
		50%	–0.15	–3.93	4.61	–0.19
	Great Lakes Ports	10%	1.39	0.07	0.04	3.42
		30%	4.22	1.60	0.16	3.42
		50%	6.36	2.48	0.28	3.22
	Lower Miss Ports	10%	0.22	0.89	0.18	0.65
		30%	0.60	2.07	0.61	1.97
		50%	1.02	4.13	1.07	2.90
Great Plains	Texas Gulf Ports	10%	—	4.35	—	1.90
		30%	—	9.15	—	10.09
		50%	—	10.09	—	16.60
	Rocky MT	10%	–0.21	–0.44	–1.73	–0.32
		30%	–0.67	–0.94	–3.47	–0.91
		50%	–1.09	–1.16	–6.36	–1.55
Lake States	Southwest	10%	—	–0.53	–2.43	—
		30%	—	–2.01	–5.24	—
		50%	—	–4.24	–7.28	—
	Lower Miss Ports	10%	0.88	0.34	6.15	0.40
		30%	2.67	1.21	16.18	0.49
		50%	4.43	2.43	23.87	2.35
South-Central	Lower Miss Ports	10%	0.17	0.36	0.55	0.14
		30%	0.53	1.29	1.71	0.37
		50%	0.85	2.72	2.61	0.69
All Regions	Texas Gulf Ports	10%	0.33	3.79	0.11	1.45
		30%	1.00	7.97	0.26	7.72
		50%	1.55	8.79	0.52	12.70
	Great Lakes Ports	10%	1.33	0.07	0.04	3.01
		30%	4.05	1.57	0.16	3.01
		50%	6.10	2.43	0.28	3.01
	Lower Miss Ports	10%	0.27	0.55	0.69	0.55
		30%	0.77	1.56	1.97	1.51
		50%	1.29	3.15	3.05	2.56
	All Regions	10%	0.09	0.08	0.08	0.08
		30%	0.28	0.24	0.23	0.25
		50%	0.46	0.38	0.38	0.42

Note: Percent changes are relative to the results in Table 6.



Note: Changes are relative to the results in Figure 10.

Figure 16. Percent change in corn shipments by modes of transportation under different GCM scenarios due to a reduction of grain exports in regions competing with the Great Lakes ports.

CONCLUDING REMARKS

This study investigated the effect of climate change on interregional transportation flows and use of inland waterways in the U.S. The overall supply of corn and soybeans was found likely to increase in the northern part, while declining in some areas of the central and southern U.S.

The analysis of changes in transportation flows due to climate-induced shifts in crop production patterns resulted in the following conclusions.

- The Corn Belt—the largest U.S. corn production region—is anticipated to ship less corn to Pacific, Northeast, Rocky Mountain, Southeast, and South-Central regions, plus the Pacific Northwest and Lower Mississippi ports; while the Great Lakes ports and Lake States are expected to receive higher corn shipments.
- The Corn Belt is expected to ship higher amounts of soybeans to the Southeast and the Northeast, plus the Great Lakes and Atlantic ports.
- The importance of Lower Mississippi ports and interior Mexico is projected to diminish, whereas the role of Pacific Northwest ports, Great Lakes ports, and Atlantic ports is projected to increase.
- Demand for rail and truck for total grain shipments is expected to rise, while demand for barge is projected to drop.

The analysis of incremental changes in transportation flows due to an extension of the navigation season in the winter along the Upper Mississippi River indicates the following.

- The Corn Belt's grain shipments to the Lower Mississippi River ports would decline and this reduction would possibly be replaced by a substantial increase in corn shipments from the Lake States.

- Overall, Lower Mississippi River ports are likely to receive higher grain flows, while Pacific Northwest ports and Great Lakes ports would tend to receive lower grain shipments.
- Seasonality of overall grain transportation flows is likely to be affected with increasing flows in the winter and decreasing flows in the fall.
- The usage of truck and rail is expected to increase, while usage of barge is projected to drop.

The extension of the navigation season in the winter along the Great Lakes would result in:

- very small impacts on corn flows;
- increasing soybean shipments from other regions to the Great Lakes ports, but lower shipments of soybeans to the Lower Mississippi River, Pacific Northwest, and Atlantic ports from other regions;
- decreasing corn flows in the fall and increasing corn flows in winter;
- increasing soybean shipments in the fall and summer seasons;
- largely unchanging demand for modes of transportation for corn flows, but changes projected for soybean shipments; and
- higher overall demand for truck, but lower demand for rail and barge.

