The Effect of Climate Change on Transportation Flows and Inland Waterways Due to Climate-Induced Shifts in Crop Production Patterns

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1 Introduction

Grain production plays a crucial role in response to the world's growing demand for food, feed, and biofuels. Corn, soybeans, and wheat are major grains crops that are most widely planted in the world and also in the US. From the past to the present, the US is a major country that plays a dominant role as a world grain producer and exporter. In crop year 2009/2010, total US supply of corn, soybean and wheat accounted for about 39, 31, and 9 percent of the world supply of corn, soybean and wheat, respectively. For the aspect of international trade, the US market shares for export of corn, soybean and wheat to the world's total export were about 52, 44, and 18 percent, respectively (USDA World Agricultural Outlook Board 2011).

A highly efficient, low-cost system of transportation is one of the major factors determining the competitiveness of US grains, which are low-valued bulky products, in the world market. Grains produced in the US move to domestic and foreign markets through a well-developed transportation system. Barges, railroads, and trucks facilitate a highly competitive market that bridges the gap between US grain producers, domestic and foreign consumers. Not only is agriculture the largest user of the transportation system accounting for 22 percent of all tons and 31 percent of all ton-miles transported via all modes in 2007, but grains also are the largest users of freight transportation in agriculture (Denicoff et al. 2010).

From 1978 to 2007 total US grain shipments significantly increased 92 percent from about 242 million tonnes to 464 million tonnes with corn movements accounted for 63 percent of all grain movements followed by movements of soybeans and wheat, which were equal to 19 percent and 14 percent, respectively in 2007. During 2002-2007, inland grain transportation via truck and rail is the principal channel for overall grain movements accounting for about 85 percent, while inland water transportation via barge represents only about 15 percent of all grain tonnages.

Although inland water transportation has a small share for overall tonnage movements, it plays a significant role as a major route to export market accounting for about 48 percent of all grain tonnages for export over the same period (Marathon and Denicoff 2011). Mississippi River and its tributaries on the Mississippi river basin are the largest inland water way system shipping grains especially corn and soybeans from the US inland to the Lower Mississippi ports for export market accounting for on average 55 and 47 percent of all US corn and soybean export, respectively during 2005-2009 (U.S. Army Corps of Engineers 2010).

The transportation flows and inland water ways are potentially affected by climate change because recent studies including those by the Intergovernmental Panel on Climate Change (IPCC) (2001a, 2001b, 2007a, 2007b) indicate that greenhouse gas (GHG) emissions and resultant atmospheric concentrations have lead to changes in the world's climate conditions such as increase in temperature, extreme temperatures, heat waves, droughts, and rainfall intensity. Such changes are expected to substantially impact agriculture since its production is highly influenced by climatic conditions (IPCC 2007b; Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2005; Deschenes and Greenstone 2007; McCarl, Villavicencio, and Wu 2008; Schlenker and Roberts 2009; Attavanich and McCarl 2011).

The most immediate reaction of agricultural producers to changes will be likely of adaptation. There are consensus from several studies that crop production is expected to increase in high latitudes and decline in low latitudes (IPCC 2007b; Smith and Tirpak 1989; Reilly 2002; Reilly et al. 2003; IPCC 2007c; Koetse and Rietveld 2009). Research suggests that current zones where crops are suitable may shift more than 100 miles northward (Reilly et al. 2003). In the US, northward shifts in the crop production mix have already been observed. Southern sections of wheat-producing regions have become northern parts of the corn-producing areas (as is already being observed in North Dakota[1]). Such developments will have an effect on the volume of grain production and the demand placed on the transport system since wheat yields on average are 44 bushels/acre, while corn yields average around 165 bushels/acre according to USDA statistics. Given differences in the typical destinations of grain shipments, there will be likely changes in the pattern and composition of grain flows in the Mississippi River Basin altering demand for transportation capacity and facilities in the near future.

The objective of this paper aims to investigate the effect of climate change on transportation flows and inland waterways in the Mississippi River Basin due to climate-induced shifts in crop production patterns. Our study contributes to climate change and transportation literature in several ways. First, we construct an International Grain Transportation Model (IGTM) to analyze grain transportation flows across the US and the rest of the world. Second, we link two large scales modeling with difference in spatial scale consisting of an Agricultural Sector Model (ASM) and an IGTM using a regionalizing downscaling model of Atwood et al. (2000) modified to allow climate-induced shifts in crop production patterns. Third, our study is the first that simulates the cropland use change due to changes in climate in the fine-scale level (county level). Fourth, although many literatures studied the effect of climate change on transportation system, through our knowledge no one carefully focuses on the effect of climate change on transportation system related agricultural sector, which is the largest user of transportation system.

The reminders of this study are organized as follow. In section 2, we review the existing literature on potential climate change impacts on land use and associated adaptation response in US agriculture, and transportation system. Section 3 provides description of model components, data, and process overview currently being used for this study. Section 4 presents key empirical findings of the analyses conducted under selected climate scenarios. Finally, section 5 contains conclusions and discusses key implications of projected climate change impacts on agriculture and grain transportation system in the US.

2 Review of the Literature

This section reviews the existing literature on potential climate change impacts on land use in US agriculture and associated adaptation response with specific to the change in crop production pattern. Finally, the effect of climate change on transportation system is reviewed.

2.1 Potential climate change impacts on land use in US agriculture

This subsection reviews previous literature studying the potential impacts of climate change on land use. There are a number of ways that land use can be affected by climate change. For example, climate change alters land values and land productivity through changes in productivity of crop, forest, pasture, and livestock. Land use can also be affected by climate change induced alteration of spatial and temporal distribution and proliferation of pests and diseases (see more details in Aisabokhae et al.). Due to the scope of this study, only literature related to changes in crop productivity and land values in agricultural sector induced by climate change is reviewed.

2.1.1 Crop productivity

A wide variety of findings have arisen regarding the effect of climate change on crop yields. Regarding the effect of temperature, Deschenes and Greenstone (2007) find that yields of corn and soybeans are negatively correlated to growing degree days. Schlenker and Roberts (2009) and Huang and Khanna (2010) find similar results and reveal a non-linear effect of temperature on yields of corn, soybeans. Attavanich and McCarl (2011) and McCarl, Villavicencio, and Wu (2008) reveal that the effect of temperature on crop yields depends on location with beneficial consequences to colder (Northern) areas and detrimental outcomes to the hotter (Southern) areas of the US.

Regarding the effect of precipitation, Chen, McCarl, and Schimmelpfennig (2004) find that increased precipitation enhances yields of corn, cotton, soybeans, winter wheat, and sorghum, while it has a negative impact on wheat as also found in McCarl, Villavicencio, and Wu (2008) and Isik and Devadoss (2006). An inverted-U shape relationship between corn and soybean yield and precipitation is found in Schlenker and Roberts (2009) and Huang and Khanna (2010). Attavanich and McCarl (2011) find that there is heterogeneity of crop yields that are affected by precipitation across US regions with negative effect over the wetter Central and Northeast regions and positive effect for the drier NP region.

A few studies consider climate variability and extreme events. Using standard deviation as a measure of variation in temperature, McCarl, Villavicencio, and Wu (2008) for instance find that increased variation has a negative impact on yields of all crops. Similar results were found for corn and soybeans by Huang and Khanna (2010). Variability measures reflecting precipitation intensity and drought severity were employed in McCarl, Villavicencio, and Wu (2008) and Attavanich and McCarl (2011). Both papers show that generally the increase in precipitation intensity decreases crop yields, while an increase in their drought measure varies depending on the crop. Chen and McCarl (2009) find that the reduction in the average state level crop yields due to hurricanes range from 0.20 to12.90 percent with the U.S. Gulf coast and the southern Atlantic coastal regions being the most vulnerable areas.

The change in crop yields can also be affected by the atmospheric CO_2 concentration. For crop yields, recent studies show mixed findings regarding the magnitude of CO_2 fertilization on crop yields with C3 crops are more responsive to the atmospheric CO_2 than C4 crops under the ample water condition (Attavanich and McCarl 2011; Ainsworth and Long 2005; Long et al. 2006; Kimball 2006). Leakey (2009) finds that unlike C3 crops, for which there is a direct enhancement of photosynthesis by elevated CO_2, C4 crops only benefit from elevated CO_2 in times and places of drought stress. Similar results are found in Attavanich and McCarl (2011).

2.1.2 Land Values

Climate change causes land use change through changes in the land productivity, which impacts land values. Overall, the effect of climate change on land values is mixed and the damage is heterogeneous across the US regions.

In one of the first key studies to examine the potential effects of climate change on the US agriculture, Mendelsohn, Nordhaus, and Shaw (1994) employ a hedonic approach to estimate the marginal value of climate by regressing land values on climate, soil, and socioeconomic variables using cross sectional data. They find that higher temperatures in all seasons except autumn reduce average farm values, while more precipitation outside of autumn increases farm values. Under their climate change scenario (a uniform 5°F increase with a uniform 8 percent precipitation increase), they reveal that the impact of global warming on farmland value in U.S. agriculture ranges from -$141 to $34.8 billion.

Applying a similar approach and climate change scenario, but with the treatment of irrigation in the analysis, Schlenker, Hanemann, and Fisher (2005) point out that the economic effects of climate change on agriculture need to be assessed differently in dryland and irrigated areas and that pooling the dryland and irrigated counties could potentially yield biased estimates. They reveal an annual loss of US farmland value to the tune of $5-$5.3 billion for dryland non-urban counties alone. In addition, Mendelsohn and Reinsborogh (2007) find that US farms are much more sensitive to higher temperature than Canadian farms. US farms also are benefit less to an increase in precipitation than Canadian agriculture.

Deschenes and Greenstone (2007) measure the economic impact of climate change on US agricultural land using a hedonic model with an attempt to address the omitted variable problems. They find that climate change will lead to a $1.3 billion (2002$) increase in annual agricultural sector profits in the long run (2070-2099). California, Nebraska, and North Carolina will be harmed substantially by climate change, while the two biggest winners are South Dakota and Georgia. In California, Schlenker, Hannemann, and Fisher (2007) examine individual farm values by matching farm values with a measure of surface water availability. They reveal that climate change could significantly affect irrigated farmland value in California, reducing values by as much as 40%.

2.2 Change in US crop production pattern as an adaptation response to climate change

A key component of the study of the effect of climate change on transportation flows and inland waterways for our study is the effect of climate change on the migration of crop production patterns as an adaptation response of farmers to changes in climate conditions. Climate change is expected to substantially impact agriculture. For the next two decades, a warming of about 0.2°C per decade is projected for a range of emission scenarios (IPCC 2007a). Increases in the amount of precipitation are likely in the high latitudes, while decreases are likely in most subtropical land regions plus an increased risk of droughts in those regions. The above outcomes are likely lead to the northward shift in crop production pattern as already observed in North Dakota where the southern sections of wheat-producing regions become northern parts of the corn-producing areas (Upper Great Plains Transportation Institute 2011). Koetse and Rietveld (2009) reviewed previous studies and found that countries at higher longitudes will become more suited for food production. The climate in countries at lower longitudes, among which the largest part is developing countries, will become substantially less suited. This likely results in an increase in freight flows from developed to developing countries.

Many studies concluded that climate change would affect crop yields and result in northward shifts in cultivated land (Smith and Tirpak 1989; Reilly 2002; Reilly et al. 2003; Smith, Richels, and Miller 2000). For example, Reilly et al. (2002) found substantial shifts in regional crop production with climate change favors northern areas and can worsen conditions in southern areas. The Lake States, Mountain States, and Pacific regions show gains in production; the Southeast, the Delta, the Southern Plains, and Appalachia generally lose. Results in the Corn Belt are generally positive. Results in other regions are mixed, depending on the climate scenario and time period.

McCarl and Reilly (2008) estimate changes of crop acreage use in the US under 2030 climate scenarios with adaptation. They find decreased acreage for cotton, soft white and hard red spring wheat, barley, hay, sugar cane, sugar beets, processed tomatoes and processed oranges; increased acreage for soybeans, hard red winter wheat, rice, potatoes, fresh tomatoes and fresh citrus; and mixed acreage results for the other crops. Combining the effect of CO_2 fertilization, Attavanich and McCarl (2011) find that percentage of planted acreage of corn, sorghum, soybeans, cotton, and winter wheat is projected to increase the most in Appalachia, Corn Belt, Mountains, and Pacific regions, respectively. However, only planted acreage of soybeans is projected to increase in 2050 across all regions in the US.

To track to the movement of crop migration, Reilly et al. (2003) constructed the geographic centroid of production for maize and soybeans and plotted its movement from 1870 (1930 for soybeans) to 1990. They find that both U.S. maize and soybean production shifted northward by about 120 miles. Similar result of soybeans is shown by Beach et al. (2009). They find that the production-weighted latitude and longitude of national soybean production trending northwest over time between 1970 through 2007. The production-weighted centroid of soybean production has been trending northward by about 3.6 miles per year on average over this timeframe. Our study applies above findings by making assumption that under the climate change scenarios grain production is likely to shift northward.

