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The United States is a global grain supplier. Agriculture uses 22 percent of all U.S. transported tonnage with grain being the largest component[1]. Crop mix shifts are an often cited consequence of climate change[2,3,4] and such shifts may change the demands grain places on the transport system. Studies also find that climate change could decrease Great Lakes water levels[5,6,7,8], shorten the duration of ice cover in the winter[9,10,11], and alter grain supplies in grain exporting countries[12]. This study investigates the effects of such phenomena on U.S. grain transportation movements both in volumes and modes. Specifically we examine the effects of possible shifts in: crop production patterns; Great Lakes water levels; winter navigation possibilities; and foreign grain production. We find that crop mix shifts reduce the importance of Lower Mississippi River (LMR) ports, but increase the role of Pacific Northwest ports, Great Lakes ports, and Atlantic ports. We also find a shift from barge to rail and truck transport. Conversely, a longer navigation season or a reduction in Great Lake water levels increases grain shipments to the LMR ports. Higher use of Great Lakes ports occurs under a reduction of grain production in European exporting countries that compete with Great Lakes ports.

The U.S. is a global grain supplier and a major user of transportation services. Climate change may relocate grain production thus altering transportation demand. Several studies indicate that climate change tends to shift U.S. grain production northward[2,3,4]. For example, ref 3 finds higher soybean production in the north and a drastic reduction in the south with a reduction in yield of as much as 70 percent. Additionally, northward shifts have already been observed. For example between 1990 and 2009, North Dakota wheat acres have fallen from 60 to 45 percent of cropland, while corn acres have increased from 5 to 10 percent and soybean acres have increased from 2 to 20 percent[13]. Such developments alter regional grain production volume and transport demand since corn yields are about four times greater than wheat[14]. Studies also suggest climate change will cause: a) drops in Great Lakes water levels[5,6,7,8]; b) shorter durations of ice cover extending the navigation season[9,10,11]; and c) altered production in grain exporting countries[12].

Such potential changes raise questions regarding transportation needs. Several studies[15,16,17] analyze how transportation usage would be affected by changes in weather and climate mainly in broad terms. However, we have not found broad-based, countrywide, agricultural studies focusing on transportation implications of the above mentioned phenomena and that is the focus of this study.

To investigate how climate change induced crop production shifts alter grain transportation demands, we first estimated crop mix shifts under different global circulation models (GCMs) and then the resultant implications for transport flows. The shifts in the location of crop production are examined using crop yield estimates under GCM based climate change scenarios and a land allocating agricultural sector model (ASM) that has been used in prior climate change studies such as refs 2, 3, and 18. Then the production shifts generated by ASM were downscaled to a county basis in a fashion consistent with historical crop mixes and climate change following the basic procedure in refs 3 and 19. We find that, under climate change in all GCM based yield scenarios, overall production of corn and soybeans increases in Northern regions and declines in Southern regions. These findings are consistent with findings in refs 2, 3, and 4. These data were then converted to estimates of excess demand and supply by crop reporting district (CRD) using the downscaled production minus regional consumption. The resultant shifts in excess supply/demand by scenario are shown in Figures 1 and 2. These results show that projected climate changes cause regional shifts in the excess supply and demand for corn and soybeans with more northern regions tending toward increases in excess supply. We subsequently used an international grain transportation model (IGTM) to see the effect on grain transportation flows. IGTM operates in the U.S. at the CRD level and is an extended version of the model in ref 20 (see more details in the Methods Section and the explanations of ASM, IGTM, and the downscaling model in Supplementary Sections S1, S2, and S3, respectively).

Tables 1 and 2 summarize the effects of climate-induced shifts in crop mix on simulated interregional transportation flows of corn and soybeans by climate scenario. Results of the Corn Belt, Lake States and Great Plains are presented here (Supplementary Table S3 covers other regions). The main results are that crop production effects stimulate farmer adaptation, in the form of changes in crop mixes and crop location, and that this causes altered supply and in turn less barge usage as the subsequent supply is less proximate to the river with more grain going east and west via rail. The Corn Belt, the dominant production region, ships less corn under all GCM crop yield (GCMCY) scenarios ranging from 4-32 percent less (Table 1). Reasons are that total supply is reduced and more grain is used locally, leading to reduced export. The Great Plains increases overall corn shipments under three of the four GCMCY scenarios largely to the Pacific region and Canada. This involves increased corn supplies in the Dakotas due to the northward crop mix migration. The Lake States, currently the third largest corn shipping region, shows expanded corn shipments under three of the four GCMCY scenarios again reflecting northward crop mix migration.