An increase in shipping cost caused by a fall in Great Lakes water levels would not affect seasonal movements of grain flows. However, as the shipping cost increases, Great Lakes ports are projected to receive fewer grain shipments from all excess supply regions, especially from the Corn Belt; while Lower Mississippi River ports and Atlantic ports are expected to receive higher grain shipments. Overall, the higher the increases in shipping cost, the greater the demand for rail and barge and the lower the demand for truck.

A drought-related reduction of grain exports from regions competing with the Great Lakes ports would not substantially affect soybean flows or seasonality of overall grain transportation flows. However, higher shipments of corn are projected to the Great Lakes ports, Texas Gulf ports, and Lower Mississippi River ports. Furthermore, the demand for barge and rail is also projected to increase.

Several clear implications arise from the analysis.

- Although overall the future demand for barge mode may drop, the Upper Mississippi River is likely to receive higher grain transportation shipments under climate change scenarios due to the predicted increase in the grain supply from the middle to northern parts of Minnesota and North Dakota. Therefore, enlarging or improving conditions of locks and dams in that segment might be appropriate to speed up passage of barge tows and increase barge efficiency, which could also increase the competitiveness of U.S. grain for export.[21]

[21] Almost all locks on the Upper Mississippi River were built between 1930 and 1950 and have lock chambers of 600 feet in length. Standard tows since then have grown from 600 feet to over 1,100 feet. Therefore the standard tow must move through the locks in two passes, requiring break up and reassembly of some tows. Passage through a 1,200-foot lock can take about 45 minutes or less, but transiting a 600-foot lock takes approximately 90 minutes, which can produce queuing delays for other barges (Frittelli 2005).

- Due to the projected increase in overall demand for rail, many components of the rail infrastructure may need to be upgraded and expanded along the routes that are simulated to have new or higher levels of grain transportation flows. This includes routes from Minnesota and North Dakota to Pacific Northwest ports; New York to North Carolina; Colorado to Idaho; Minnesota to New Mexico and Oklahoma; Nebraska to California; Pennsylvania to Virginia; South Dakota to Texas Gulf ports; and Michigan to Atlantic ports.

- To collect grain from rural farmlands in the northern region grain elevators, short line rail track beds and bridge structure should be expanded.[22] To increase the speed of the shipments and their reliability, expanding mainline rail track and increasing the number of sidings should be considered.

- Transportation by truck is also a mode that is projected to receive increasing grain transportation flows. Road infrastructure may need to be expanded and upgraded to accommodate the heavy future truck traffic from the areas where grain supply is expected to increase to nearby excess demand locations and ports. Examples include

    - roads in rural areas along the Upper Mississippi River in Minnesota, the Ohio River, the Arkansas River, and the Lower Mississippi River in Kentucky leading toward nearby barge locations shipped to the Lower Mississippi ports;

    - routes in northern parts of Ohio leading toward the Great Lakes ports at Toledo

    - roads in Ohio, Pennsylvania, and New York leading toward Atlantic Ports at Norfolk, Virginia.

  Finally, due to a multifaceted grain supply chain, improving intermodal connectors such as truck routes connecting highways with ports and rail terminals might be suitable in those areas.

[22] Many short line railroads were formerly part of a main line railroad's network, but they were abandoned by the main line railroad due to low profitability on those routes. Before abandonment, the main line railroad typically deferred maintenance on these sections of track. Most importantly, the main line railroads currently utilize the larger 286,000 pound railcars (Frittelli 2005). Track beds and bridge structures of these short line railroads cannot support these heavier cars.

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APPENDIX A: AGRICULTURAL SECTOR MODEL (ASM) DESCRIPTION

The ASM framework can be summarized by the following equations.

