Kansas State University | Department of Agricultural Economics

Weather Extremes and Agricultural Exports in the U.S. Midwest: Evidence from Corn and Soybeans

Atif Rao and Nelson Villoria

Major Professor: Nelson Villoria

Aug 21, 2025
Manhattan, Kansas

Motivation

Global Leader in Exports
- USA is #1 in corn, #2 in soybeans exports volume (Beckman et al., 2023)

Export Volume
- **Corn**: 57.8 MMT for 2025/26
- **Soybeans**: 52.5 MMT for 2025/26(USDA FAS, 2025)

Midwest's Global Role
- Produces ⅓ of the world's corn and soybeans (FAO, 2017)

Climate Threat to Agriculture
- Climate change induces frequency and intensity of extreme weather events
- Risks to production volatility and its spillovers to trade (IPCC, 2022)

Literature and Research Gap

Production & Climate Change

- Warming significantly reduces U.S. crop yields and productivity (Schlenker & Roberts, 2009; Zhao et al., 2017; Tack et al., 2015; Hogan & Schlenker, 2024)

Trade and Climate Change

- Rising temperatures have significant negative impacts on agricultural exports (Nes et al., 2025; Jones and Olken 2010; Gassebner et al., 2010)
- Agricultural exports are sensitive to weather shocks (Cass, 2023; Zhang et al., 2014; Dallman, 2019)

Trade as Adaptation Mechanism

- Trade and production reallocation help mitigate climate-induced losses (Costinot et al., 2016; Gouel and Laborde, 2021; Baldos et al., 2019)

Literature and Research Gap

Research Gap

- Existing climate-trade research lacks granular, state-level analysis of climate impacts on agricultural exports
- The mechanisms linking climate-induced production shocks to export fluctuations, particularly in terms of region-specific vulnerabilities at the subnational level, remain underexplored

Significance of the Study

1. **Spatially Disaggregated Impact Analysis**
   – This study offers the first systematic, state-level empirical analysis that quantifies what climate-induced production shocks, as driven by weather extremes and precipitation variability, affect agricultural trade.

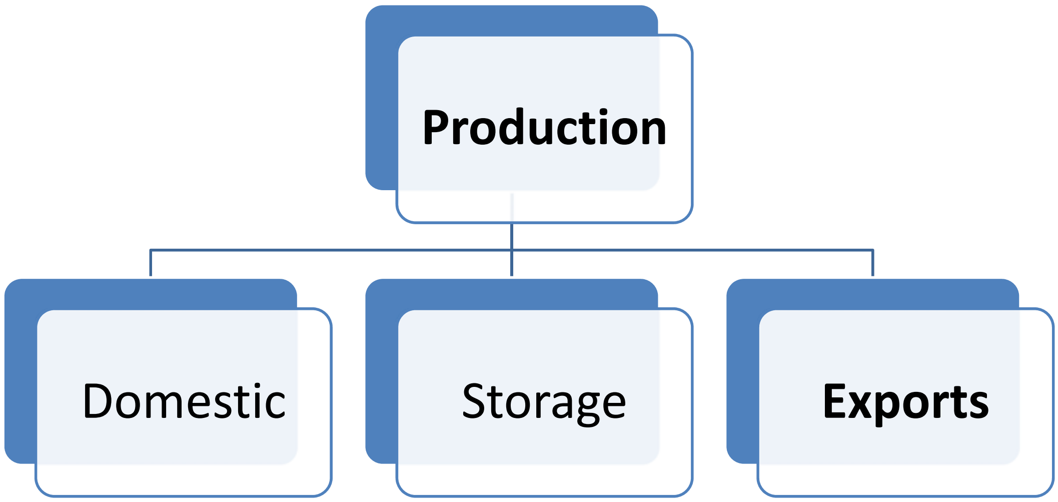
2. **Quantifying Exports Portion of Production Shock**
   – We rigorously assess the role of exports as an adjustment mechanism by quantifying the proportion of production shock absorbed by exports at state level.