For soybeans (Table 2), the results show shipment alterations but not ones as large as for corn. For example, soybean flows from the Great Plains to Pacific Northwest ports increase by as much as 21 percent while flow declines in Corn Belt shipments to the south-central region by as much as 66%. We also find growing importance for Great Lakes and Atlantic ports, plus for interior locations shipping overland to Mexico.

There is disagreement in the results across the GCMCY scenarios for a number of flows including flow of corn from Corn Belt to the Great Plains and Southwest; and flow of soybeans from the Corn Belt to itself, the LMR ports and Atlantic ports.

Collectively the results also indicate shifts in mode usage. Usage of barge transportation of corn declines under all GCMCY scenarios of 11-55 percent because of reduced excess supplies in the Corn Belt and southern Minnesota. However, barge shipments of soybeans remain relatively stable (Supplementary Figure S1). Railroad usage increases ranging from 8-14 percent due to the more northward shifts in crop mix and a reduction in proximity to the river system. Truck transport increases in three of the four GCMCY scenarios ranging from 6-34 percent.

In addition to the effects of crop production shifts, we also investigated the effects of a longer navigation season, lower Great Lakes levels and altered international competition. All of these were investigated in terms of their impact relative to grain transport under the GCMCY scenarios with crop mix shifts.

Rising temperatures are projected to reduce ice cover duration in the Upper Mississippi River (UMR) and the Great Lakes, extending the navigation season. To reflect this, the IGTM was modified to allow expanded capacity in the winter quarter along the UMR above St. Louis (MO) and in the Great Lakes. The results show a small impact on transportation flows primarily with lower shipments from the Corn Belt to the LWR ports (as much as a 4 percent reduction) but with a substantial increase in shipments from the Lake States (19-86 percent). On net we find greater shipment volumes to the LMR and Great Lakes ports, while other ports receive lower grain shipments. The seasonality of transportation flows is also affected with increasing winter quarter flows (2-15 percent) and decreasing fall (1-3 percent) and spring quarter (27-84 percent) flows. Finally, truck transport increases (1-4 percent), while usage of other modes varies ranging from -3-0.3 percent for rail and -4-4 percent for truck (see details in Supplementary Table S4 and Figure S2).

Several studies suggest that climate change would reduce Great Lakes water levels, thus potentially increasing shipment costs[21]. We examined 5, 10, and 20 percent increases in waterborne shipping costs. The results show reduced shipments to Great Lakes ports under all scenarios ranging from 4-45, 7-73 and 32-92 percent for the 5, 10 and 20 percent cases, respectively. At the same time, all scenarios reflect higher grain shipments to LMR ports (up to 3 percent) and to Atlantic ports (up to a 49 percent increase). Overall, the higher the shipping costs increase, the greater the usage of rail and barge (up to 1 and 3 percent, respectively) and the lower the usage of trucks (up to 5 percent). Seasonality of movements is unaffected (see details in Supplementary Tables S5 and Figures S3).

One possible consequence of climate change is reduced grain production in many world regions due to stronger drought conditions[22]. Among the countries that could be affected are Ukraine, Serbia, Moldova, and Kazakhstan and these countries compete with the Great Lakes ports for exports[12]. We examined 10, 30, and 50 percent reductions in exports from those countries. The result is higher grain shipments mostly for corn to the Great Lakes, Texas Gulf, and LMR ports. For example, Texas Gulf ports are forecasted to receive higher grain flows under all GCMCY scenarios (ranging from 0.1-3.7 and 0.4-12.7 percent for the 10 and 50 percent reductions, respectively). The usage of barge and rail use also increases ranging from

0.3-3.6 and 0.1-0.4 percent, respectively. Seasonality is largely unaffected (see details in Supplementary Tables S6 and Figures S4).

Climate change is likely to influence U.S. crop mix and interregional transportation flows and mode usage. Several clear implications arise from the analysis.