2.3 The effect of climate change on transportation system

The changing climate raises critical questions for the transportation sector in the US. Its causes and extent continue to be debated. This section reviews existing literature related to the effect of climate change on transportation system. Peterson *et al.* (2008) analyzed how transportation would be affected by change in weather and climate extreme consisting of predicted higher temperatures, higher levels of liquid precipitation, changes in sea level, and increasing severity of storms. Similar analysis was presented by Koetse and Rietveld (2009) and in a special report of the Transportation Research Board (Humphrey 2008).

For example, Koetse and Rietveld (2009) survey the empirical literature including what is found in IPCC (2007b) and conclude that flooding of coastal roads, railways, transit systems, and runways due to global rising sea levels and coupled with storm surges may be some of the most worrying consequences of climate change for North America's transportation systems.

Using 21 different general circulation models, Savonis, Burkett, and Potter (2008) indicates that a vast portion of the Gulf Coast from Houston, Texas to Mobile, Alabama, where seven of the ten largest commercial ports (by tons of traffic) in the country are located may be inundated over the next 50 to 100 years due to sea level rise (up to 122 cm), while 27 percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are at or below 122 cm (4 ft) in elevation.

Sea level rise also affects the East Coast of the United States. By using digital elevation models, ICF International (2008) finds that only small parts of roads and railroads are affected by sea level rise and storm surge, while port areas affected are substantially. For example, under the scenario of a sea level rise from 6-59 cm, about 22-26 percent and 28-31 percent of port areas in New York and Virginia are affected.

For storm surge, the 6.7-7.3 meters potential storm surge (rated a Category 3 at landfall) are projected in Savonis, Burkett, and Potter (2008), which implies that about 64 percent of interstates, 57 percent of arterials, almost half of the rail miles, and virtually all of the ports are subject to flooding in the Gulf Coast area. They also find that combined effects of an increase in mean and extreme high temperatures are likely to affect the construction, maintenance, and operations of transportation infrastructure and vehicles. For instance, rail lines may be affected by more frequent rail buckling due to an increase in daily high temperatures.

Several studies find that watersheds supplying water to the Great Lakes–St. Lawrence River system are likely to experience drier conditions, resulting in lower water levels and reduced capacity to ship agricultural and other bulk commodities, and hence increase costs of inland waterway transport (Millerd 2005; Millerd 2011; Chao 1999; Easterling and Karl 2001). Millerd (2005) find that predicted lowering of Great Lakes water levels would result in an estimated increase in Canadian shipping costs between 13 and 29 percent by 2050. The impacts vary between commodities and routes. For grains, the annual average shipping cost shipped from upper lakes to St. Lawrence River is simulated to increase about 11 percent in 2050 compared to shipping cost in 2001. For the US, Millerd (2011) projected the increase in the US vessel operating costs of grains and agricultural products exported from the Great Lakes, which is slightly lower than the Canadian vessel operating costs. They reveal that the US vessel operating costs of grains and agricultural products range from 4.15-4.95, 7.96-9.30, and 21.71-22.62 percent by 2030, 2050, and under doubling CO_2 scenario, respectively. However, many studies found that warming temperatures are likely to result in more ice-free ports, improved access to ports, and longer shipping seasons, which could offset some of the resulting adverse economic effects from increased shipping costs.

Based on the above studies, all of them mostly focus on the direct influence of climate change on transportation sector especially transportation infrastructures and costs; however no one focuses on the indirect effect of climate change on this sector through climate induced changes in agriculture.

3 Model Components, Data, and Process Overview

To examine implications of transportation flows and inland waterways due to shifts in crop production patterns under climate change, this study employs two large scale modeling systems. In this section, we provide a detailed description of the two component modeling systems, their data used, and technical approach developed to link the two.

3.1 Model Components

3.1.1 Agriculture Sector Model (ASM)

An ASM is employed so that we could analyze the complex market mechanism that would occur in the agricultural sector as a result of climate change. For example, the increases in the production of corn and soybeans induced by climate change would decrease their prices (anything being equal), thereby providing economic incentives for farmers to convert their land to plant other crops, which have relatively high prices due to the reduction in their production induced by climate change. The ASM has been developed on the basis of past work by McCarl and colleagues as reported in Adam et al. (2005). It has been used in a large number of climate change–related studies for the IPCC, Environmental Protection Agency (EPA), United States Department of Agriculture (USDA), and others.

In brief, ASM is a price endogenous, spatial equilibrium mathematical programming of the US agricultural sector. It includes all states in the conterminous US, broken into 63 subregions for agricultural production and 10 market regions for agricultural sector as shown in table A1 in Appendix. The model also links the US to the rest of the world (ROW) via international trade of major commodities such as corn, wheat, soybeans, rice, and sorghum across 37 foreign regions. It also depicts land transfers and other resource allocations within agricultural sector in the US. The model also allows the northward migration of crop production pattern under climate change. (See more details in Adams et al. 2005).

3.1.2 International Grain Transport Model (IGTM)

IGTM analyzes changes in transportation flows due to climate-induced shifts in crop production patterns. IGTM is a price endogenous, inter-temporal, spatial equilibrium mathematical programming employing non-linear programming to maximize the total net welfare. The latter is determined as producer plus consumer surplus minus grain handling, storage, and transportation costs. Several constraints are imposed when maximizing the objective function. They consist of regional supply and demand balance, transportation mode balance, and storage capacity balance for each region, type of grain, and quarter. The theoretical underpinnings of the model can be found in Samuelson (1952), and Takayama and Judge (1971).

The IGTM estimates optimal quarterly grain production, consumption, prices, and storage. It also predicts quarterly transportation flows by modes consisting of truck, rail, barge, small ship, and big ship across 303 U.S. regions going to through 42 intermediate shipping points where modes can be changed. It also considers 118 foreign exporting and importing countries around the world. Grains in the model consist of corn and soybeans, representing 82 percent of grains produced in the U.S. (Marathon and Denicoff 2011).

In our IGTM, truck, rail, and barge play a crucial role for US domestic movements of grains, while small ship and big ship are key modes that ship grains from the US and other grain exporting countries to grain importing countries around the world. Empirically, modes often compete head-to-head to supply transportation for grains. Despite a high degree of competition in some markets, they also complement each other. Before a bushel of grain reaches its final destination, it has often been transported by two or more modes. This balance between competition and integration provides grain shippers with a highly efficient, low-cost system of transportation (Marathon and Denicoff 2011). For more details of IGTM, please read Zafar et al. (2011).

3.2 Data

Simulated changes of crop yields under climate change scenarios are important for this study since climate change affects crop yields, which finally influences land productivity. Hence land use change results. We obtain simulated changes of crop yields from Beach et al. (2009). In their study, a modified version of the Environmental Policy Integrated Climate (EPIC) model, which was first developed by Williams et al. (1984), is used to simulate changes of yields of 14 crops[2]. They employ projected climate data from four global circulation models (GCMs)[3] used in the recent assessment report of IPCC in 2007 with the IPCC SRES scenario A1B, which is characterized by a high rate of growth in CO_2 emissions[4]. GCMs consist of

- GFDL-CM 2.0, GFDL-CM 2.1 models developed by the Geophysical Fluid Dynamics Laboratory (GFDL), USA;

- Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model (MRI-CGCM 2.3.2) developed by the Meteorological Research Institute and Meteorological Agency, Japan and;
- Coupled Global Climate Model (CGCM) 3.1 developed by the Canadian Centre for Climate Modeling and Analysis, Canada.

In turn, these simulated results of 14 crops are used as an input in ASM to simulate changes in crop land use. Overall, crop yields from dryland are more sensitive under climate change conditions that those from irrigated land since they are encountering with the water limitations. Due to the scope of this study and limited space, we present only simulated changes of corn and soybean yields under climate change from GCMs simulated during 2045-2055, which are illustrated in figure 1 and figure 2, respectively.

For the simulated yield of corn, generally for dryland it is simulated to increase almost all of states in the Rocky Mountains, Pacific Southwest and Pacific Northwest West in all GCMs, while it is projected to decrease almost all of states in the Corn Belt. MRI-CGCM 2.2 provides the most optimistic change in corn yield from both dryland and irrigated land. For dryland, it projects small to large increase in corn yield across the US regions except only Utah, some regions of Texas, and Virginia. For irrigated land, small increase in corn yield is predicted. On the other hand, GFDL 2.1 projects the most pessimistic change in corn yield from both dryland and irrigated land. Under GFDL 2.1, corn yield is projected to decrease almost everywhere in irrigated area as shown in figure 1.

Like corn yield, MRI-CGCM 2.2 provides the most optimistic change in soybean yield, while GFDL 2.1 projects the most pessimistic change in corn yield as illustrated in figure 2. However,

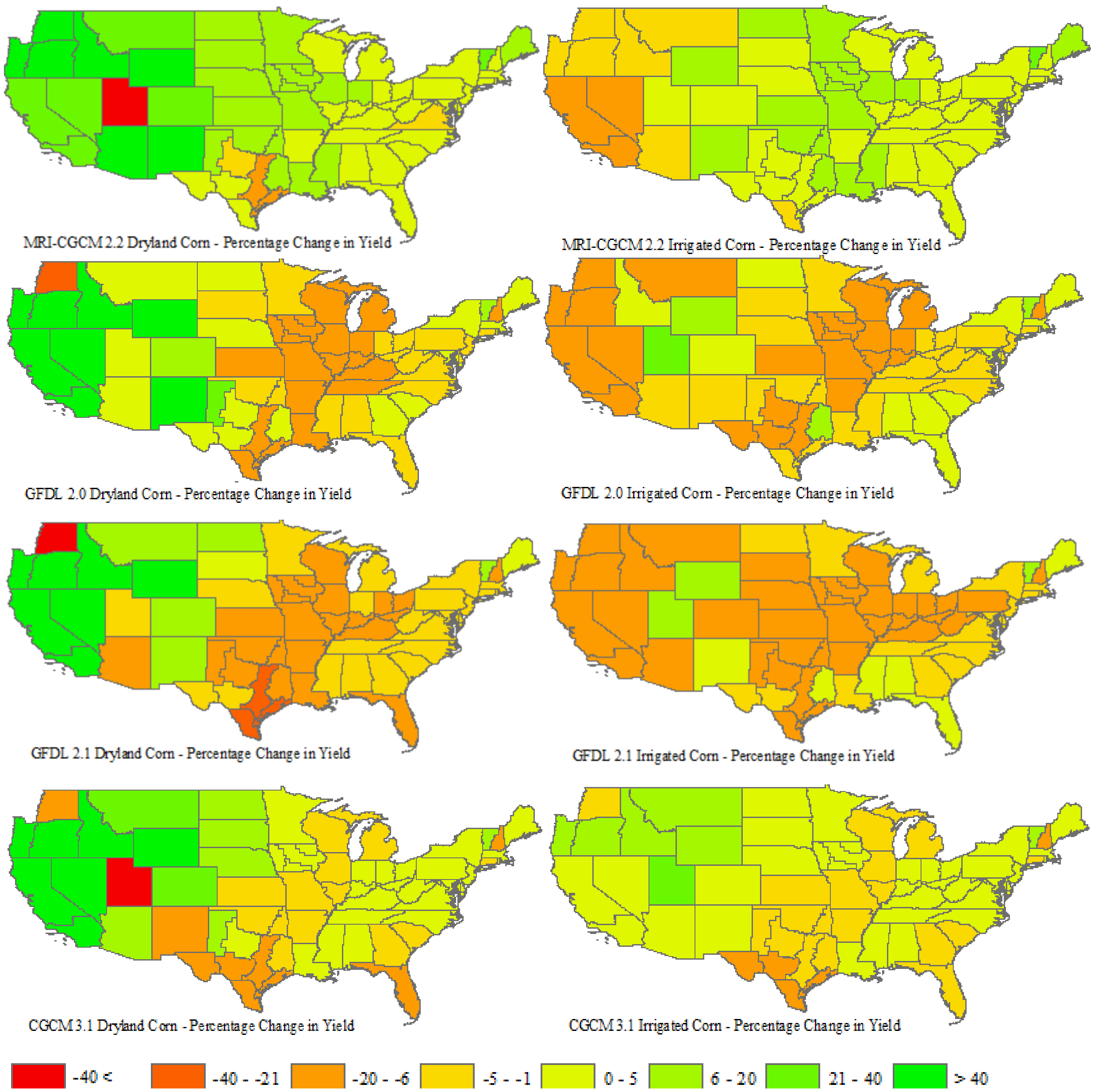

Figure 1. Percentage change in dryland and irrigated corn yields under the GCMs simulated during 2045-2055

the variation of the change in soybean yield is large than that of the change in corn yield. Soybean yield is projected to dramatically drop greater than 21 percent in the large part of Corn Belt, Southwest, and South Central in GFDL 2.0 and GFDL 2.1. On the other hand, small to large increase of the change in soybean yield is found in almost all of the upper part of the US (Great Plains, Northern part of the Rocky Mountains, Lake States, and Northeast) in all GCMs.