3. **Long-Horizon Climate Projections**
   – By incorporating long-horizon climate projections (2023–2100) from an ensemble of CMIP6 models under SSP2-4.5 and SSP5-8.5, we assess the future subnational vulnerability and absorption capacity of agricultural exports to climate change.

Shared Socioeconomic Pathways (SSPs)

1. **SSPs Definitions**
   – SSPs were developed by the climate research community describing how global society and the economy might evolve in the coming decades. They are a crucial component of climate modeling, as they represent different assumptions about future population, economic growth, technology, and policy..
2. **SSP245**
   – This is a "Sustainability" pathway. It represents a future where the world shifts toward sustainable development, with high technological innovation, low population growth, and a focus on environmental policies. This scenario leads to a moderate level of climate change.
3. **SSPs585**
   – This is a "Fossil-fueled Development" pathway. It represents a future with a return to fossil fuels, slow technological progress in energy, and a lack of international cooperation on climate policy. This leads to a high level of climate change.

Conceptual Background



6

Research Question

1. What is the impact of temperature extremes and precipitation variability on corn and soybean export performance in the U.S. Midwest?
2. Do exports function as an adjustment mechanism to absorb production shocks resulting from weather extremes for corn and soybeans?
3. What is the potential future impacts of climate change on corn and soybean exports under projected SSP scenarios 245 and 585?

7

Temperature and Production

1. This research uses a specific model to measure how temperature affects crop production and exports. It's not just about a simple average temperature; it's about the timing and intensity of heat.
2. The core idea is that crops are non-linear in their response to temperature. They don't just get slightly worse as it gets hotter; they thrive in an optimal range and then suffer dramatic losses once a certain temperature threshold (like 30∘C) is crossed.
3. Temperature Bins
   1. Growing Degree Days (0–29∘C):
   2. Heating Degree Days (29-44)

Descriptive Statistics

Descriptive Statistics of **Weather Variables**

Variable	Obs	Mean	Std. dev.	Min	Max
tMin	1,056,234,698	2.86	11.40	-43.92	31.16
tMax	1,056,234,698	15.29	12.52	-31.75	46.59
Prec	1,056,234,698	2.15	5.37	0	230.64

(PRISM 2000-2022)

Descriptive Statistics of **Independent Variables**

Variable	Obs	Mean	Std. dev.	Min	Max
GDD	276	3500.87	427.75	2721.87	4429.08
HDD	276	40.97	38.28	1.08	207.36
Prec	276	2.79	.708	1.16	5.22
Freezing	276	16.04	9.16	1.72	47.17

- **Temperature Exposure Bins**
  - Daily tMin and tMax data were interpolated into 1°C bins from 0°C to 44°C, following Schlenker & Roberts (2009)
- **GDD and HDD**
  - GDD and HDD were computed using 0–28°C and >28°C thresholds during the March–September growing season (Yu et al., 2021)
  - Aggregated at the state-year level
- **Additional Weather Metrics**
  - Annual precipitation and freezing days were aggregated at the state and year level

Descriptive Statistics

Descriptive Statistics of **Dependent Variables**

Variable	Obs	Mean	Std. dev.	Min	Max
Corn Yield	276	151.94	26.25	75	214
Corn Exports	276	661.20	595.43	36.97	3302.09
Corn Production	276	3.55e+09	3.13e+09	1.52e+08	1.64e+10
Soybean Yield	276	43.94384	8.868818	20	65
Soybean Exports	276	1141.91	909.25	70.33	5506.14
Soybean Production	276	2.42e+08	1.45e+08	4.68e+07	6.83e+08