(A1) $$Max \; -\sum_{j,k} \mathbf{g}_{jk}\mathbf{X}_{jk} - \sum_{k,r}\int \boldsymbol{\alpha}(\mathbf{R}_{rk})\mathbf{dR}_{rk} + \sum_{i}\int \boldsymbol{\varphi}(\mathbf{Q}_i)\mathbf{dQ}_i$$

$$+\sum_{i,f}\int \boldsymbol{\gamma}(\mathbf{FQD}_{if})\mathbf{dFQD}_{if} - \sum_{i,f}\int \boldsymbol{\beta}(\mathbf{FQS}_{if})\mathbf{dFQS}_{if} - \sum_{i,k,f}\mathbf{USFTC}_{ikf} * \mathbf{USFTRD}_{ikf}$$

$$-\sum_{i.f.f1}\mathbf{FFTC}_{iff1} * \mathbf{FFTRD}_{iff_1} - \sum_{i,k,k1}\mathbf{USTC}_{ikk1} * \mathbf{USTRD}_{ikk1}$$

Subject to

(A2) $$\sum_{j}\mathbf{y}_{ijk} * (\mathbf{1}+\mathbf{dyield}_{ik}) * \mathbf{X}_{jk} - \sum_{k}\mathbf{USFTRD}_{ifk} - \sum_{k1}\mathbf{USTRD}_{ik1k} + \sum_{k}\mathbf{USFTRD}_{ikf}$$

$$\sum_{k1}\mathbf{USTRD}_{ikk1} \le \mathbf{0}, \forall i,k$$

(A3) $$\sum_{j}\mathbf{a}_{rjk} * \mathbf{X}_{jk} \le \boldsymbol{b}_{rk}, \forall r,k$$

(A4) $$\mathbf{Q}_i - \sum_{i,j,k}\mathbf{y}_{ijk} * (\mathbf{1}+\mathbf{dyield}_{ik}) * \mathbf{X}_{jk} + \sum_{k,i}(\mathbf{USFTRD}_{ikf} - \mathbf{USFTRD}_{ifk}) \le \mathbf{0}, \forall i$$

(A5) $$\mathbf{FQD}_{ik} + \sum_{k}\mathbf{USFTRD}_{ifk} + \sum_{f1}\mathbf{FFTRD}_{iff1}$$

$$-\mathbf{FQS}_{if} - \sum_{k}\mathbf{USFTRD}_{ikf} - \sum_{f1}\mathbf{FFTRD}_{iff1} \le \mathbf{0}, \forall i, f$$

where *i* indexes the commodities; *f* and *f1* index the rest of the world (ROW) regions; *j* indexes production processes; *k* and *k1* index U.S. regions; *r* indexes resources;

$\mathbf{g}_{jk}$ is the cost of the j^{th} production process per acre in U.S. region *k*;

$\mathbf{X}_{jk}$ is the acreage of the j^{th} production process in U.S. region *k*;

$\boldsymbol{\alpha}(\mathbf{R}_{rk})$ is the inverse U.S. factor supply function for resource *r* in region *k*;

$\mathbf{R}_{rk}$ is the resource supply for U.S. region *k* of resource *r*;

$\varphi(\mathbf{Q}_i)$ is the inverse U.S. demand function for commodity *i*;

$\mathbf{Q}_i$ is the U.S. domestic consumption of the i^{th} commodity;

$\gamma(\mathbf{FQD}_{if})$ is the inverse excess demand function for commodity *i* in importing ROW region *f*;

$\mathbf{FQD}_{if}$ is the excess demand quantity for commodity *i* in importing ROW region *f*;

$\beta(\mathbf{FQS}_{if})$ is the inverse excess supply function for commodity *i* in exporting ROW region *f*;

$\mathbf{FQS}_{if}$ is the excess supply quantity for commodity *i* in exporting ROW region *f*;

$\mathbf{USFTC}_{ikf}$ is the transportation cost from U.S. region *k* to ROW region *f* for commodity *i*;

$\mathbf{USFTRD}_{ikf}$ is the trade between U.S. region *k* and ROW region *f* for commodity *i*;

$\mathbf{FFTC}_{iff1}$ is the transportation cost between ROW regions *f* and *f1* for commodity *i*;

$\mathbf{FFTRD}_{iff_1}$ is the trade between ROW regions *f* and *f1* for commodity *i*;

$\mathbf{USTC}_{ikk1}$ is the transportation cost between U.S. regions *k* and *k1* for commodity *i*;

$\mathbf{USTRD}_{ikk1}$ is the quantity shipped between U.S. regions *k* and *k1* for commodity *i*;

$\mathbf{y}_{ijk}$ is per acre yield for commodity *i* using j^{th} production process of U.S. region *k*;

$\mathbf{dyield}_{ik}$ is the crop yield percentage change due to the change in climate, atmospheric CO_2, and crop production technology;

$\mathbf{a}_{rjk}$ is the amount of resource *r* used in the j^{th} production process of U.S. region *k*; and

$\mathbf{b}_{rk}$ is the amount of resource *r* available in U.S. region *k*.