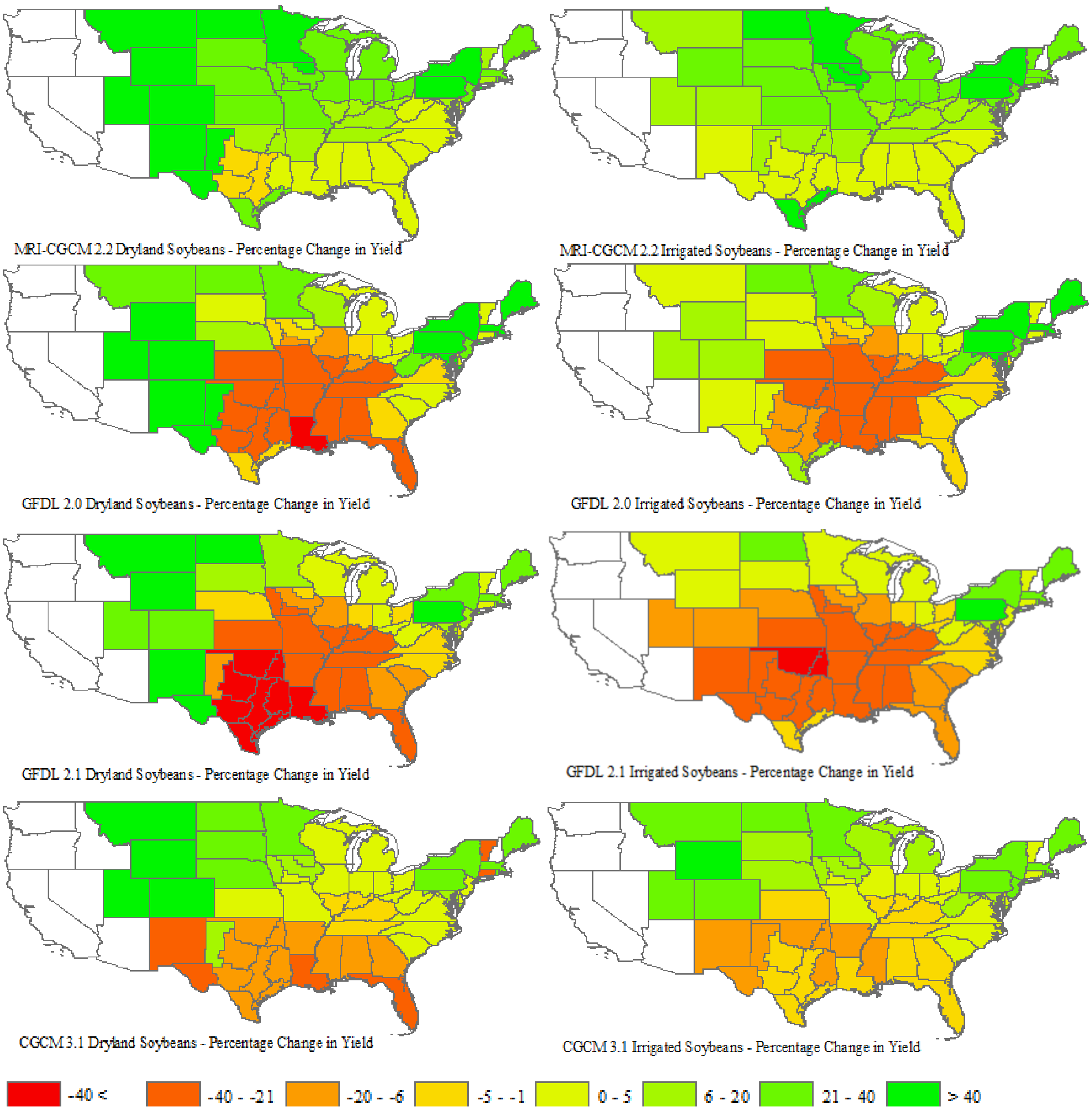

Figure 2. Percentage change in dryland and irrigated soybean yields under the GCMs simulated during 2045-2055

3.3 Model process and technical approach for analyzing the effect of climate change on transportation flows due to climate-induced shifts in crop production patterns

To link the effect of climate change on agricultural sector to change in transportation flows, we integrate ASM simulated changes in production of grains due to the change in crop yields under climate change scenarios as input to be used by IGTM. The change in crop production reflects agricultural reaction to future climate conditions using market mechanism. In turn, IGTM is employed to predict changes in grain transportation flows across US regions. This study compares “baseline” scenario in 2007/2008 (without climate change) with the climate change scenario projected from four GCMs in 2050 as discussed in section 3.2. An overview of the model system is presented in Figure 3 and discussed in detail below.

We first utilize the agricultural sector model (ASM) to predict regional shifts in cropping patterns and land use change due to climate change employing yield effects simulated during 2045-2055 provided in Beach et al. (2009) for 63 regions in the US. Although this is a fairly fine level of spatial detail for economic analysis, it is not sufficiently detailed for grain transportation modeling. Therefore, additional spatial mapping was required to incorporate ASM results into the IGTM[5].

We disaggregate the ASM solution of crop acreage to the county level by using a multi-objective mathematical programming developed by Atwood et al. (2000) and also employed in Pattanayak et al. (2005). The model contains the fundamental choice variable being the area of a particular crop allocated to an irrigation status in each county. This choice variable is constrained so it matches the land area shift in the ASM, but minimally deviated from the Census of Agriculture, US Bureau of Census, USDA National Resource Inventory (NRI), and USDA county crops data after taking into account the crop migration due to climate change.

However, our study advances Atwood et.al (2000) by adjusting their model to better reflect the possibility of crop expansion into new production areas under climate change scenarios[6]. This is very important for climate change studies since it is expected that climate change is likely to affect temperature and precipitation distributions, which finally affect crop yields and induces

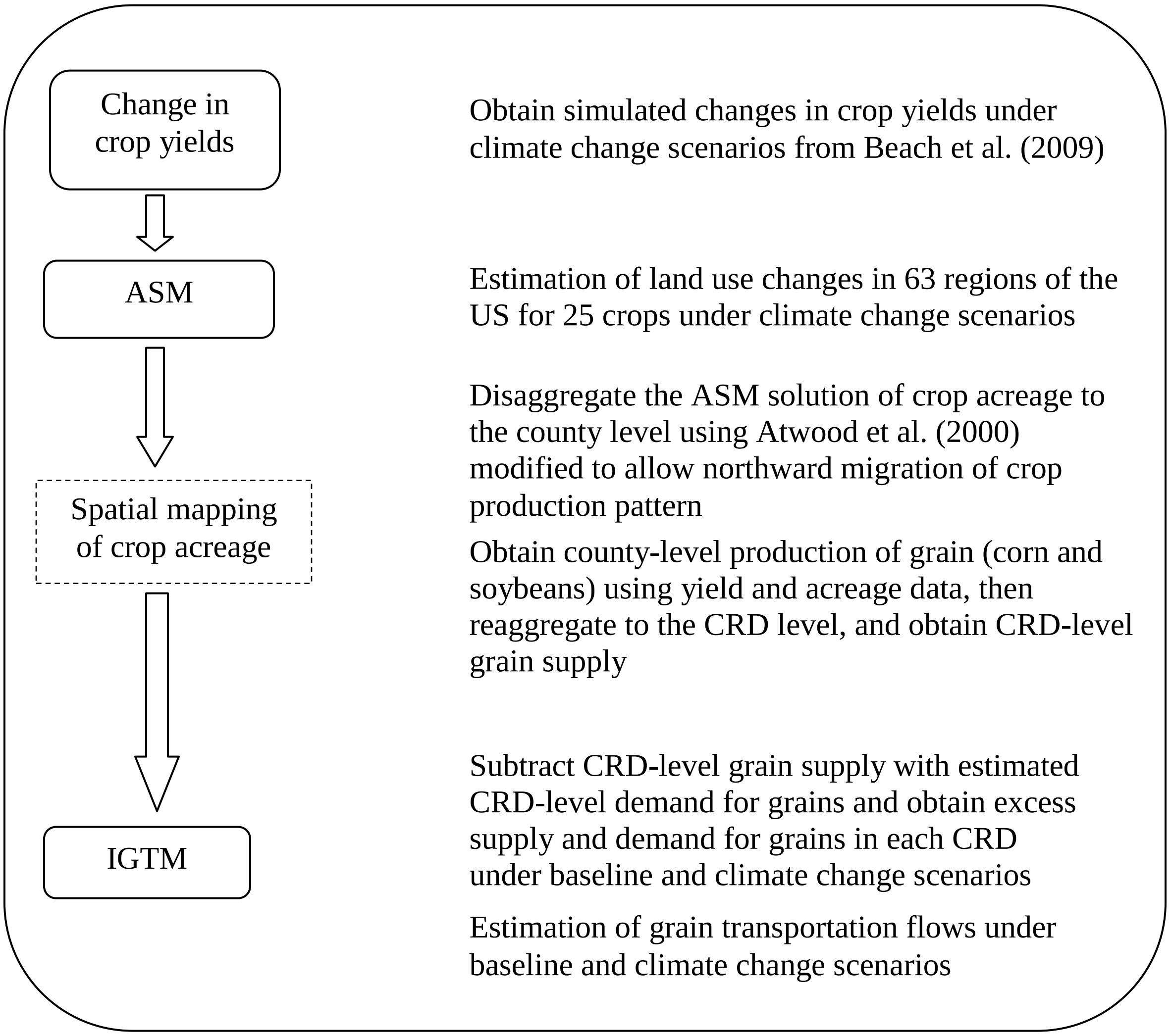

Figure 3. Overview of process for linking ASM and IGTM

the shift of crop production pattern. There are some historical evidences of production shifts over the past few decades as shown in figure 6. In this figure, the production-weighted latitude and longitude of national production of corn and soybeans tends to shift in the northwest direction overtime with about 100 and 138 miles for corn and soybeans, respectively from 1950-2010.

This study also updated data used in Atwood et al. (2000)[7] to the recent 2007 Census of Agriculture as we think longer period of study, 1970-2007, could reflect shifts in crop production patterns as an adaptation response of farmers due to climate change better than shorter period.

In the next step, the county-level crop mix acreage is reaggregated to the region defined in the IGTM, which is the crop reporting district (CRD) level. We then calculate the CRD level grain (corn and soybeans) supply, using yield and acreage data simulated from each scenario. Then we subtract grain supply with the estimated CRD-level grain demand[8] to obtain the excess demand or supply of grain in each CRD, which will be employed in the IGTM to analysis grain transportation flows due to climate-induced shifts in crop production patterns.

4 Model Results

This section reports and analyzes our empirical findings from the ASM and IGTM. The base scenario (without climate change) is first estimated in both models[9], and then its results are compared to results under climate change simulated from GCMs in 2050, which reflect the change in crop yields and shifts of crop production patterns as a result of climate change. Due to the uncertainty of factors in the future, for supply side our analysis fixes all factors 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. For demand side, we assume that grain demand is constant overtime[10]. The introduction of change in crop yields and possibility of northward migration of crops cause ASM to change its equilibrium allocation of land use, crop mix, trade flows, and commodity prices, production and consumption. Changes in acreage of grains and their production are then transferred into IGTM to model resulting changes in transport flows.

4.1 Results from ASM

The results generated by ASM are shown in table 1. The effect of future climate change is described in terms of three major categories: 1) economic welfare, 2) agricultural activities, and 3) crop land use. The key economic results affected by climate induced shifts in crop production patterns and change in crop yields are:

- *US welfare and total social welfare rises.* The US and total social welfare are forecasted to increase ranging from $2.77-27.00 and $2.36-28.51 billion, respectively, while estimated welfare of the rest of the world is varied.
- *Crop producer welfare varies across US regions; however at national level it is projected to increase in three out of four GCMs.* From all GCMs, Northeast, Rocky Mountains, Pacific Southwest, Pacific Northwest East, South Central, and Southeast are projected to increase, while Great Plains and Southwest are regions that are forecasted to drop. The results from remaining regions are mixed. By breaking down to the sub-regional level, we find that a majority of GCMs simulate the drop in crop producer surplus in IllinoisN, IndianaN, IowaW, IowaNE, IowaS for Corn Belt; Kansas, Nebraska, and South Dakota for the Great Plains; Michigan for the Lake States; Maryland for Northeast; Wyoming for the Rocky Mountains; Oklahoma and Texas (except Texas Trans Pecos).
- *Production and prices of all crops including corn and soybeans varies.* These results are consistent with the simulated change in crop yields as stated in section 3.2. GFDL 2.1 projects the decrease in crop production as a result of the drop in crop yields, which lead to the rise in crop prices. In contrast to GFDL 2.1, 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 from MRI-CGCM 2.2, while soybean production is simulated to increase in three out of four GCMs.
- *National total cropland use increases with the expansion of irrigated land and contraction of dryland.* For corn dryland are constant in all GCMs, while for soybeans it tends to increase (except result from GFDL 2.1). For irrigated land, both corn and soybeans are projected to increase (except predicted result from GFDL 2.1 for soybeans).