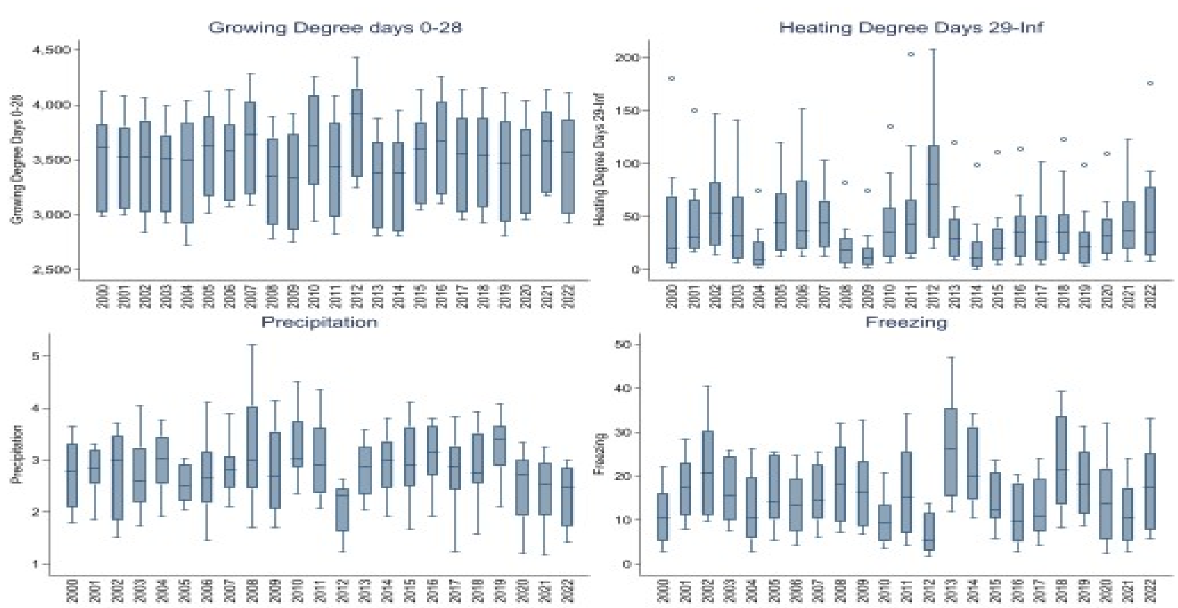
Descriptive Statistics of **Weather Variables**

Variable	Obs	Mean	Std. dev.	Min	Max
tMin	17,593,368	16.84	9.78	-33.96	37.13
tMax	17,593,368	27.77	10.86	-25.54	53.35
Prec	17,593,368	2.21	5.28	0	208.6724

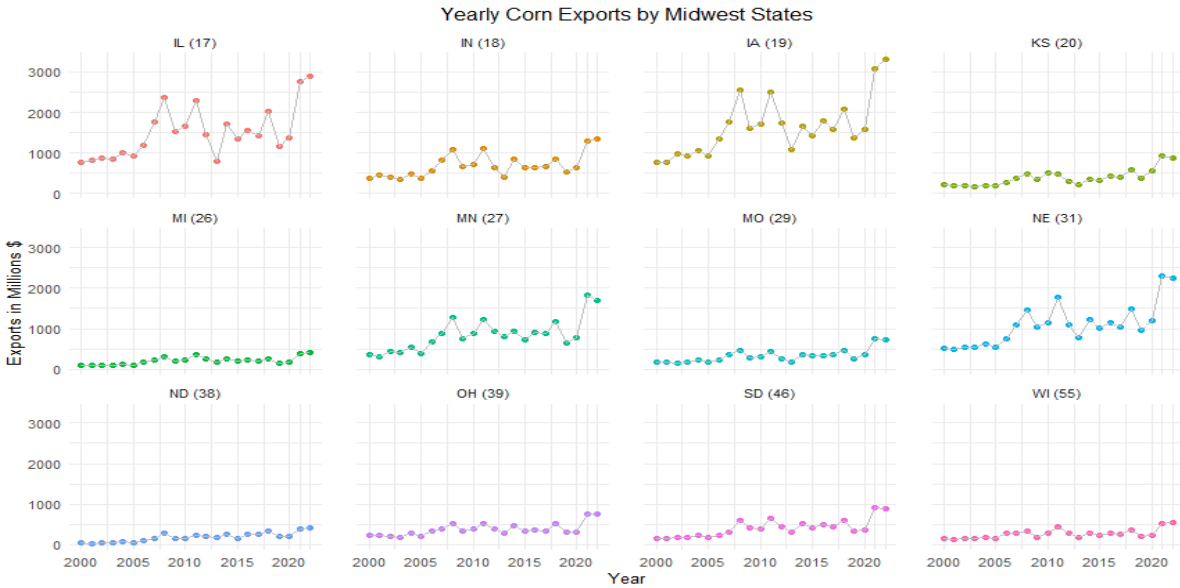
(CMIP6 GCMs (NorESM2-MM) 2023-2100)