- The LMR ports are likely to receive reduced grain shipments due to the northward shift in grain supply with lower supplies along the river. Therefore, investment appraisals in grain storage facilities, locks and dams might carefully consider climate change effects.
- The UMR is likely to receive higher grain transportation shipments due to the predicted increase in grain supply from Minnesota and North Dakota. Enlarging or improving conditions of UMR locks and dams might be appropriate.
- The increase in overall rail usage, especially out of the northern regions, indicates northern rail capacity may need to be upgraded. 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.
- The northern grain volume expansions suggest a possible need to add grain elevators, mainline rail tracks, sidings, and short line rail track beds plus roads as discussed next.
- Trucks are likely to receive increasing grain transportation flows in northern regions. Regionally road infrastructure may need to be expanded and upgraded to accommodate heavier future truck traffic. Places where this is likely needed include:
    - roads in rural areas along the UMR in Minnesota, the Ohio River, the Arkansas River, and the LMR in Kentucky;
    - roads in northern parts of Ohio leading toward ports on Lake Erie;

  - roads in Ohio, Pennsylvania, and New York leading to Atlantic Ports at Norfolk, Virginia.
- Finally, improving intermodal connectors such as truck routes connecting highways with ports and rail terminals might be desirable particularly in the northern areas.

Methods

Shifts in crop mix and production were estimated using a sector model run under climate change shifted crop yields (see details regarding yield effects across GCM scenarios in Supplementary Figures S5 and S6 for corn and soybeans, respectively). Those results were then downscaled to counties and re-aggregated to CRDs. Finally implications for transport flows were evaluated using a grain transport model as were the scenarios on changes in navigation conditions and international competition.

The sector model projected changes in crop mix and production given climate affected yields. The model used was the U.S. agricultural sector model (ASM) as used in prior climate change studies[2, 3, 18]. The model structure and documentation are summarized in Supplemental Section S1 (and detailed in ref 23). ASM solutions give a spatial pattern of land use, crop management, production and market prices. The model is run under baseline "no climate change" and climate change cases. The climate change effects included were effects on crop yields plus the effects on pesticide costs, livestock productivity, irrigation water use, and water supply following the basic procedure in ref 23 as explained in Supplementary Section S1.

The ASM gives production levels for 63 regions and needed to be downscaled for use in the 303 region grain transportation model. To do this, we followed the downscaling procedure developed in ref 19 coupled with possible northward crop mix migration (See Supplementary

Section S3 for more details). In turn the data were aggregated to the 303 CRDs to give regional shifts in total production.

Finally we used a detailed U.S. domestic-international grain transportation model (IGTM) to simulate the effects on transport flows. IGTM is an extended and updated version of the model in ref 20. It depicts U.S. domestic and world-trade transportation of corn and soybeans (commodities that account for 82% of U.S. grain transport and accounted for 4.2 percent of 2007 total transport tonnage and 6.6 percent of ton-miles[24]). The model structure and documentation are summarized in Supplemental Section S2. The model is solved with and without the GCMCY induced crop mix-production shifts.

We used crop yield sensitivity data from ref 25 that were based on climate change scenarios from the 2007 IPCC report under the A1B SRES scenario. The underlying GCMs were GFDL-CM 2.0; GFDL-CM 2.1, MRI-CGCM 2.2, and CGCM 3.1. A1B is a scenario that moves away from fossil fuel reliance with lower emissions than today's levels but less reduction than in the more optimistic B1 and B2 scenarios. We also note that for our time frame (2050) the choice of SRES scenarios does not make much difference as emissions and climate change implications of different SRES scenarios do not diverge significantly. The GCMs were chosen by the authors of ref 25 who argue they represent a broad spectrum of cases with: a) GFDL-CM 2.0 projecting reduced precipitation and the largest temperature increase; b) MRI-CGCM 2.2 predicting the smallest temperature increase and the largest precipitation increase; c) GFDL-CM 2.1 having a smaller temperature increase than GFDL-CM 2.0, but a more severe precipitation reduction; and d) CGCM 3.1 results tending to fall in the middle of the other GCMs.

To examine the other climate phenomena we use the IGTM with the climate induced excess supply/demand shifts as the baseline. To reflect shortened duration of ice cover, we first allow grain shipments during the winter season along the UMR above St. Louis and in the Great Lakes where such shipments were precluded in the base analysis. To reflect a reduction of Great Lakes water levels, we increased all lake based shipping costs by 5, 10, and 20 percent based on ref 21. To reflect climate change in competitor regions, we reduced excess supplies in Ukraine, Serbia, Moldova, and Kazakhstan, countries that compete with the Great Lakes ports for exports[12]. The IGTM model was used to examine 10, 30, and 50 percent reductions in exports from those countries by decreasing their excess supplies by 10, 30, and 50 percent following arguments in ref 22.