Table 1. Summary of welfare, agricultural activities, and cropland use

	Base	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Welfare (billions of constant 2004 $)					
US	1,534.44	1,561.44	1,541.05	1,537.21	1,550.15
Rest of the world	42.05	43.55	41.75	41.63	42.59
Total social welfare	1,576.48	1,604.99	1,582.81	1,578.84	1,592.74
Agricultural regional and national crop producer welfare (million 2004 $)					
Corn Belt	21,404.55	25,349.92	23,289.23	18,466.92	19,600.73
Great Plains	11,958.50	11,883.44	11,129.99	6,470.71	10,672.45
Lake States	7,346.95	8,067.93	6,289.09	7,764.68	6,896.45
Northeast	1,793.34	2,369.37	2,289.11	2,476.35	1,895.63
Rocky Mountains	3,922.05	4,950.74	5,417.20	4,654.65	4,717.89
Pacific Southwest	3,441.09	5,046.71	6,460.30	6,044.03	10,415.91
Pacific Northwest East	2,013.25	6,571.59	2,356.22	2,334.97	2,218.58
South Central	5,720.71	6,124.77	6,466.15	6,068.06	6,231.17
Southeast	2,704.49	2,740.88	2,835.07	2,879.09	3,689.21
Southwest	3,295.84	3,311.65	2,538.02	2,386.63	2,227.53
Total	63,600.76	76,417.00	69,070.37	59,546.09	68,565.56
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 soybean	100.00	92.07	100.00	101.19	97.16
Crop land use (1,000 acres)					
Corn, irrigated land	9,997.20	12,052.20	13,690.70	13,677.50	14,311.60
Corn, dryland	69,043.80	69,043.80	69,043.80	69,043.80	69,043.80
Corn, total land use	79,041.00	81,096.00	82,734.50	82,721.30	83,355.40
Soybean, irrigated land	2,684.60	3,833.10	3,637.20	2,577.40	3,421.60
Soybean, dryland	46,868.30	54,124.70	46,332.40	47,464.20	49,816.10
Soybean, total land use	49,552.90	57,957.80	49,969.60	50,041.60	53,237.70
All crops, irrigated land	38,387.90	41,759.06	40,929.98	43,213.39	41,917.47
All crops, dryland	264,613.54	261,381.16	262,531.30	260,061.94	261,543.80
All crops, total land use	303,001.43	303,140.22	303,461.28	303,275.33	303,461.28

4.2 Spatial mapping results

4.2.1 Supply sources of grains

This section reports estimated total supply of corn and soybeans for the base scenario and GCMs simulated in 2050 demonstrated in figure 4 and figure 5, respectively[11]. Under climate change, overall supply of corn and soybeans likely increases in the Northern part, while it tends to decline in some areas in the Southern part of the US. This finding is consistent with the projected increase in temperature across US regions from studies (see for example, IPCC 2007a), which could damage crop production in the Southern part, while it is likely beneficial to crop production in the Northern part.

For corn, all GCMs provide mixed results. Nevertheless, generally corn supply is projected to increase in middle to upper section of the Rocky Mountains (Colorado and Wyoming), Great Plains (North Dakota, South Dakota, and Upper part of Nebraska), Lake States (Minnesota), Northeast (Connecticut, New Jersey, New York, Pennsylvania, and Rhode Island), and Pacific Southwest (California) regions, while in the lower section of these regions supply of corn is predicted to fall (Arizona and New Mexico for the Rocky Mountains; Kansas for the Great Plains; Michigan and Wisconsin for Lake States; Delaware, Maryland, and West Virginia for Northeast). For traditional planted locations of corn especially Corn Belt, three out of four GCMs project the decline in corn supply (except Ohio). Corn production in Southeast (except Virginia), South Central (except Alabama and Arkansas), Southwest (except some parts of Texas), and Pacific Northwest is anticipated to diminish under climate change. Finally, we find that supply of corn is likely to expand into new production areas including Connecticut; Rhode Island; Massachusetts; parts of Idaho, Oregon, and Montana; and Northern part of Arkansas, Minnesota, Colorado, and California as shown in figure 4.

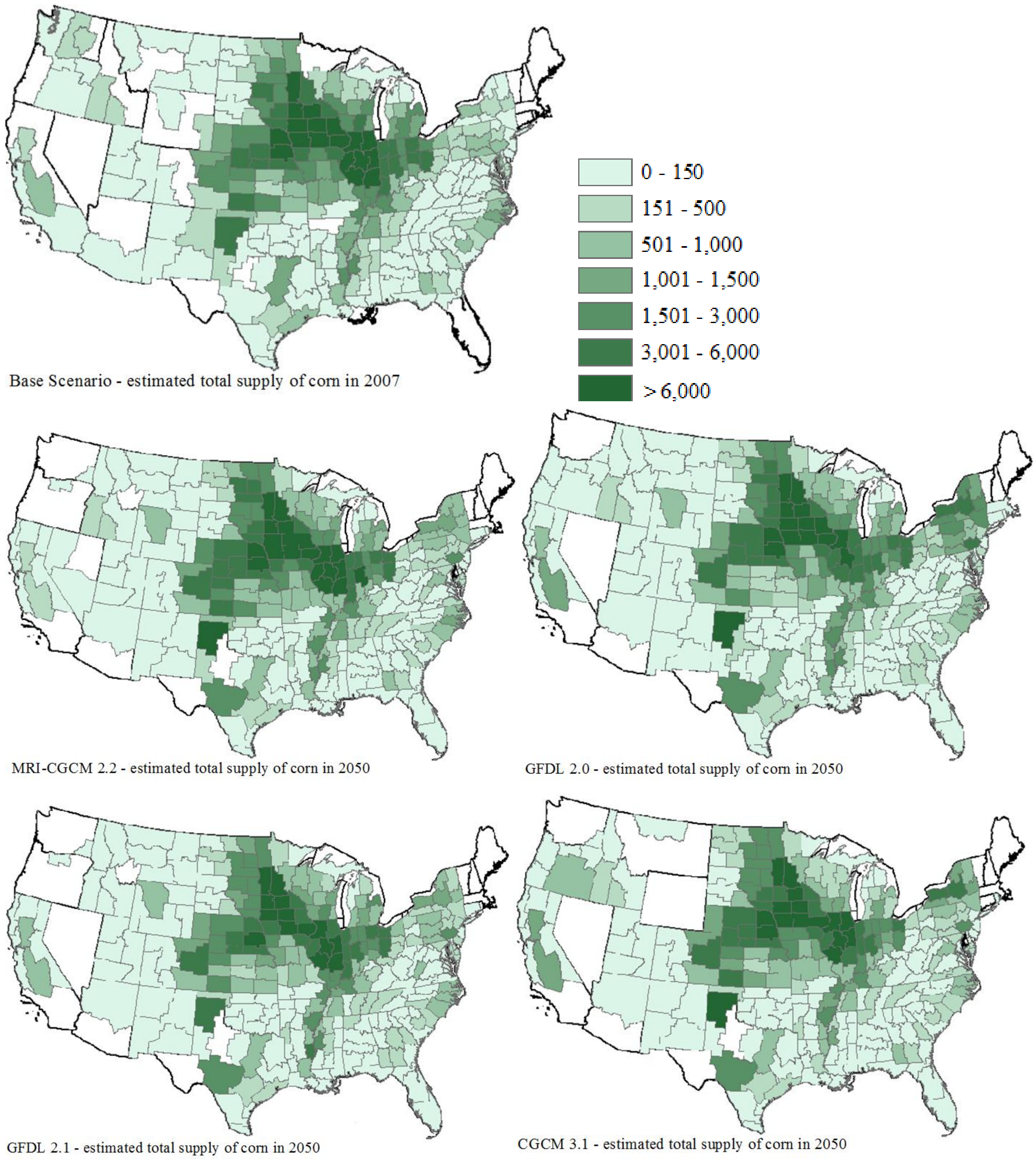

Figure 4. Estimated total supply of corn (thousand tonnes) for the base scenario in 2007/2008 marketing year and GCMs in 2050.

For soybeans, MRI-CGCM projects the raise in its supply across all US regions, while remaining GCMs provide mixed results. All GGMs predict the increase in supply of soybeans in Pennsylvania and New Jersey for Northeast; North Dakota for the Great Plains; Michigan for

Lake States; Indiana for Corn Belt; and Texas for Southwest. On the other hand, supply of soybeans is simulated to fall in Maryland and West Virginia for Northeast; South Dakota for the Great Plains; Virginia and Florida for Southeast; Mississippi for South Central; and Oklahoma for Southwest. Moreover, soybean supply in Corn Belt is predicted to fall in GFDL 2.1 and CGCM 3.1, while it is projected to rise in MRI-CGCM 3.1 and GFDL 2.0. Finally, this study finds that supply of soybeans is likely to expand into new production areas such as Kentucky; Northern part of Minnesota and Georgia; and Western part of South and North Dakota as illustrated in figure 5.

Figure 6 illustrates supply-weighted location of US grain supply under the base and climate change scenarios in 2050 from GCMs. For corn, we find that it moves northward about 20 miles from the baseline scenario. Corn supply is projected to move in the northwest and northeast direction under CGCM 3.1 and GFDL 2.1, respectively, while it tends to shift in the northern direction for GFDL 2.0 and MRI-CGCM 2.2. For supply of soybeans, it is projected to shift northward about 18 miles from the base scenario. It is likely to shift in the southeast under MRI-CGCM 2.2 and GFDL 2.0, where as it is anticipated to move in the northeast and northwest under GFDL 2.1 and CGCM 3.1, respectively.

4.2.2 Demand destinations for grains

Because IGTM employs excess supply and demand for grains, this study estimates demand for grains as mentioned in section 3.3, and then we subtract it with estimated supply of grains. Figure 7 shows estimated CRD-level total demand for corn and soybeans in 2007/2008 marketing year. We find that Corn Belt has the largest share of grain domestic demand accounting for 37 and 59 percent of total domestic demand for corn and soybeans, respectively.

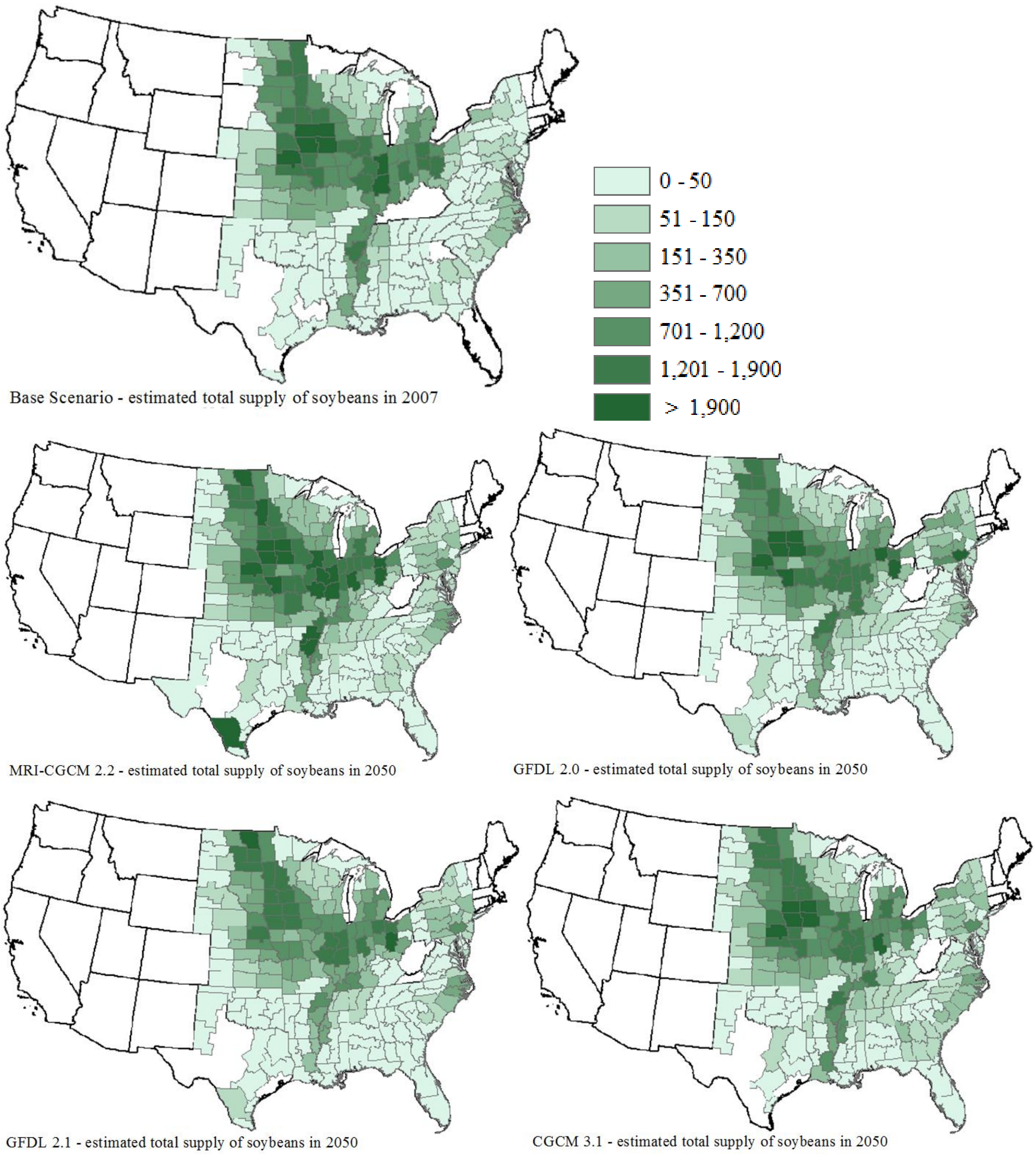

Figure 5. Estimated total supply of soybeans (thousand tonnes) for the base scenario in 2007/2008 marketing year and GCMs in 2050.