- **Dependent Variables**
  - Corn/Soybean Yield: yield busher per Acre
  - Corn/Soybean Exports: Volume of crop (in millions $)
  - Corn/Soybean Production: Total crop Production (in $)
- **Weather Variables**
  - Daily tMin and tMax and Prec values from CMIP6 (NorESM2-MM) model
  - Use the same procedure to calculate GDD and HDD for these variables

Annual Distribution of Weather Variables

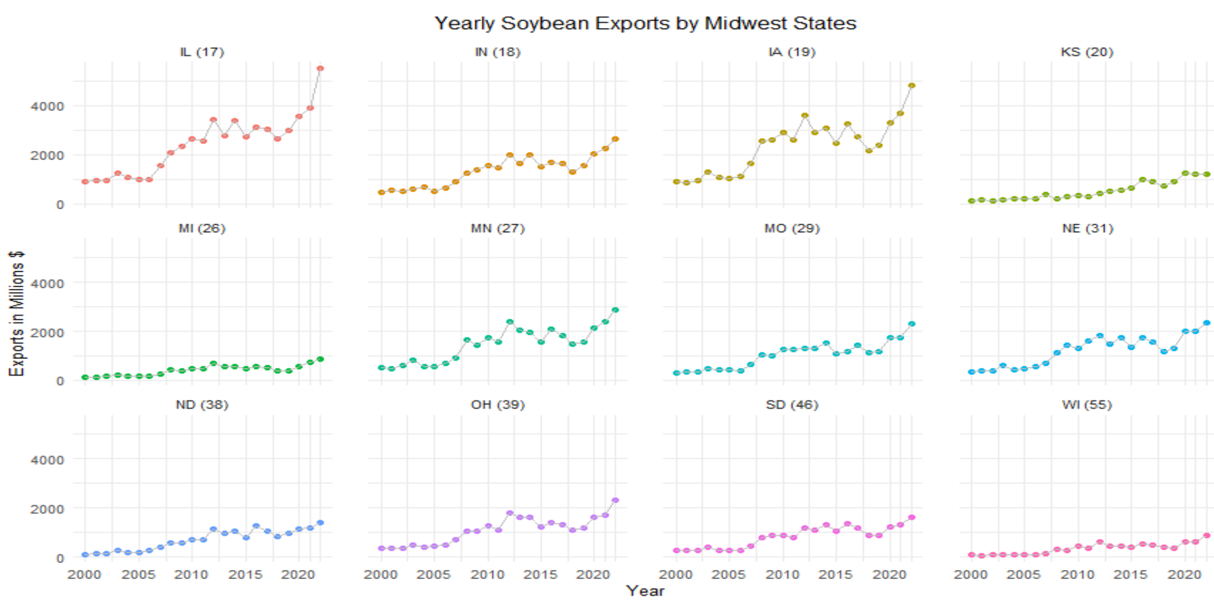


State level Corn Exports



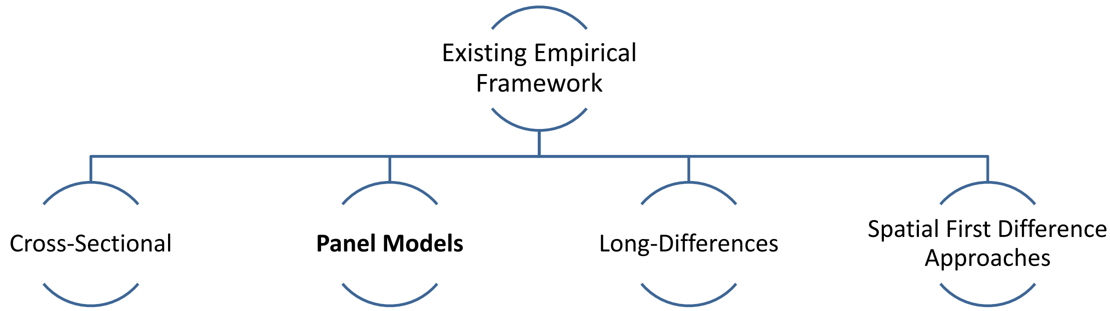
11

State level Soybean Exports



12

Methodology



13

Source: (Hsiang, 2016; Auffhammer, 2022; Kolstad & Moore, 2020; Druckenmiller & Hsiang, 2018

Methodology

- **Study Empirical Framework**

1. We measure how warmer, hotter, or wetter seasons affect corn and soy production, and exports, while holding constant other state and year differences.
2. Climate Drivers
   - Growing Degree Days (0–28°C): helps growth
   - Heating Degree Days (>28°C): harms crops
   - Precipitation: water availability