Finally, we note the limitations of this study. First, the ASM used in this study is a deterministic model, which does not fully account for shifts in production due to altered extreme events frequency and altered weather uncertainty. More complicated (nonlinear) functional forms of supply and demand functions can be used in future research to better reflect the dependencies between extreme weather and weather uncertainty and agricultural production (e.g. water-dependent yield functions). Next, the base analysis holds constant the production patterns in countries other than the U.S. Simultaneously, the spatial scale and detail in international countries does not match that of the U.S. and could be disaggregated. Lastly, we only model corn and soybeans in IGTM and other commodities like wheat and possibly sorghum could be included.

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Additional information

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Author contributions

W.A. collected the data set, developed the modified Atwood et al.'s model and the IGTM, carried out the estimations and analyses for the entire paper. B.A.M. provided the conceptual ideas, analyses and recommendations for the entire paper. Z.A collected the data set for the IGTM. S.W.F. provided the conceptual ideas, analyses and recommendations in the IGTM. D.V.V. provided the conceptual ideas. All authors contributed to writing the manuscript.

Competing financial interests

The authors declare no competing financial interests.

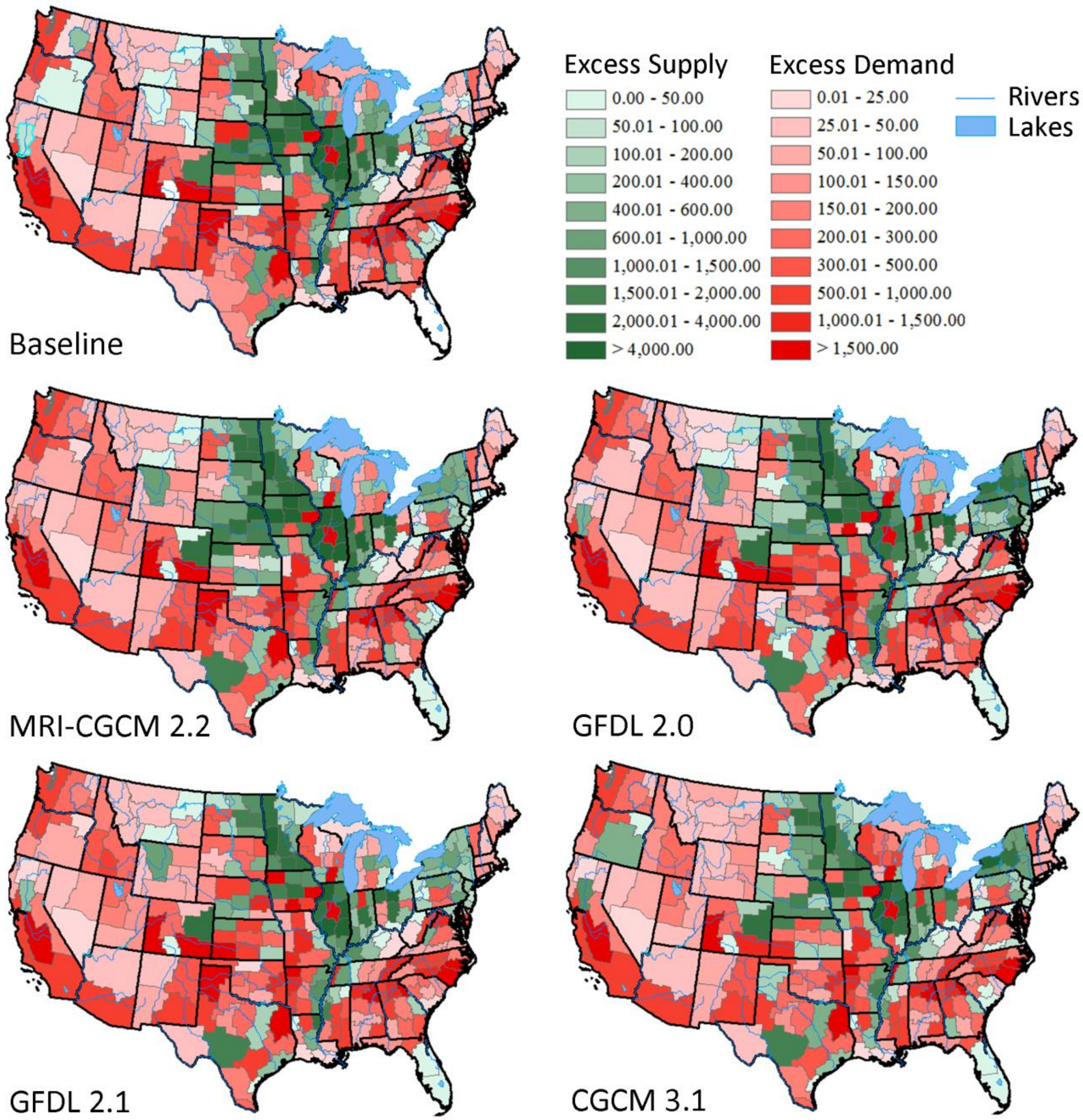

Figure 1 Excess supply and demand for corn for the baseline and under different GCM scenarios. Quantities are in 1,000 metric tons. The baseline data are from the 2007/2008 marketing year. The projected agricultural data reflect GCM scenarios for 2050.