Equation A1 is the objective function mixing the price endogenous and spatial equilibrium components. The first line of equation A1 represents the area under the demand curves for commodity *i* less the area under the regional U.S. factor supply curves for perfectly elastic production costs associated with the production process *j* and quantity-dependent prices for factor *r* summed across all *k* regions. The next three lines include terms typically used in the spatial equilibrium model. The first two terms of the second line give the area under the ROW excess demand curves minus the area under the excess supply curves for commodity *i* in ROW region *f*. The last term of the second line and terms in the third line provide the summation of the transportation costs between the U.S. and the ROW regions, among ROW regions, and among the U.S. regions involved with trade, respectively. Equation A2 represents the regional balance constraint for goods depicted with a spatial equilibrium trade model in the U.S. Equation A3 is a usual resource constraint for U.S. region *k*. Equation A4 provides the national balance constraint for commodities in the U.S. Equation A5 is the balance constraint for traded goods in the ROW region *f*. ASM regions and subregions are shown in Table A1.

Table A1. ASM Regions and Subregions

Market Region	Production Region (States/Subregions)
Northeast (NE)	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
Lake States (LS)	Michigan, Minnesota, Wisconsin
Corn Belt (CB)	All regions in Illinois, Indiana, Iowa, Missouri, Ohio (Illinois North, Illinois South, Indiana North, Indiana South, Iowa West, Iowa Central, Iowa Northeast, Iowa South, Ohio Northwest, Ohio South, Ohio Northeast)
Great Plains (GP)	Kansas, Nebraska, North Dakota, South Dakota
Southeast (SE)	Virginia, North Carolina, South Carolina, Georgia, Florida
South-Central (SC)	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, Eastern Texas
Southwest (SW)	Oklahoma; all of Texas except the Eastern Part (Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos)
Rocky Mountains (RM)	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Pacific Southwest (PSW)	All regions in California (California North, California South)
Pacific Northwest (PNW)	Oregon and Washington, east of the Cascade mountain range

Source: Adams et al. (2005)

APPENDIX B: THE EXTENSION OF ATWOOD ET AL. (2000) MODEL

The Atwood (2000) model is used in order to extend ASM to allow the possibility of crop expansion into new production areas under climate change. First, the coefficients for the projected climate-induced crop mix migration in 2050 are constructed based on historical crop acreage data from the Agricultural Census and Agricultural Survey provided by the USDA-NASS. Each coefficient provides information regarding the percentage of the crop mix pattern in one CRD that will shift to another CRD. For example, if the coefficient of the projected climate-induced crop migration from Iowa CRD50 to Iowa CRD20 is 0.4, then 40 percent of the crop mix pattern in Iowa CRD50 could possibly shift to Iowa CRD20. These coefficients are not presented here due to space limitations. However, the data can be provided by the authors upon request.

Next, equations B1 and B2 quantify county-level crop acreage that accounts for the climate-induced shifts in crop production patterns mentioned above.

(B1) $$\mathbf{fipsshift}_{s,crd2,p,c,t} = \mathbf{fipsnoshift}_{s,crd2,p,c,t} \mathbf{*Max}\left\{0\mathbf{,}\left(1-\Sigma_{crd}\,\mathbf{cropshiftcoeff}_{crd,crd2}\right)\right\} + \mathbf{TransferIn}_{s,crd2,p,c,t}$$

(B2) $$\mathbf{TransferIn}_{s,crd2,p,c,t} = \sum_{crd}\left\{\mathbf{avereagefips}_{s,crd,c,t}\mathbf{*cropshiftcoeff}_{crd,crd2}\mathbf{*}\left(\frac{\mathbf{fipsallcrops}_{s,crd2,t}}{\mathbf{fipsallcrops}_{s,crd,t}}\right)\right\}\mathbf{,}\forall p$$

where *s* indexes ASM regions as shown in Table A1; *crd* and *crd2* index crop reporting districts; *p* indexes counties; *c* indexes crops; *t* indexes crop year;