3. Controls & Fixed Effects:
   - Freezing days, state-specific trends
   - State effects → permanent state differences
   - Year effects → national/global shocks

15

Methodology

- **Study Empirical Framework**
  - Builds on panel data methods from (Deschênes & Greenstone, 2007; Schlenker & Roberts, 2009; Hogan & Schlenker, 2024) to capture climate impacts on economic outcomes.
  - Uses a fixed-effects panel model with exposure metrics (GDD, HDD), following Yu et al. (2021), to isolate the effect of temperature and precipitation variability on state-level exports.

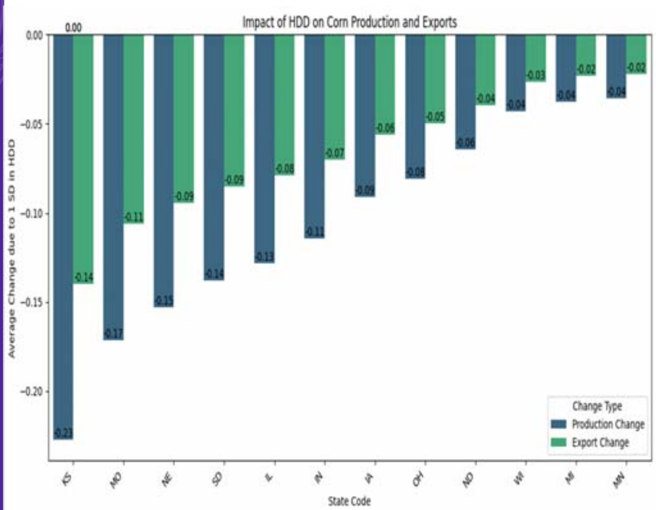
Methodology

Two-Way Fixed Effects (TWFE) Model

- Controls for state and year fixed effects to handle unobserved heterogeneity and common temporal shocks (Hogan & Schlenker, 2024)
- This framework accommodates nonlinear weather effects (Schlenker & Roberts, 2009) and allows for spatiotemporal heterogeneity (Carleton et al., 2022)

State Level Impact of HDD on Production and Exports (2000-22)