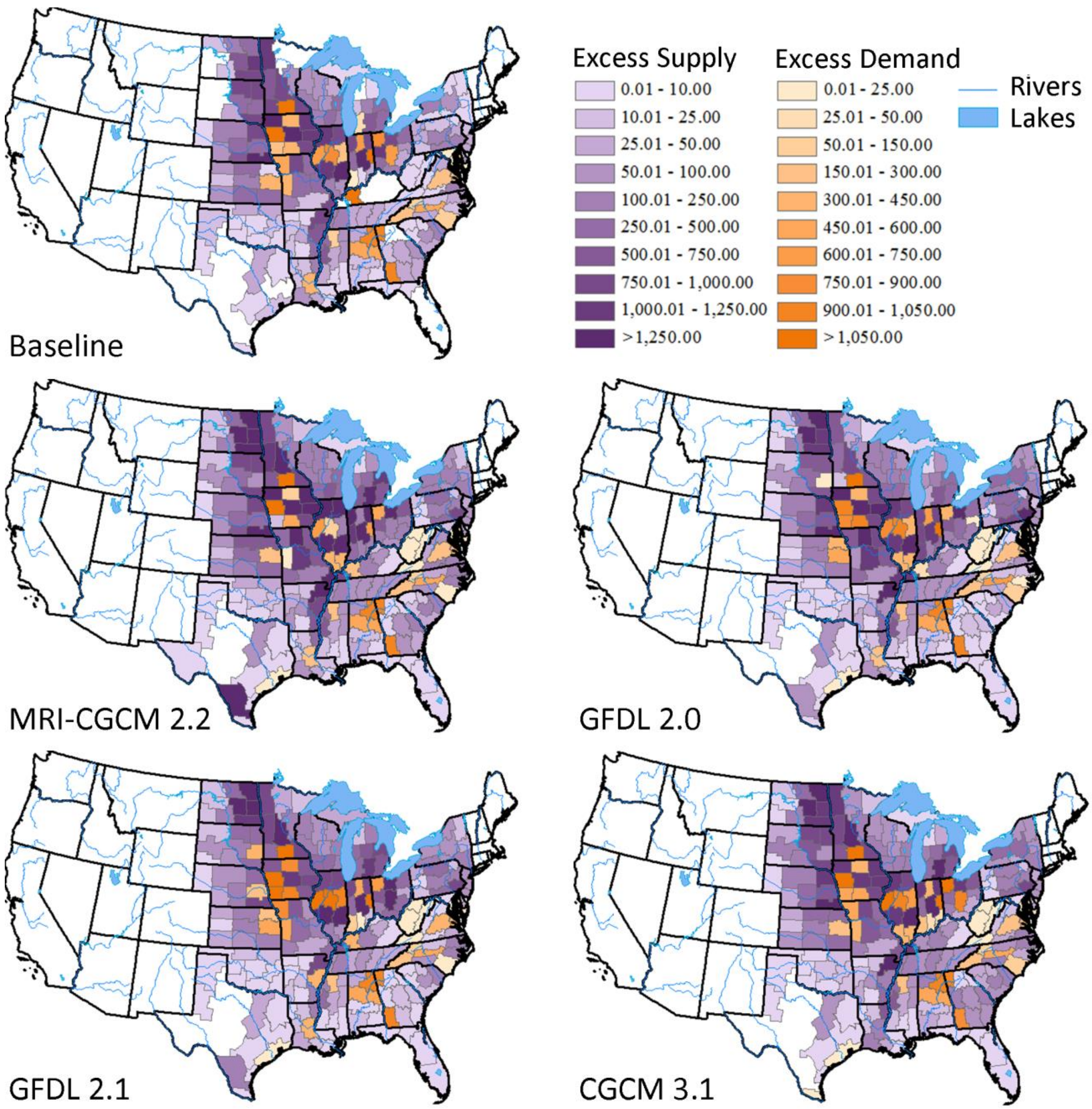

Figure2 Excess supply and demand for soybeans for the baseline and under different GCM scenarios. Quantities are in 1,000 metric tons. The baseline data are from the 2007/2008 marketing year. The projected agricultural data reflect GCM scenarios for 2050.