$\mathbf{fipsshift}_{s,crd2,p,c,t}$ is the acres of crop *c* in county *p* in crop reporting district *crd2* of subregion *s* at year *t* accounting for the projected climate-induced shifts in crop production patterns

$\mathbf{fipsnoshift}_{s,crd2,p,c,t}$ is the historical acres of crop *c* in county *p* in crop reporting district *crd2* of subregion *s* at year *t*

$\mathbf{TransferIn}_{s,crd2,p,c,t}$ is a term representing the acres of crop *c* shifting from counties in other regions *crd* to county *p* in crop reporting district *crd2* of subregion *s* at year *t*

$\mathbf{cropshiftcoeff}_{crd,crd2}$ is the coefficient of the projected climate-induced crop mix migration in 2050 – specifically, the projected percentage of crop mix pattern in crop reporting district *crd* that will shift to crop reporting district *crd2*

$\mathbf{avereagefips}_{crd,c,t}$ is the average county-level acreage of crop *c* in crop reporting district *crd* in year *t*

$\mathbf{fipsallcrops}_{crd,t}$ is the average county-level acreage of all crops in crop reporting district *crd* at year *t*

The first term on the right-hand side represents the remaining original acres of crop *c* in county *p* after part of the original crop mix pattern in crop reporting district *crd2* is replaced by crops from other *crd*s. The second term represents the acres of crop *c* shifting from counties in other regions to county *p*. The last term on the right-hand side in equation B2 adjusts for the difference in size of the total acres farmed in each county. By using the same method, one can also calculate the irrigated acres for individual crops at county level taking into account the climate-induced shifts in crop production ($\mathbf{irracreshift}_{s,crd2,p,c,t}$). Based on the USDA-NASS data, it is assumed that corn and soybean could shift northward up to 120 miles by2050. Moreover, it is assumed that the total acres of southern crops that are suitable under an environment of rising temperature, including orange and grapefruit planted in Arizona, Florida, South Texas, and California, can expand by 2050 up to two times their historical levels.

Next, the calculated acres of crops reflecting climate-induced shifts in crop production patterns ($\mathbf{fipsshift}_{s,crd2,p,c,t}$) are used to recalculate values for maximum and minimum observed county-level farmed acres, maximum and minimum observed county-level acreages of individual crops, county-level crop mix acreage of individual crops, and total county crop mix acreage (Atwood 2000). These terms are represented by $\mathbf{maxuse}_{p}$, $\mathbf{minuse}_{p}$, $\mathbf{maxcrop}_{p,c}$, $\mathbf{mincrop}_{p,c}$, $\mathbf{asmmix}_{p,c}$, and $\mathbf{totalland}_{p}$ respectively. Note that in Atwood (2000), the values for these terms are the historical acres and not fully accounting for climate change influence ($\mathbf{fipsnoshift}_{s,p,c,t}$). Similarly, the calculated irrigated acres of individual crops accounting for climate change ($\mathbf{irracreshift}_{s,crd2,p,c,t}$) are used to recalculate values for maximum observed total irrigated acres at county level ($\mathbf{maxirracre}_{p}$). Again, in Atwood et al. (2000), the irrigated acres of individual crops are the historical ones and thus not fully accounting for climate change influence ($\mathbf{irracrenoshift}_{s,crd2,p,c,t}$). With these new values, the Atwood (2000) model is solved again to obtain the acreage solutions that account for the projected climate-induced shifts in crop production patterns.

Appendix C: International Grain Transportation Model (IGTM) Description[23]

General Description

Domestic regional excess demands and supplies, and transportation, storage, and grain handling rates/charges are modeled at the crop reporting district level in the IGTM. Internationally, all foreign trading countries are treated as an excess supply or excess demand region except for Canada and Mexico. Mexico includes five regions (Northwest, Northeast, West, Central, and South) and Canada two regions (East and West). Each region's demand, supply, and shipments are modeled on a quarterly basis. In addition, the model depicts modal choice among truck, rail, barge, lake-vessel, and ocean-going ships. Total transportation flows depict grain flows to and from 303 U.S. domestic regions going through 42 U.S. intermediate shipping points and internationally to and from 118 foreign exporting and importing countries/regions.