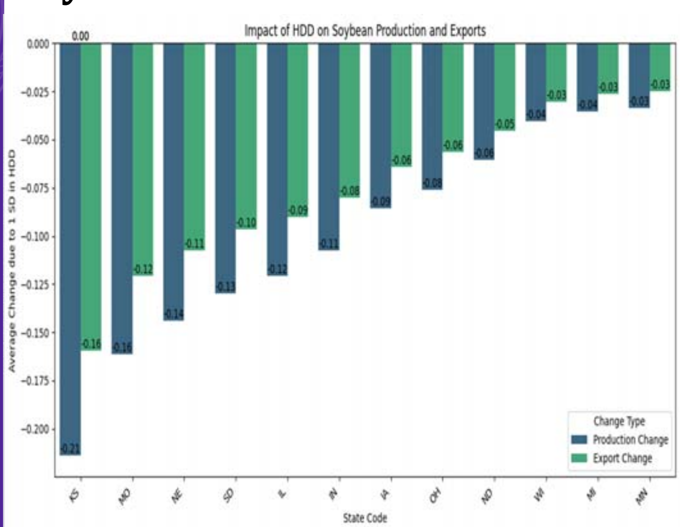
Corn



- **HDD impact corn**
  - HDD reduce both corn production and exports
- **Exports bear larger shock**
  - When production drops, the states exports market absorbs a larger portion of the production loss
  - Reflects a limited domestic buffering capacity
- **State Specific Impacts**
  - Significant variation across states
  - Hotter states such as KS, MO and NE are hit much harder than others

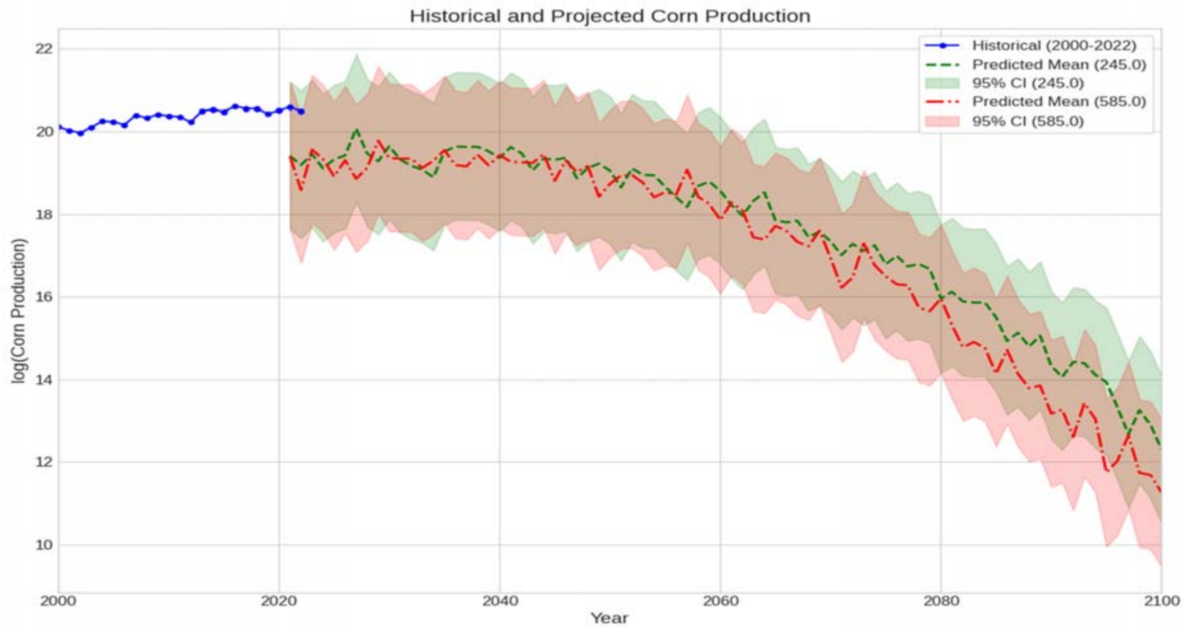
State Level Impact of HDD on Production and Exports (2000-22)