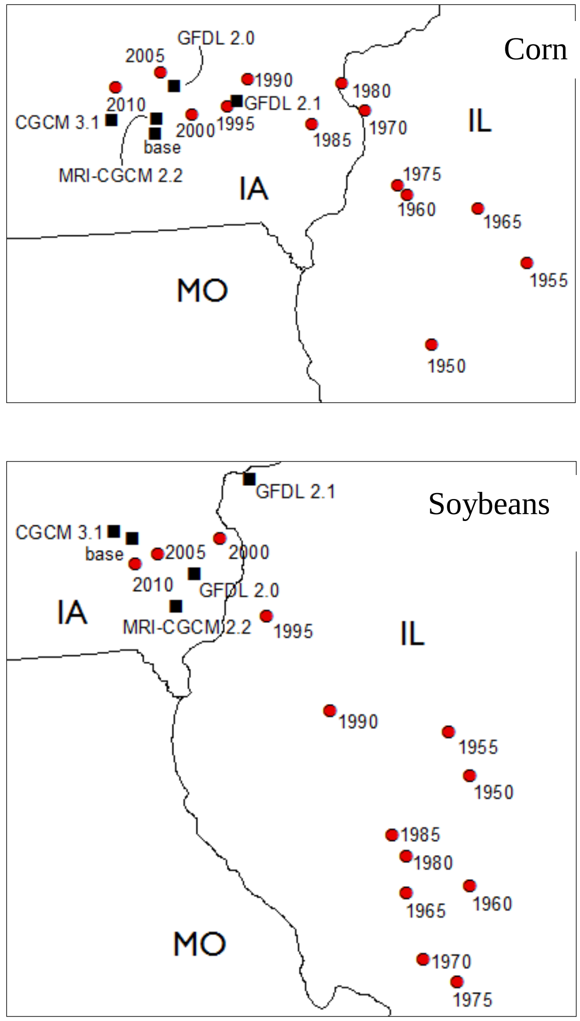

Figure 6. Production-weighted location of US grain production from 1950 – 2010 (circle) and supply-weighted location of US grain supply under the base and climate change scenarios in 2050 from GCMs (square)[12]

More than half of Corn Belt's demand for corn and soybeans comes from Iowa and Illinois. Great Plains, Lake States, South Central, and Southeast are also major destinations for the consumption of corn and soybeans. Top-ten states that have the largest amount of domestic demand for corn are Iowa, Nebraska, Illinois, Minnesota, Indiana, Texas, North Carolina, Kansas, Wisconsin, and South Dakota, respectively. For soybeans, Iowa, Illinois, Minnesota, Indiana, Ohio, Missouri, Nebraska, Georgia, North Carolina, and Kansas, respectively, are the first ten states that have the largest amount of domestic demand for soybeans.

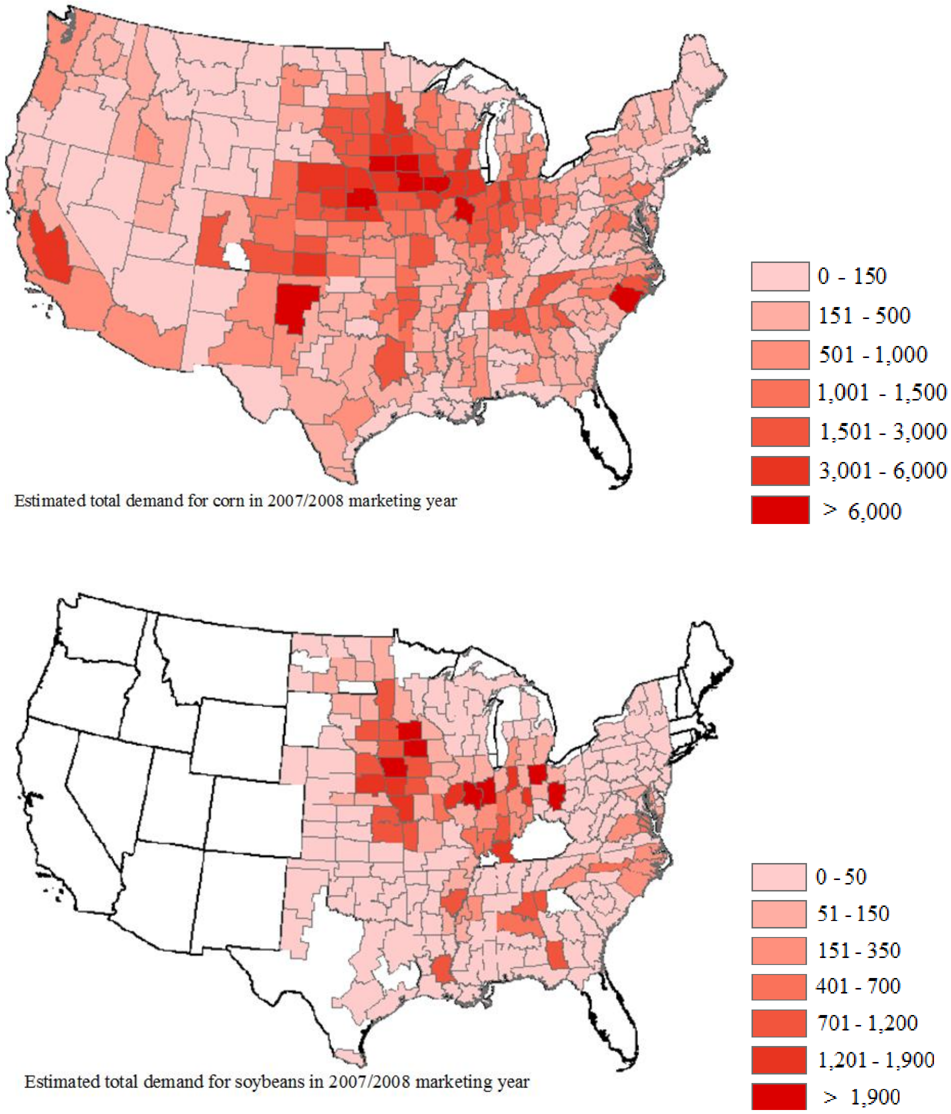

Figure 7. Estimated total demand for corn and soybeans (thousand tonnes) in 2007/2008 marketing year

4.2.3 Excess supply and demand locations for grains

This section reports estimated excess supply and demand for grains and identifies the status of a location to be either excess demand or supply location for grains as illustrated in figure 8 and figure 9 for corn and soybeans, respectively. The results then are used as an input in IGTM. We observe that although some locations produce a large volume of grains as shown in figure 4 and figure 5, after taking into account their domestic demand for grains (figure 7) these

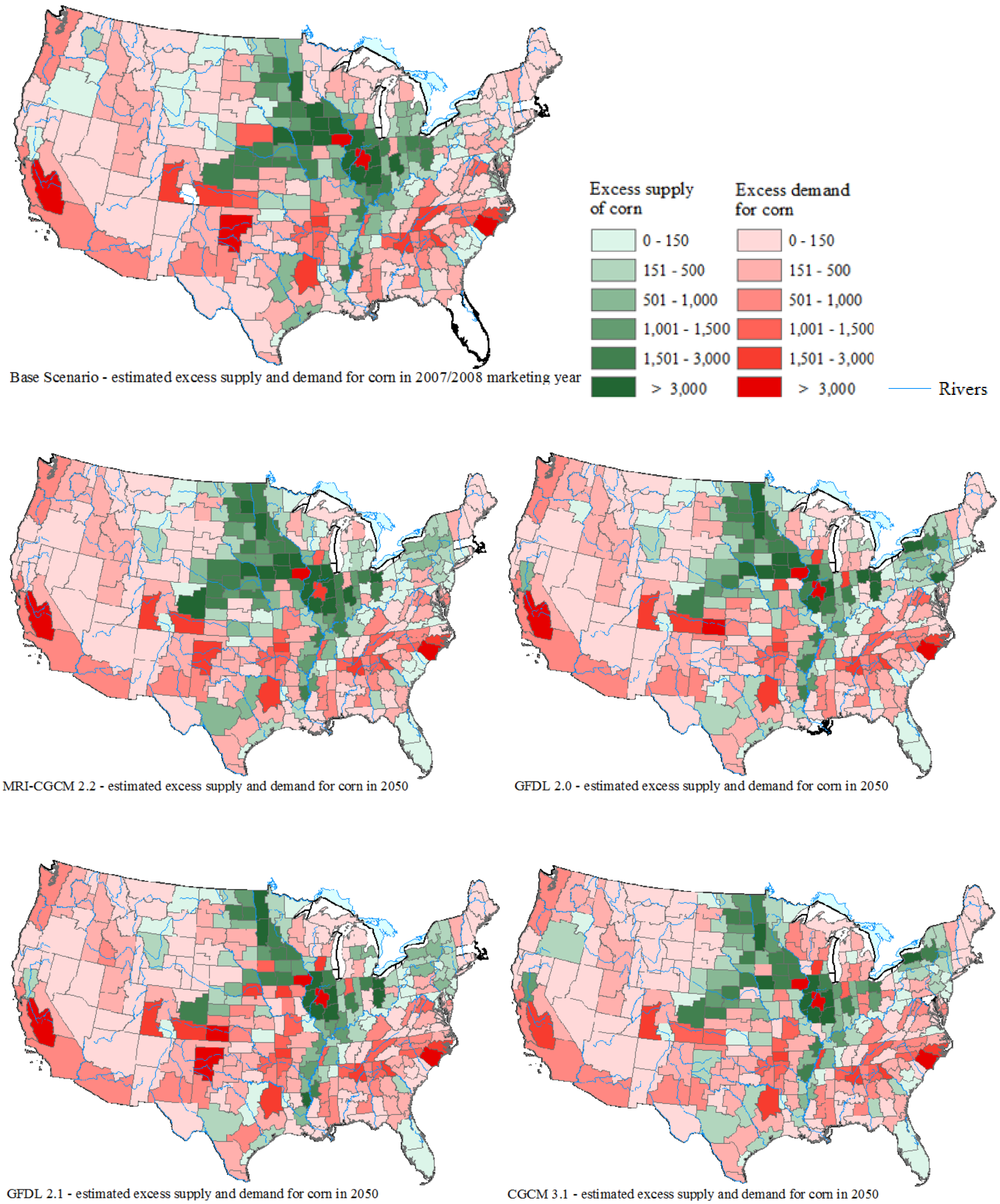

Figure 8. Excess supply and demand for corn (thousand tonnes) for the base scenario in 2007/2008 marketing year and GCMs in 2050.