Shipments in the continental U.S. are modeled as a quarterly and modal dependent transportation network (rail, barge, and truck) that links domestic excess supply regions with barge-loading/unloading sites, domestic excess demand regions, and ports where appropriate grain handling and storage charges, and quarterly truck, rail and barge rates apply. Grain barge loading sites on the inland waterways are linked to barge unloading elevators at Texas Gulf ports and barge unloading elevators on the Lower Mississippi River, Cumberland River, and Tennessee River through quarterly barge rates.

The barge unloading points on the Texas Gulf and at the Lower Mississippi ports incur charges associated with receiving the grain and loading the grain to ocean-going vessels, while barge unloading facilities on the Cumberland and Tennessee Rivers incur costs of receiving and loading grain to truck and rail cars. Domestic excess supply regions are directly linked to excess demand regions and all U.S. ports by truck and rail modes with applicable grain loading (supply region) and unloading charges and quarterly transportation rates. In addition, truck and rail modes connect excess supply regions to barge loading sites or the barge unloading elevators to nearby excess demand regions through corresponding quarterly rates. Some selected domestic excess supply regions are also linked to foreign excess demand regions in Mexico and Canada with applicable quarterly rail rates. Mexico may also import grain via the ocean port at Veracruz (Southern part of Mexico), which is linked by truck and rail rates to the other five Mexican excess demand regions.

In the base IGTM, the domestic portion includes 126 corn excess supply regions and 181 soybean excess supply regions. It also contains 174 corn excess demand regions and 35 soybean excess demand regions. Geographic regions in the domestic portion of the model are CRDs, generally including 10 to 20 counties. The foreign component of IGTM includes 20 corn excess supply regions (exporting countries) and 92 corn excess demand regions (importing countries), as shown in Table C1. For soybeans, IGTM includes 11 foreign excess supply regions (exporting countries) and 58 foreign excess demand regions (importing countries), as shown in Table C2.

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[23] This section is based on the description of IGTM model in Final Report for UTCM Project 08-15-14 by Vedenov *et al.* (2010).

The grain is stored in the excess supply region until it is shipped via the transportation/logistic network to other locations. The stored grain can be shipped to barge loading elevators that are linked to barge unloading elevators. Included in the model are 32 barge loading/unloading sites on the Upper Mississippi (7), Illinois (3), Missouri (6), Arkansas (3), Ohio (4), Lower Mississippi (5), Cumberland (1), White (1) and Tennessee (2) Rivers. River elevators at these sites are barge loading facilities with the exception of the two sites on the Tennessee River (Huntsville and Knoxville) and a site on the Cumberland River (Nashville) that may both ship and receive grain. In the base model, the Upper Mississippi River elevators are closed above St. Louis during the winter in order to account for river freezing.

Domestic excess supply regions are also linked through quarterly truck and rail rates to the port elevator locations in the Lower Mississippi, Texas Gulf, Atlantic, Pacific Northwest, and the Great Lakes. In the model, these ports (except for the Great Lakes ports) can ship directly to foreign excess demand regions at quarterly bulk grain carrier rates.

The Great Lakes ports can only ship grain to Ports at Montreal (Canada) using lakers. Then the grain is unloaded from lakers at St. Lawrence River elevators in Montreal and subsequently loaded onto large ocean-going bulk grain carriers that travel to foreign excess demand regions. The Great Lake ports are assumed closed during the winter months due to freezing.

Representative foreign ports are associated with foreign corn excess demand regions and include Odessa, Ukraine, for Ukraine and Moldova corn exports; Durban, South Africa, for corn exports from South Africa; Madras, India, for corn exports of that country; Bangkok, Thailand, for corn exports from Burma, Cambodia, and Thailand; Shanghai, China, for corn exports from China; Buenos Aires, Argentina for corn exports from Argentina; and Santos (Sao Paulo), Brazil, for exports from Bolivia, Brazil, and Paraguay. In the soybean portion of the model, most of the same ports are used with the addition of Buenos Aires, Argentina, as the representative port for Uruguay, Canada exports through Vancouver and the St. Lawrence River ports (Quebec), and India shipments via Madras.