Table 1 Estimated percent change in transportation flows of corn from selected regions due to climate-induced shifts in crop production patterns.

Source	Destination	MRI–CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	-2	70	47	49
	Great Plains	-85	124	63	-51
	Lake States	100	465	-100	6,772
	Pacific	0	-100	-100	-81
	Northeast	-31	-75	-77	-45
	Rocky MT	-27	-99	-40	-57
	Southeast	-12	-47	-26	-41
	South-Central	23	-21	-31	-19
	Southwest	3	-16	43	-19
	LMR Ports	-10	-77	-56	-49
	PNW Ports	448	-100	-100	-100
	Great Lakes Ports	187	389	315	-17
	Atlantic Ports	—	—	724[a]	—
	Interior, Mexico	—	—	1,031[a]	—
	All Regions	-4	-32	-23	-27
Great Plains	Corn Belt	44[a]	—	—	589[a]
	Great Plains	-55	-29	-47	-24
	Pacific	103	304	11	183
	Rocky MT	9	-31	-87	-28
	South-Central	469[a]	—	—	—
	Southwest	-45	-80	-50	-66
	Texas Gulf Ports	—	2,437[a]	—	1,735[a]
	PNW Ports	19	43	-24	47
	Interior, Mexico	11	-13	-63	-23
	Interior, Canada	312	546	522	539
	All Regions	3	15	-40	12
Lake States	Corn Belt	-89	-100	46	-100
	Great Plains	-6	-100	966	-45
	Lake States	60	94	45	104
	Pacific	-3	4	281	-15
	Northeast	-100	-100	-100	-100
	Rocky MT	-30	26	54	-7
	Southeast	-69	-100	44	-100
	South-Central	2	56	-100	53
	Southwest	—	943[a]	2,555[a]	—
	LMR Ports	-33	52	-68	5
	PNW Ports	277	340	388	219
	Great Lakes Ports	72	56	0	68
	Atlantic Ports	-91	-100	-87	-100
	Interior, Mexico	—	—	171[a]	—
	Interior, Canada	-61	-100	-100	-100
	All Regions	-3	32	66	3
All Regions	All Regions	0	0	-6	-6

Notes: [a]Because some quantities in the baseline are equal to zero, quantities are reported in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. PNW and LMR are the abbreviation of "Pacific Northwest" and "Lower Mississippi River", respectively. Small interregional transportation flows are not reported here.

Table 2 Estimated percent change in transportation flows of soybeans from selected regions due to climate-induced shifts in crop production patterns.

Source	Destination	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn Belt	Corn Belt	-30	-6	21	21
	Great Plains	0	271	0	0
	Lake States	183	335	-100	179
	Northeast	2[a]	1[a]	1[a]	2[a]
	Southeast	1,534	459	268	77
	South Central	-23	1	-47	-66
	LMR Ports	61	16	-34	-32
	Great Lakes Ports	174	134	195	-13
	Atlantic Ports	-100	154	24	-100
	Interior, Mexico	438[a]	0	0	0
	All Regions	24	18	-7	-10
Great Plains	Corn Belt	-96	22	-60	110
	Great Plains	-36	76	263	-11
	Pacific	44	106	67	72
	South Central	-29	-70	-100	-47
	Southwest	35	0	235	0
	LMR Ports	98	-98	-100	-15
	PNW Ports	8	14	-12	21
	Interior, Mexico	-7	1	-27	0
	All Regions	2	1	-19	17
Lake States	Corn Belt	13	-29	196	62
	Great Plains	0	0	102[a]	0
	Lake States	-5	-10	32	-24
	Southeast	-64	-20	-11	-45
	South Central	0	0	213[a]	0
	LMR Ports	-6	-33	-53	16
	PNW Ports	47	-63	-54	11
	Great Lakes Ports	186	19	-100	454
	Atlantic Ports	198	38	115	69
	Interior, Mexico	0	0	183[a]	0
	All Regions	22	-26	15	14
All Regions	All Regions	23	9	-6	8

Notes: [a]Because some quantities in the baseline are equal to zero, quantities are reported in 1,000 metric tons. The baseline scenario is the 2007/2008 marketing year. PNW and LMR are the abbreviation of "Pacific Northwest" and "Lower Mississippi River", respectively. Small interregional transportation flows are not reported here.