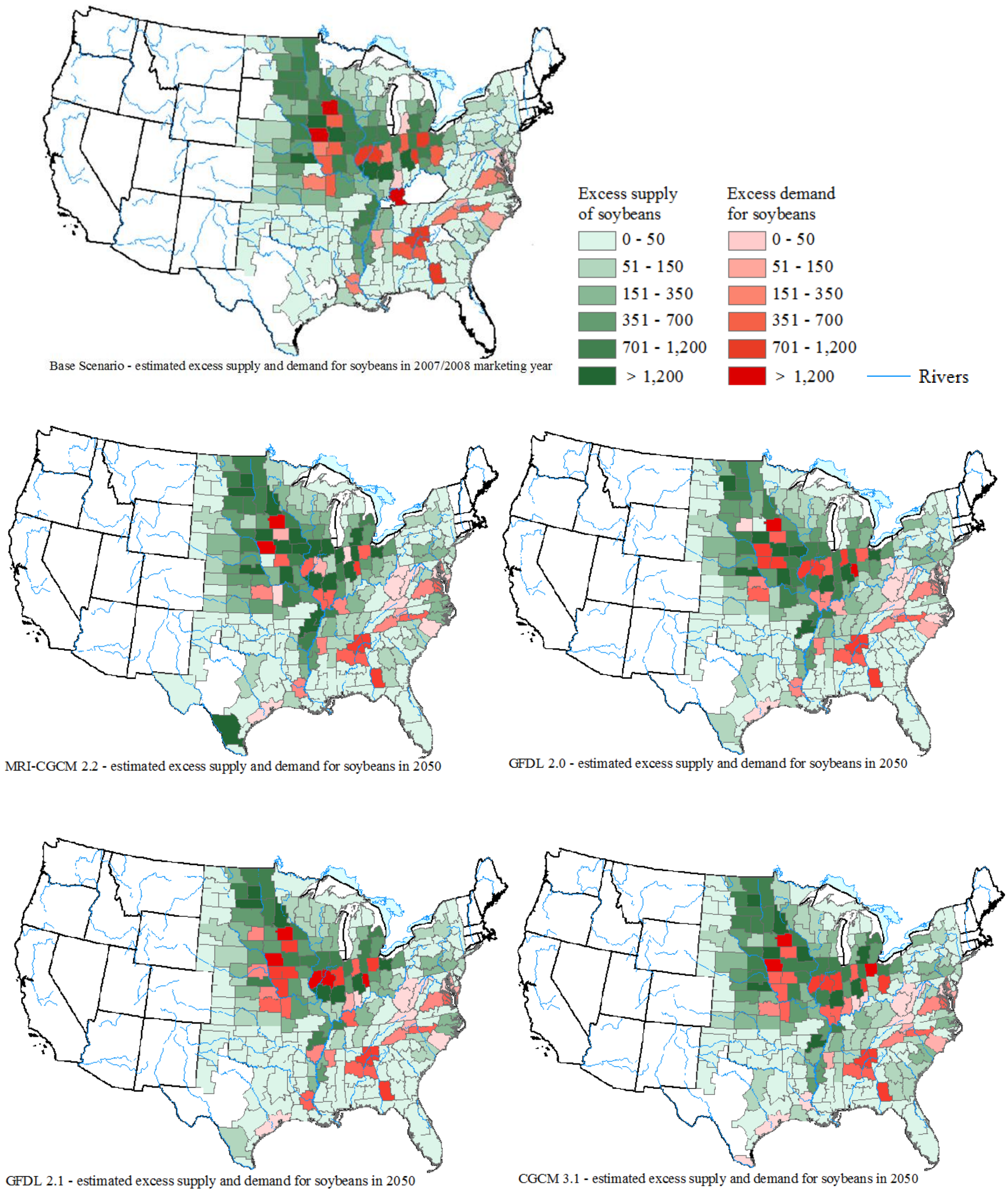

Figure 9. Excess supply and demand for soybeans (thousand tonnes) under the base scenario in 2007/2008 marketing year and GCMs simulated in 2050.

regions have their status of excess demand locations (see for example, CRD 40 of Illinois, CRD 60 of Iowa for corn; and CRD 20, CRD 40, CRD 70, and CRD 80 of Iowa for soybeans in the base scenario). In all GCMs, climate-induced shifts in crop production patterns potentially increase excess supply of corn in the Rocky Mountains (mainly Northern part of Colorado and Wyoming) and Northeast (mainly New York and Pennsylvania), while it reduces excess supply of corn in Southeast (Georgia and Virginia). Three out of four GCMs project the increase in excess supply of corn in Lake States (mainly in the central to northern part of Minnesota), South Central (mainly in Arkansas and Louisiana), and Pacific Southwest (mainly in the Northern part of California), where as they predict the drop in excess supply of corn in the Great Plains (except North and South Dakota), Corn Belt (except Ohio), and Southwest.

For soybeans, a majority of GCMs generally projects the increase in its excess supply to almost all of US regions. Northeast (mainly in Maryland, New Jersey, and Pennsylvania) is the only region that its excess supply is forecasted to increase from all GCMs. Three out of four GCMs report the increase in the Great Plains (mainly in North Dakota and Nebraska), Lake States (mainly in Michigan), and South Central (mainly in Alabama, Kentucky, and Louisiana). On the other hand, Southeast and Corn Belt are only two regions that more than one GGMs project the drop in corn’s excess supply.

We also find that under climate change some excess demand locations especially locations in the upper part of the US change their status to excess supply locations such as CRD 20 of Colorado, , CRD 20, 30, 50, and 60 of Minnesota, CRD 20 of Nebraska, and many CRDs in NY for corn; and CRD 70 of Indiana, CRD10 and 20 of Maryland, CRD 50 of Ohio, CRD 20 and 30 of Pennsylvania for soybeans. On the other hand, some excess supply locations especially areas in south and central parts of the US change their status to excess demand locations such as CRD 90 of Iowa, CRD 60 of Kansas, CRD 20 of Missouri, CRD 40 and 70 of Ohio, and CRD 40 of Oklahoma for corn; and CRD 80 and 90 of Illinois, CRD 80 of Indiana, CRD 90 of Texas, CRD 70 of Virginia for soybeans.

4.3 Results from IGTM

4.3.1 Regional transportation flows

This section reports results of grain transportation flows due to climate-induced shifts in crop production patterns. To minimize transportation costs, we expect the western section of grains' excess supply region such as Nebraska, Colorado, and Iowa ships grains to fill in the demand in its nearby areas, Pacific Southwest, and southern to central part of the Rocky Mountains regions and export to Mexico via rail and other countries via Pacific Northwest ports. The left part of the northern section of grain's excess supply region such as North Dakota, South Dakota, and Minnesota ships grains to meet the demand in its nearby areas, the Pacific Northwest, Pacific Southwest, and the Rocky Mountains; exports to the rest of the world (ROW) via Pacific Northwest ports, the Great Lakes ports, Lower Mississippi ports and; exports via rail to meet the demand in Canada.

On the other hand, the right part of the northern section of grains' excess supply region such as New York and Pennsylvania and Eastern section such as Michigan and Ohio are expected to move corn to fill in the demand in its nearby areas, the Northeast and Southeast regions of the US; export corn to the ROW via the Great Lakes ports, and the Atlantic ports; export via rail to Canada. Finally, this study expects grain shipments from the central (such as Illinois, Indiana, and Missouri) and southern (such as Texas, Arkansas, and Kansas) section of grains' excess supply region to its nearby areas, the excess demand locations in the South Central, Southwest, and Southeast regions of the US; to the Lower Mississippi ports and Texas Gulf ports for export.

Under climate change the volume of grain supply in each location and the distribution of excess supply and demand locations are projected to change as discussed in section 4.2.3. These changes will likely affect the pattern of grain flows across the US regions. Table 2 and table 3 provide results of simulated transportation flows of corn and soybeans, respectively, from region to region, and region to destinations for export under climate change from GCMs in 2050 compared to the baseline scenario.

Under climate change, considering regional transportation flows, Corn Belt, the largest producer of corn in the US, is anticipated to ship less corn supply to Pacific[13], Northeast, Rocky Mountains, Southeast, and Mississippi Lower ports as shown in table 2. One of the main reasons is that some corn shipments that used to export to other locations now are expected to fill in demand in its owned region and nearby locations (Great Plains and Lake States) where climate change tends to threaten their corn supply. For export destinations, only the Great Lakes ports and Mexico are expected to receive higher corn shipments from Corn Belt. For the Great Plains, it is projected to ship higher level of corn supply to the Pacific, Pacific Northwest ports, and Canada due to the expected increase in corn excess supply in its northwestern section (North Dakota and South Dakota). In contrast, it is forecasted to export less corn to demand locations in its owned region and Southwest.

Next, Lake States is predicted to ship more corn to its owned region, Great Plains, Pacific, Rocky Mountains, Southwest, Mexico, and ports along Texas Gulf, Pacific Northwest, and the Great Lakes. On the other hand, corn shipments to Canada, Atlantic ports, and Northeast are projected to decline. Due to the expected increase in the corn supply relative the corn demand, Rocky Mountains, Pacific, and Northeast will be able to move more corn to fill in their owned demand, while the leftover are shipped to other regions. For example, Northeast is projected to

Table 2. Transportation flows of corn (thousand tonnes) from region to region and to destinations for export under climate change from GCMs in 2050 compared to the baseline

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	12,184	11,965	20,593	17,935	18,192
	Great Plains	2,472	390	5,880	4,291	1,302
	Lake States	5	-	241	-	2,974
	Pacific	4,670	4,296	-	-	952
	Northeast	2,096	1,444	525	494	1,188
	Rocky Mountains	1,548	966	-	881	56
	Southeast	16,459	14,493	8,167	11,939	9,625
	South Central	12,700	13,144	11,060	8,713	10,751
	Southwest	2,790	2,596	1,946	4,184	2,219
	Miss Lower Ports	28,678	26,132	6,024	12,584	14,647
	PNW Ports	1,175	2,449	-	-	-
	Great Lakes Ports	602	3,620	3,475	3,630	508
	Interior, Mexico	-	205	-	745	-
	All Regions	85,379	81,700	57,911	65,396	62,414
Great Plains	Corn Belt	-	44	2	-	538
	Great Plains	2,966	1,276	2,013	1,506	2,282
	Pacific	2,096	2,595	5,320	2,122	3,971
	Rocky Mountains	2,574	2,821	1,826	371	1,881
	South Central	-	471	-	-	-
	Southwest	6,028	3,464	1,492	3,423	2,114
	Texas Gulf Ports	-	-	1,409	-	475
	PNW Ports	9,136	12,130	14,591	6,185	15,343
	Interior, Mexico	6,390	6,859	5,553	2,664	4,900
	Interior, Canada	236	953	1,461	1,402	1,444
	All Regions	29,426	30,613	33,667	17,673	32,948
Lake States	Corn Belt	1,114	119	-	1,613	-
	Great Plains	237	213	-	2,412	-
	Lake States	2,322	3,736	4,419	3,310	4,645
	Pacific	1,309	2,021	1,535	4,807	1,014
	Northeast	588	-	-	-	-
	Rocky Mountains	1,412	1,158	1,854	2,222	1,976
	Southeast	1,055	295	-	1,746	-
	South Central	-	-	54	-	-
	Southwest	-	81	965	2,161	124
	Miss Lower Ports	4,798	3,615	7,053	1,802	4,734
	Texas Gulf Ports	-	147	-		
	PNW Ports	1,766	4,395	6,572	7,908	4,927
	Great Lakes Ports	-	73	57	17	74
	Atlantic Ports	754	50	-	71	-
	Interior, Mexico	-	-	-	171	-
	Interior, Canada	1,681	630	-	-	-
	All Regions	17,036	16,533	22,509	28,240	17,494
Rocky Mountains	Pacific	-	-	22	-	-
	Rocky Mountains	1,894	3,217	3,632	3,507	3,074
	All Regions	1,894	3,217	3,654	3,507	3,074

Table 2. Transportation flows of corn (thousand tonnes) from region to region and to destinations for export under climate change from GCMs in 2050 compared to the baseline (continue)

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Pacific	Pacific	91	-	709	486	1,416
	Rocky Mountains	196	-	1	-	116
	PNW Ports	341	-	-	-	457
	All Regions	628		710	486	1,989
Northeast	Northeast	998	2,471	1,775	2,436	2,589
	Southeast	208	2,479	9,500	3,677	6,998
	Atlantic Ports	-	5	4,687	415	140
	Interior, Canada	390	788	820	770	803
	All Regions	1,596	5,743	16,782	7,298	10,530
Southeast	Northeast	156	-	-	-	-
	Southeast	892	781	289	268	668
	South Central	-	-	-	-	6
	Atlantic Ports	-	118	-	-	77
	All Regions	1,048	899	289	268	751
South Central	Pacific	-	-	-	316	-
	Southeast	565	598	1,164	830	854
	South Central	6,222	5,890	7,773	9,101	8,109
	Southwest	-	-	-	19	-
	Miss Lower Ports	4,074	3,385	4,112	7,098	1,286
	All Regions	10,861	9,873	13,049	17,364	10,249
Southwest	Southwest	466	894	816	705	814
	Texas Gulf Ports	1,551	904	385	387	872
	All Regions	2,017	1,798	1,201	1,092	1,686
All Regions	Corn Belt	13,298	12,128	20,595	19,548	18,730
	Great Plains	5,675	1,879	7,893	8,209	3,584
	Lake States	2,327	3,736	4,660	3,310	7,619
	Pacific	8,166	8,912	7,586	7,731	7,353
	Northeast	3,838	3,915	2,300	2,930	3,777
	Rocky Mountains	7,624	8,162	7,313	6,981	7,103
	Southeast	19,179	18,646	19,120	18,460	18,145
	South Central	18,922	19,505	18,887	17,814	18,866
	Southwest	9,284	7,035	5,219	10,492	5,271
	Miss Lower Ports	37,550	33,132	17,189	21,484	20,667
	Texas Gulf Ports	1,551	1,051	1,794	387	1,347
	PNW Ports	12,418	18,974	21,163	14,093	20,727
	Great Lakes Ports	602	3,693	3,532	3,647	582
	Atlantic Ports	754	173	4,687	486	217
	Interior, Mexico	6,390	7,064	5,553	3,580	4,900
	Interior, Canada	2,307	2,371	2,281	2,172	2,247
	Domestic	88,312	83,916	93,574	95,475	90,448
	Export	61,573	66,460	56,198	45,849	50,687
	Total	149,885	150,376	149,772	141,324	141,135

Source: Authors’ calculation

ship higher level of corn to Southeast, Atlantic Ports, and Canada. For Southeast, it is expected to ship constant to less corn to other regions (except Atlantic ports) including itself. South Central is projected to play an increasing role as a corn supplier for Pacific, Southeast, Southwest, and excess demand locations in its owned region. Texas Gulf ports are expected to receive less corn supply from Southwest region.