Representative foreign ports for foreign corn excess demand regions (importers) include Rotterdam for European Union North; Barcelona, Spain, for Western Europe; Bari, Italy, for Southeast Europe; Odessa, Ukraine, for Eastern Europe; Haifa for East Mediterranean; Algiers for North Africa; Dammam for Persian Gulf; Singapore for Southeast Asia; Kaohsiung for Taiwan; Ulsan for Korea; Yokohama for Japan; Veracruz for Mexico; Callao for West South America; Puerto Cortes for Central America; and Maracaibo for Caribbean/North South America. For soybeans, the primary foreign ports and associated excess demand regions include Rotterdam for European Union North; Barcelona, Spain, for Western Europe; Bari, Italy, for Southeast Europe; Odessa, Ukraine, for Eastern Europe; Haifa for East Mediterranean; Dammam for Persian Gulf; Singapore for Southeast Asia; Kaohsiung for Taiwan; Ulsan for Korea; Yokohama for Japan; Shanghai for China; and Veracruz for Mexico.

Table C1. Foreign Corn Excess Supply and Demand Regions

Regional Status	Region/Country
Excess Supply Regions (Exporting Countries)	Argentina, Australia, Bolivia, Brazil, Burma, Cambodia, China, India, Kazakhstan, Malawi, Moldova, Nigeria, Paraguay, Serbia, South Africa, Tanzania, Thailand, Uganda, Ukraine, and Zambia
Excess Demand Regions (Importing Countries)	Canada East, Canada West, Mexico Northwest, Mexico Northeast, Mexico West, Mexico Central, and Mexico South, Albania, Algeria, Angola, Azerbaijan, Belarus, Belgium, Bosnia-Herzegovina, Botswana, Bulgaria, Cameroon, Cape Verde, Chile, Colombia, Costa Rica, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, France, Georgia, Germany, Ghana, Greece, Guatemala, Guyana, Honduras, Hong Kong, Indonesia, Iran, Iraq, Israel, Italy, Jamaica, Japan, Jordan, Kenya, North Korea, South Korea, Kuwait, Kyrgyzstan, Lebanon, Lesotho, Libya, Lithuania, Macedonia, Malaysia, Malta, Morocco, Mozambique, The Netherlands, Nicaragua, Norway, Pakistan, Panama, Peru, The Philippines, Poland, Portugal, Ireland, Romania, Russia, Saudi Arabia, Senegal, Singapore, Slovakia, Somalia, Spain, Swaziland, Switzerland, Syria, Taiwan, Trinidad and Tobago, Tunisia, Turkey, United Kingdom, Uruguay, Venezuela, Vietnam, Yemen, and Zimbabwe

Table C2. Foreign Soybean Excess Supply and Demand Regions

Regional Status	Region/Country
Excess Supply Regions (Exporting Countries)	Argentina, Australia, Brazil, Canada East, Canada West, Ecuador, India, Paraguay, Uganda, Ukraine, and Uruguay
Excess Demand Regions (Importing Countries)	Bangladesh, Barbados, Bolivia, Belgium, Bosnia-Herzegovina, Chile, China, Colombia, Costa Rica, Croatia, Cuba, Denmark, Egypt, France, Germany, Greece, Guatemala, Hungary, Indonesia, Iran, Israel, Italy, Japan, North Korea, South Korea, Malaysia, Mexico Northwest, Mexico Northeast, Mexico West, Mexico Central, Mexico South, Morocco, the Netherlands, Nigeria, Norway, Pakistan, Panama, Peru, the Philippines, Portugal, Ireland, Romania, Russia, Serbia, Singapore, South Africa, Spain, Sweden, Switzerland, Syria, Taiwan, Thailand, Turkey, United Arab Emirates, United Kingdom, Uzbekistan, Venezuela, and Vietnam

STRUCTURE OF THE MODEL

IGTM is a spatial equilibrium model of the following form:

(C1)
$$\begin{aligned}\mathbf{Max} - \sum_{i\in l,g,q}\int \boldsymbol{\alpha}(\mathbf{S}_{igq})\mathbf{dS}_{igq} + \sum_{j\in l,g,q}\int \boldsymbol{\varphi}(\mathbf{D}_{jgq})\mathbf{dD}_{jgq} - \sum_{i,j,g,q,m}\mathbf{tc}_{ijgqm} * \mathbf{Transport}_{ijgqm} \\ - \sum_{l,g,q}\mathbf{s}_{lgq} * \mathbf{I}_{lgq} - \sum_{l,g,q,m}\mathbf{cul}_{lgqm} * \mathbf{Fromtran}_{lgqm} - \sum_{l,g,q,m}\mathbf{cl}_{lgqm} * \mathbf{Totran}_{lgqm} \\ - \sum_{l,g,q,m,m1}\mathbf{CMS}_{lgqmm1} * \mathbf{ModeShift}_{lgqmm1}\end{aligned}$$