Soybean



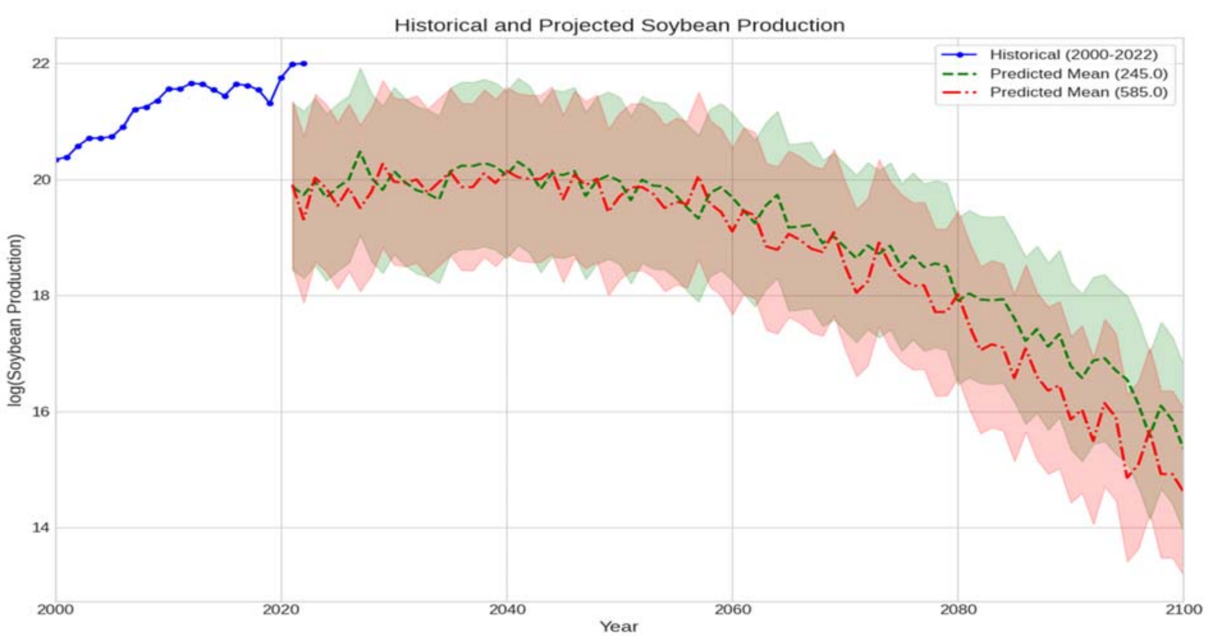
- **HDD impact soybean**
  - HDD reduce both corn production and exports
- **Exports bear larger shock**
  - Soybean export market absorbs a proportionally larger share of the production shortfall
  - Reflects a weaker domestic buffering capacity.
- **State Specific Impacts**
  - Differential vulnerability across states.
  - Hotter states such as KS, MO and NE are hit much harder than others