Overall, for the aspect of supplier, Corn Belt, Southeast, and Southwest are expected to ship less level of corn shipments to all US excess demand locations, while the Rocky Mountains and Northeast regions are projected to ship higher level of corn supply to all US excess demand locations. The results are mixed for other remaining regions depending on GCMs. For the aspect of importer, more than two out of four GCMs projected that Corn Belt and the Great Plains are expected to import more corn to fill in their excess demand locations. On the other hand, more than three out of four GCMs predict the lower level of the corn's import in other remaining regions. For the aspect of export, in all GCMs, the importance of Lower Mississippi ports, the largest destination for corn export from the US to the rest of the world, is going to diminish, where as the role of Pacific Northwest ports are simulated to increase. Two out of four GCMs results indicate that the Pacific Northwest ports are likely to be the largest destination for corn exports instead of Lower Mississippi ports. Finally, more than three out of four GCMs project the increase of corn shipments for export to the Great Lakes ports, while they predict the reduction of them to Texas Gulf ports, Atlantic ports, Mexico, and Canada. Except the predicted results from MRI-CGCM 2.2, total domestic shipments of corn are forecasted to increase, while total US export shipments and total US shipments of corn are projected to decline in all GCMs.

Climate change induced shifts in crop production pattern is likely to generate higher or new transportation flows for corn that never exist under the current condition. The Great Plains is expected to ship corn to Corn Belt, South Central, Pacific South west, and Texas Gulf ports. Transportation flows from North Dakota to Texas; South Dakota to California, Texas and Texas Gulf ports; Northern parts of Nebraska to California; and Kansas to Missouri are examples of these new transportation flows. Pacific Southwest, South Central, Southwest, Texas Gulf ports, and Mexico are new destinations that receive corn shipments from Lake States. For example, Minnesota will ship soybeans to California, and Michigan will export soybeans to Mississippi, and South Carolina. The increase in excess supply of corn in the upper section and the decrease in excess supply of corn in the middle to lower section of Corn Belt and the Great Plains (Nebraska and Kansas) may be the main reason to support these findings.

Next we turn our attention to regional transportation flows of soybeans. As demonstrated in table 3, all GCMs report the increase of soybean shipments from Corn Belt to Southeast, Northeast, the Great Lakes ports, and Atlantic ports, while less amount of soybeans is expected to ship to South Central. For the Great Plains, there is no anonymous result from all GCMs. However, three out of four GCMs predict the increase in soybean shipments to Pacific Northwest ports, while they simulate the reduction in soybean shipments to South Central. Soybean shipments are expected to rise from Lake States to Atlantic ports in all GCMs. Moreover, three out of four GCMs predict the increase of soybeans' transportation flows from Lake States to Corn Belt, Southeast, and the Great Lakes ports, where as they forecast the drop in transportation flows from Lake States to excess demand locations in its owned region and Pacific Northwest ports.

Due to the expected increase in soybean production in the Northeast, Northeast is projected to ship soybeans to fill in excess demand locations in its owned region, and ships higher amount of soybean shipments to Southeast, South Central, Atlantic ports, and Canada. Similar to Northeast, Southeast and South Central are projected to ship soybeans to fill in excess demand locations in its owned region. Southeast will ship more soybeans to the Atlantic ports (except GFDL 2.0), where as South Central are anticipated to export more soybeans to Lower Mississippi ports (except GFDL 2.1). Southwest is expected to export higher volume of soybeans to Texas Gulf ports and Mexico.

Overall, for the aspect of supplier, only Northeast that all GCMs project to ship more soybeans to all US excess demand locations, while other remaining regions (except Corn Belt) are predicted to ship higher amount of soybeans to all US excess demand locations. For the aspect of importer, soybean shipments to excess demand locations in Lake States, Northeast, and Southwest are expected to increase. For the aspect of export, the Great Lakes ports and Atlantic ports are only two destinations that all GCMs predict to receive increasing shipments of soybeans. Three out of four GCMs report the increase in soybean shipments to Texas Gulf ports, Pacific Northwest ports, Mexico, and Canada. Results of Lower Mississippi ports are mixed, but unlike corn, Lower Mississippi ports will maintain its position as the largest destination for soybean export from the US to the ROW. Considering total US domestic shipments of soybeans, all GCMs (except MRI-CGCMs) simulate higher soybeans transportation flows. On the other hand, total soybean transportation flows of the US and total US export are predicted to rise in all GCMs (except GFDL 2.1).

Similar to corn, climate change is likely to generate new transportation flows for soybean shipments that never exist under the current condition. Some locations in Southeast, Corn Belt and Mexico are expected to receive shipments from Lake States. Michigan to Missouri and Mississippi; Wisconsin to Iowa; and Minnesota to Mexico are some of examples. Some locations in Northeast are projected to ship new or higher shipments of soybean to Southeast and Canada

Table 3. Transportation flows of soybeans (thousand tonnes) from region to region and to destinations for export under climate change from GCMs in 2050 compared to the baseline

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	8,581	5,585	8,126	10,869	9,955
	Great Plains			263		
	Lake States	308	1,258	1,939		665
	Northeast		2	1	1	2
	Southeast	33	202	111	111	72
	South Central	2,578	1,766	1,629	1,524	612
	Miss Lower Ports	10,355	16,248	12,179	5,965	8,168
	Great Lakes Ports	283	1,076	1,517	1,649	372
	Atlantic Ports		481	401	454	137
	Interior, Mexico		481			
	All Regions	22,138	27,099	26,166	20,573	19,983
Great Plains	Corn Belt	968	36	1,270	456	2,012
	Great Plains	394	252	699	1,626	352
	South Central	424	583	149		11
	Southwest		2			2
	Miss Lower Ports	1,231	2,136	28	0	1,315
	PNW Ports	6,900	7,277	7,916	6,116	8,363
	Interior, Mexico	2,585	2,436	2,614	2,089	2,595
	All Regions	12,502	12,722	12,676	10,287	14,650
Lake States	Corn Belt	1,229	1,285	807	2,349	2,281
	Great Plains				94	
	Lake States	2,019	1,791	1,680	2,479	2,004
	Southeast	746	986	889	748	499
	South Central				517	
	Miss Lower Ports	2,117	2,277	1,520	999	2,381
	PNW Ports	1,412	2,530	671	1,052	1,356
	Great Lakes Ports	333	729	0	531	471
	Atlantic Ports	496	587	638	644	533
	Interior, Mexico				227	
	All Regions	8,352	10,185	6,205	9,640	9,525
Northeast	Northeast	61	312	423	475	276
	Southeast	940	785	1,245	939	1,154
	South Central			84	37	
	Atlantic Ports	5	7	65	9	8
	Interior, Canada		114	337	93	
	All Regions	1,006	1,218	2,154	1,553	1,438
Southeast	Northeast	17			5	6
	Southeast	616	1,014	252	670	1,149
	Atlantic Ports	210	385	120	214	328
	All Regions	843	1,399	372	889	1,483

Table 3. Transportation flows of soybeans (thousand tonnes) from region to region and to destinations for export under climate change from GCMs in 2050 compared to the baseline (continue)

Source	Destination	Baseline	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
South Central	Southeast	1,475	1,594	1,633	1,281	1,206
	South Central	970	1,516	1,633	1,654	1,642
	Southwest	-	-	2	1	-
	Miss Lower Ports	2,880	4,477	3,860	1,607	4,401
	Texas Gulf Ports	10	1	8		1
	All Regions	5,335	7,588	7,136	4,543	7,250
Southwest	Southwest	-	-	-	22	1
	Miss Lower Ports	141	1,277	77	43	68
	Texas Gulf Ports	39	874	86	136	9
	Interior, Mexico	46	72	92	82	81
	All Regions	226	2,223	255	283	159
All Regions	Corn Belt	10,778	6,906	10,203	13,674	14,248
	Great Plains	394	252	962	1,720	352
	Lake States	2,327	3,049	3,619	2,479	2,669
	Northeast	78	314	424	481	284
	Southeast	3,810	4,581	4,130	3,749	4,080
	South Central	3,972	3,865	3,495	3,732	2,265
	Southwest	-	2	2	23	3
	Miss Lower Ports	16,724	26,415	17,664	8,614	16,333
	Texas Gulf Ports	49	875	94	136	10
	PNW Ports	8,312	9,807	8,587	7,168	9,719
	Great Lakes Ports	616	1,805	1,517	2,180	843
	Atlantic Ports	711	1,460	1,224	1,321	1,006
	Interior, Mexico	2,631	2,989	2,706	2,398	2,676
	Interior, Canada	-	114	337	93	-
	Domestic	21,360	18,969	23,083	25,857	23,900
	Export	29,042	43,465	31,881	21,911	30,588
	Total	50,402	62,434	54,964	47,768	54,488

Source: Authors' calculation

such as New York to Canada and North Carolina. Due to the change in their status from excess demand to excess supply location under climate change, Kentucky and Maryland are projected to ship new excess supply of soybeans to other excess demand locations For example, Kentucky ships soybeans to Alabama, Georgia, and Mississippi Lower ports, where as Maryland exports soybean shipments to Atlantic ports, Virginia, and excess demand locations in its owned region.

4.3.1.1 Demand for modes of transportation

Figure 10 shows estimated overall demand for modes of transportation of corn, soybeans, and grain (corn and soybeans) under climate change compared to the baseline scenario. Considering both domestic and export grain transportation, rail has the largest share of grain (both corn and soybeans) transportation between excess supply and demand locations in terms of tonnes and is expected to have an increasing role under baseline and climate change scenarios compared to truck and barge modes. Three out of four GCMs reveal an increasing demand for truck for corn, soybeans, and total grain shipments. It is worth to mention that our calculation for transportation flows considers only transport flows between locations, crop reporting districts. The study does not take into account transport flows within the same location, in which truck generally play a crucial role[14]. As a result, the role of truck mode is smaller than what it should be. Our results of transport flows by rail and barge are in the range of results estimated by Marathon and Denicoff (2011), if we assume that almost all of transport flows between CRDs employ rail and barge modes.

On the other hand, barge mode, playing a significant role as a major route to export market via Lower Mississippi ports, is expected to receive fewer amounts of total grain shipments (three out

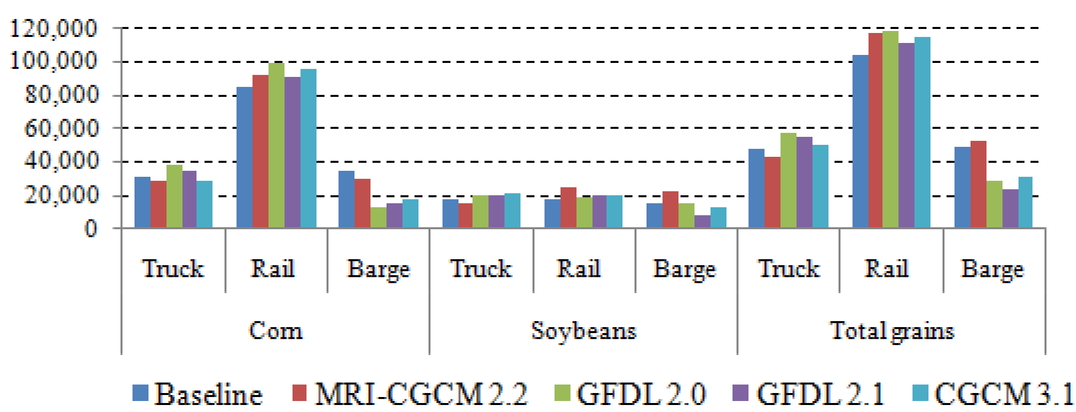

Figure 10. Supply shipments of grains (thousand tonnes) classified by modes of transportation under climate change from GCMs in 2050 compared to the baseline

of four GCMs). Demand for barge mode of corn shipments is projected to drop in all GCMs, while soybean shipments tend to employ relatively stable barge mode under climate change. The reduction of corn supply in Corn Belt and lower section of Minnesota could be the main reason of the decline in demand for barge mode since a majority of corn is shipped via barge locations along the Illinois water ways, Ohio River, and the lower part of the Upper Mississippi River.

After breaking modes of transportation down into regions, we find that demand for truck mode tends to increase in Corn Belt (except MRI-CGCM 2.2), and Northeast, and Rocky Mountains for corn; and the Great Plains (except MRI-CGCM 2.2), South Central, and Northeast for soybeans, where as it is likely to drop in the Great Plains, Southeast, and Southwest for corn; and Southwest for soybeans. Considering the demand for rail mode, it is projected to increase in almost all of regions from a majority of GCMs (both corn and soybeans) except Corn Belt for corn and South Central for soybeans. For barge mode, a majority of GCMs predicts the reduction of its demand in all regions for corn, while they provide mixed results for soybeans. South Central is the only region that more than two GCMs project to increase in the barge's demand for soybean shipments.