Subject to

(C2)
$$\mathbf{D}_{jgq} + \sum_{m}\mathbf{Totran}_{lgqm} + \mathbf{I}_{lgq} \le \mathbf{S}_{igq} + \sum_{m}\mathbf{Fromtran}_{lgqm} + \mathbf{S}_{igq(-1)} \quad \forall l,g,q$$

(C3)
$$\begin{aligned}\mathbf{Fromtran}_{lgqm} + \sum_{j}\mathbf{Transport}_{ijgqm} + \sum_{m1}\mathbf{ModeShift}_{lgqmm1} \\ \le \mathbf{Totran}_{lgqm} + \sum_{i}\mathbf{Transport}_{ilgqm} + \sum_{m1}\mathbf{Modeshift}_{lgqm1m} \quad \forall l,g,q,m\end{aligned}$$

(C4)
$$\mathbf{I}_{lgq} \le \mathbf{storagecap}_{lg} \quad \forall l,g,q$$

where

l indexes all regions encompassing excess supply and demand regions, barge locations, and ports and is used to identify areas where grain can be transshipped, stored or switch modes;

i indexes excess supply regions, $i \subset l$;

j indexes excess demand regions, $j \subset l$;

g indexes the grains (corn and soybeans);

q indexes quarter of the year;

m indexes the type of transportation modes;

$\mathbf{S}_{igq}$ gives the excess supply in region *i* of grain *g* in quarter *q*;

$\boldsymbol{\alpha}(\mathbf{S}_{igq})$ is the inverse excess supply function in region *i* of grain *g* in quarter *q*;

$\mathbf{D}_{jgq}$ is excess demand in region *j* of grain *g* in quarter *q*;

$\boldsymbol{\varphi}(\mathbf{D}_{jgq})$ is the inverse excess demand function in region *j* for grain *g* in quarter *q*;

$\mathbf{Transport}_{ijgqm}$ is the quantity shipped from excess supply location *i* to excess demand location *j* of grain *g* in quarter *q* by mode *m*;

$\mathbf{I}_{lgq}$ is the amount of grain *g* stored at region *l* in quarter *q*;

$\mathbf{Totran}_{lgqm}$ is the amount of grain *g* entered into transport from storage or local supply in region *l* in quarter *q* by mode *m*;

$\mathbf{Fromtran}_{lgqm}$ is the amount of grain *g* removed from transport to meet demand or be entered into storage at region *l* in quarter *q* by mode *m*;

ModeShift$_{lgqmm1}$ is the amount of grain *g* in region *l* that changes mode of transportation from mode *m* to mode *m1* in quarter *q*;

tc$_{ijgqm}$ is transportation costs ($) per unit of grain shipment from excess supply source *i* to excess demand destination *j* of grain *g* by mode *m*;

cul$_{lgqm}$ is the cost of unloading per unit of grain *g* unloaded at region *l* in quarter *q* by mode *m;*

cl$_{lgqm}$ is the cost of loading per unit of grain *g* loaded at region *l* in quarter *q* by mode *m;*

CMS$_{lgqmm1}$ is the cost of mode shift per unit of grain *g* at region *l* in quarter *q* from mode *m* to mode *m1*;

s$_{lgq}$ is the storage costs per unit of grain *g* stored at region *l* in quarter *q*; and

storagecap$_{lg}$ is the storage capacity for grain *g* in region *l.*

Equation C1 is the objective function. It maximizes the total net welfare, which is determined as the area under the demand curves minus that under the excess supply curves minus grain transportation costs, loading, unloading, mode shift, and storage costs. Demand and supply functions in IGTM are assumed to be linear.

Constraints are imposed when maximizing the objective function. Equation C2 is the regional balance constraint for grain going into and out of the transport system in each region in each time period. Equation C3 is a balance for the grain in the transport system on a particular mode by location, grain, mode, and quarter. Finally, equation C4 is the storage capacity constraint for each grain in each region and each time period.

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