5 Concluding Remarks

This study aims to investigate the effect of climate change on transportation flows and inland waterways in the Mississippi River Basin due to climate-induced shifts in crop production patterns in 2050 using two large scale modeling systems, an Agricultural Sector Model (ASM) and an International Grain Transportation Model (IGTM), with technical approach developed to link the two models. Simulated results from ASM show that 1) US and total social welfare rises; 2) crop producer welfare varies across US regions; 3) production and prices of all crops including corn and soybeans also varies; 4) National total cropland use increases with the

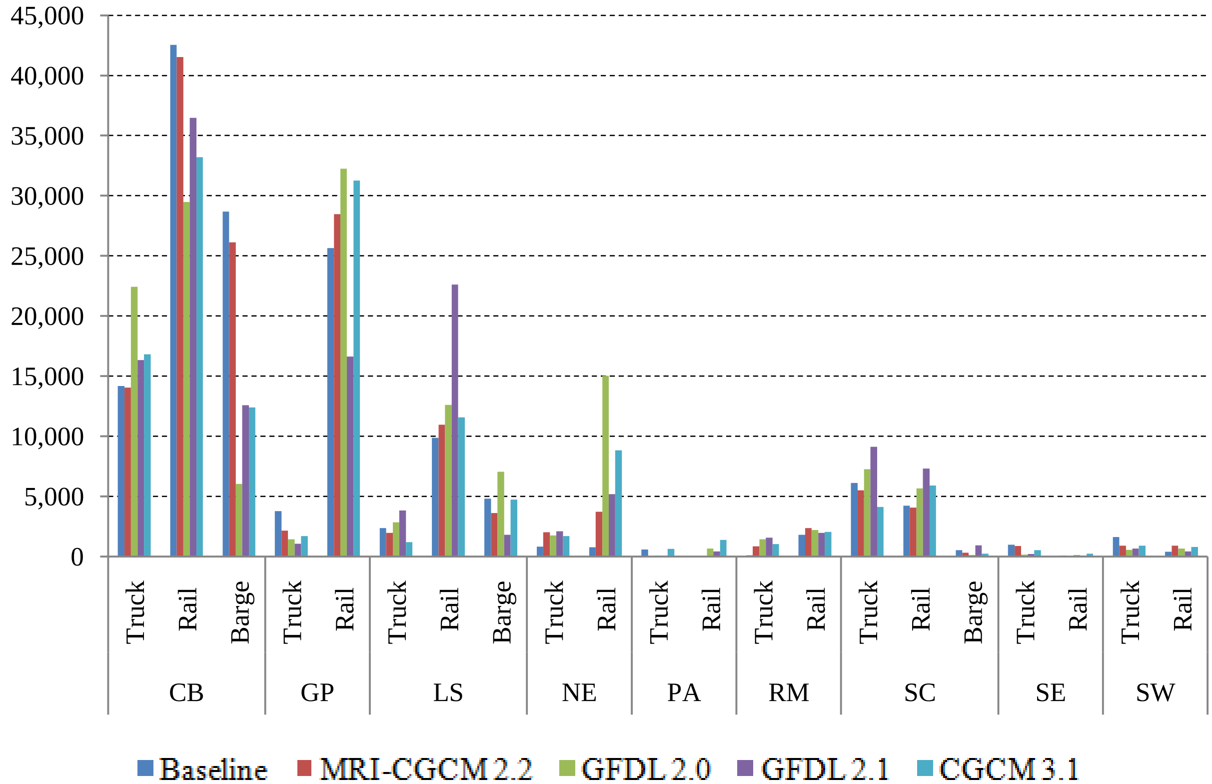

Figure 11. Supply shipments of corn (thousand tonnes) from regions classified by modes of transportation under climate change from GCMs in 2050 compared to the baseline

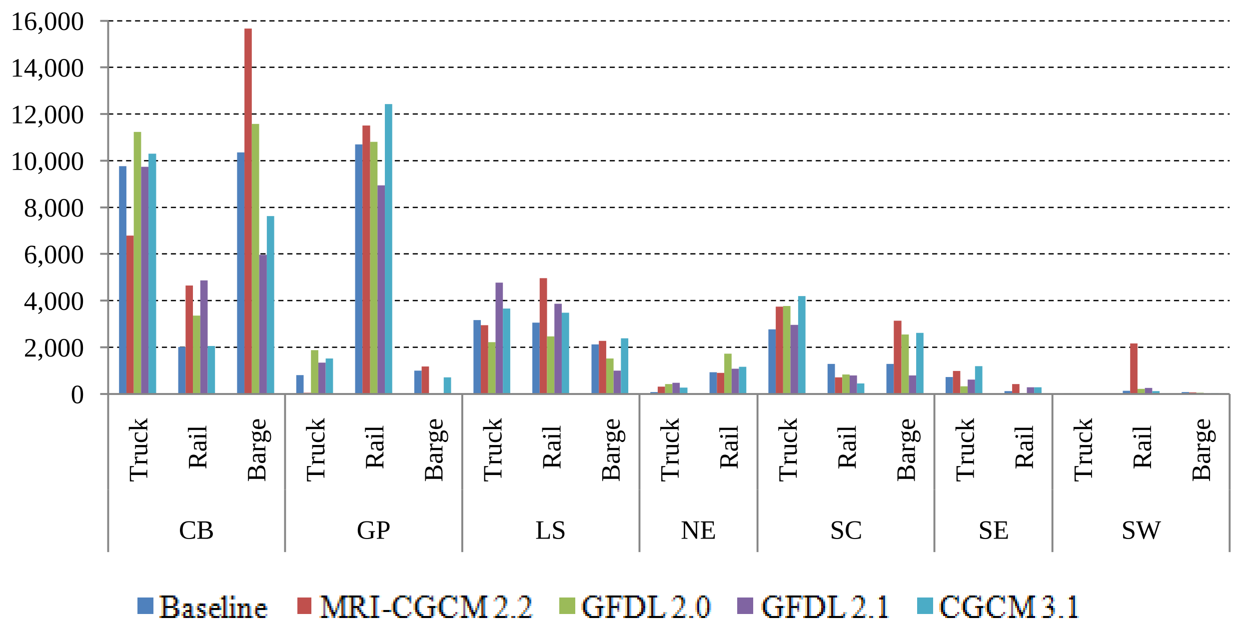

Figure 12. Supply shipments of soybeans (thousand tonnes) from regions classified by modes of transportation under climate change from GCMs in 2050 compared to the baseline

expansion of irrigated land and contraction of dryland. After breaking down crop acreage results of ASM to the county level and reaggregating to the crop reporting district (CRD) level, which is the spatial scale employed in IGTM. Our study finds that overall supply of corn and soybeans likely increases in the Northern part, while it tends to decline in some areas from Central to Southern part of the US. By subtracting demand for grains assumed to constant overtime with simulated supply of grains, we obtain the amount of excess supply and demand for grains, which are used as inputs in IGTM. Various interested findings from IGTM are revealed. For example, Corn Belt, the largest producer of corn in the US, is anticipated to ship less corn supply to Pacific, Northeast, Rocky Mountains, Southeast, and Mississippi Lower ports, while the Great Lakes ports, Lake States, and the Great Plains are expected to receive higher corn shipments from Corn Belt. For the aspect of export, the importance of Lower Mississippi ports, the largest destination for grain export from the US to the rest of the world, is going to diminish, where as the role of Pacific Northwest ports are simulated to increase. Considering overall demand for modes of transportation for total grain shipments, demand for rail and truck is expected to rise, while demand for barge mode is projected to drop.

Several clear policy implications arise:

- From ASM results, farm programs, disaster relief registration should be designed to assist producers in regions where their welfare losses are founded as reported in section 4.1 especially Southwest and the Great Plains regions. Moreover, adaptation plan such as providing knowledge to farmers and introduction of new crops that are suitable for specific areas under future climate should be prepared in advance.
- Our fine scale projected change in production patterns of corn and soybeans could be useful for private sector regarding to the future investment plan for the construction of biorefinery,

which need to build close to areas where the production of corn and soybeans are projected to increase to reduce feedstocks' transportation cost, which is the main factor in the production cost of bioenergy and hence increase in competitiveness of bioenergy products relative to tradition petroleum products.

- Storage capacity in areas where the production of grains is projected to increase may need expansion.
- Although overall the future demand for barge mode is likely to drop, some locks and dams (Lock and Dam No. 1 – No.8) in the Upper Mississippi River are likely to receive higher grain transportation shipments due to the predicted increase in the grain supply from the middle to northern parts of Minnesota and North Dakota under climate change. Therefore, enlarging or improving conditions of these locks and dams might be appropriated to speed up passage of barge tows and increase the barge efficiency, which could increase the competitiveness of US grain for export[15].
- Due to the projected increase in overall demand for rail mode, many rail infrastructures may need to be upgrade and expand along routes that are simulated to have new or higher levels of grain transportation flows such as routes from Minnesota and North Dakota to ports in Pacific Northwest and the Great Lakes; North Dakota to Texas; and New York and Pennsylvania to North Carolina. To collect grain from rural farmlands to grain elevators, upgrading short line rail track beds and bride structure could be implemented[16]. To increase the speed of the shipments and their reliability, expanding mainline rail track to double or even triple tracking, and increasing the number of sidings should be taken into the consideration of transportation planners[17].

- Like rail, truck is also a mode that is projected to receive increasing grain transportation flows. Road infrastructure may be needed to be expanded and upgraded to accommodate the heavy future truck traffic from areas that grain supply are expected to increase to nearby excess demand locations and ports. Rural areas along the Ohio River and Arkansas River toward nearby barge locations shipped to the Lower Mississippi ports; northern parts of Ohio toward the Great Lakes ports at Toledo; Ohio, Pennsylvania, and New York toward Atlantic Ports at Norfolk (VA) are some of examples. Finally due to a multifaceted system of grain supply chain, improving intermodal connectors which are the truck routes connecting highways with ports and rail terminals might be suitable in those areas.

Appendix

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 (IllinoisN, IllinoisS, IndianaN, IndianaS, IowaW, IowaCent, IowaNE, IowaS, OhioNW, OhioS, OhioNE)
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 but 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 (CaliforniaN, CaliforniaS)
Pacific Northwest (PNW)	Oregon and Washington, east of the Cascade mountain range

Source: Adam et al. (2005)

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[1] In 1990, roughly 60 percent of the crop land 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. From 1990 to 2009, wheat acres have reduced from roughly 60 percent of the cropland in North Dakota to 45 percent, while corn acres have increased from 5 to 10 percent of cropland and soybean acres have risen from 2 to 20 percent of crop land in North Dakota (Upper Great Plains Transportation Institute 2011).

[2] Their studied crops are barley, corn, cotton, forage production, oats, peanuts, potatoes, rice, rye, sorghum, soybeans, sugarbeets, tomatoes, and wheat.

[3] It is common practice in climate change analysis to use several GCM projections to reflect the uncertainty inherent in such projections.

[4] Scenario A1B most closely reproduces the actual emissions trajectories during the period since the SRES scenarios were completed (2000-2008). It is reasonable to focus on A1B scenario group versus those in the B1 and B2 scenario groups that have lower emissions projections because in recent years actual emissions have been above the A1B scenario projections. At the same time, there has been considerable interest and policy development to encourage non-fossil fuel energy, which is consistent with the A1B scenario vs. A1F1 or A2 that assume a heavier future reliance on fossil fuels (Beach et al. 2009).

[5] Development of a crop reporting district (CRD)-level counterpart to the ASM crop mix would not be necessary if we 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. Thus, we run ASM at a more aggregate level and reduce the solution crop mixes to the county level and then we reaggregate to CRDs.

[6] 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.

[7] Data used in Atwood et.al (2000)'s model is from 1970-1992.

[8] Demand for grains in the IGTM is estimated using 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 (please see more details in Zafar et al. 2011).

[9] The ASM employs year 2005 in the base scenario (ASM is the five-year period model.), while IGTM utilized 2007/2008 marketing year in the base scenario.

[10] This assumption may not be true in the reality. However, the main focus of this study is to predict the effect of climate change on supply side of grain. Consideration of the future grain demand is outside the scope of this study.
[11] Due to the baseline scenario used in ASM and IGTM is different, we adjust ASM baseline scenario (2005) to baseline scenario set in IGTM (2007/2008 marketing year) by assuming that the change in patterns of grain supply under climate change in IGTM follows ASM results.
[12] The difference between 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.
[13] Due to the low volume of grain shipments from Pacific Southwest and Pacific Northwest to all excess demand locations, we merge these two regions and call them as "Pacific" region.
[14] In general, truck have an advantage in moving grains over shorter distances, while rail and barge favor hauling large volumes of grains long distances.
[15] Almost all of locks on the Upper Mississippi River were built between 1930 and 1950, which have standard tows around 600 feet. 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).
[16] 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 that route. Before abandonment, the main line railroad typically deferred maintenance on these sections of track. Most importantly and currently, the main line railroads utilize the larger 286,000 pound railcars (Frittelli 2005). Therefore, track beds and bridge structures of these short line railroads cannot support these heavier cars.
[17] A majority of the main line network is single tracked. Currently, railroad main lines (Class I) are experiencing high track utilization rates. Some studies reveal that the privately financed Class I freight railroads are failing to keep pace with the growth in demand for freight transportation capacity (Frittelli 2005).