Historical and Future Corn Production from 2000-2100



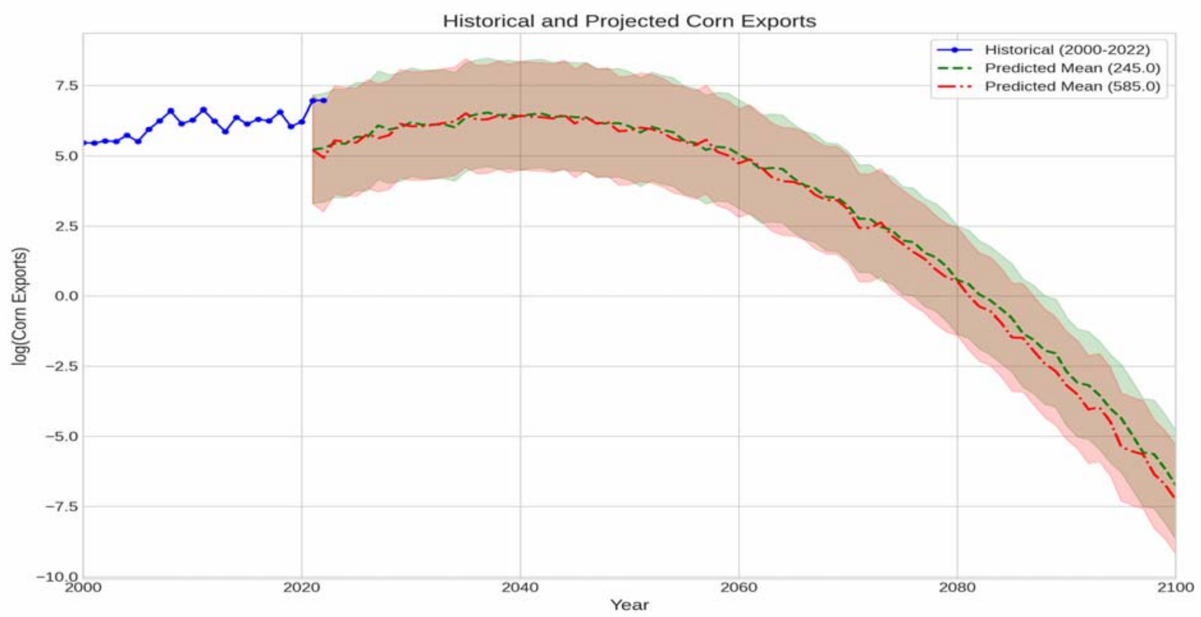
17

Historical and Future Soybean Production from 2000-2100



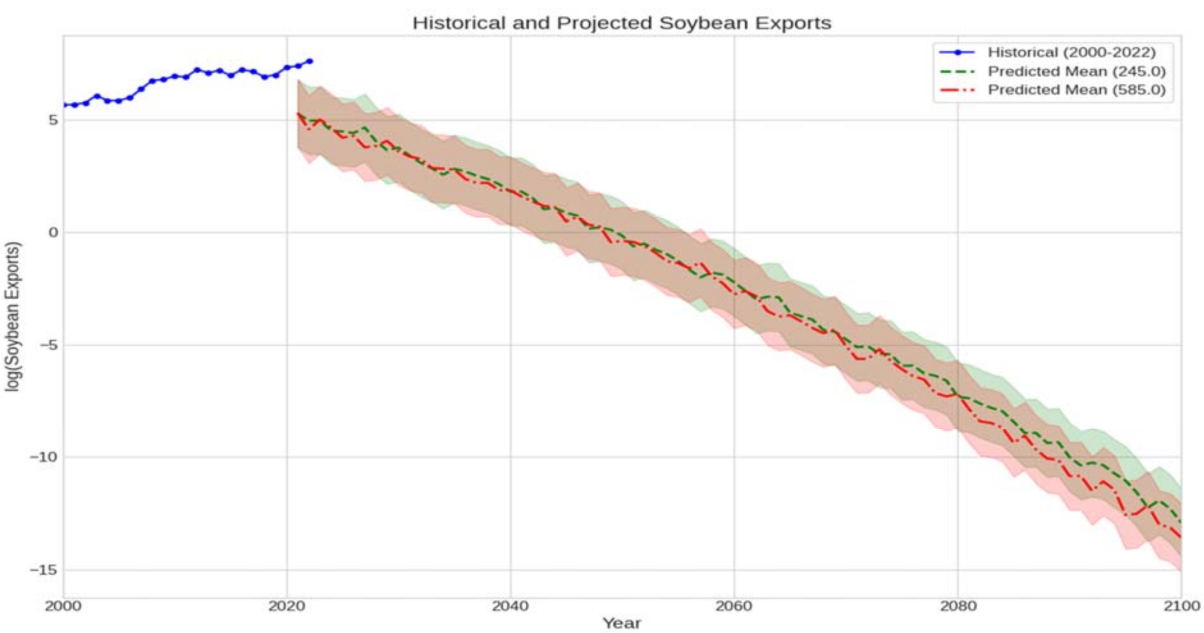
18

Historical and Future Corn Exports from 2000-2100



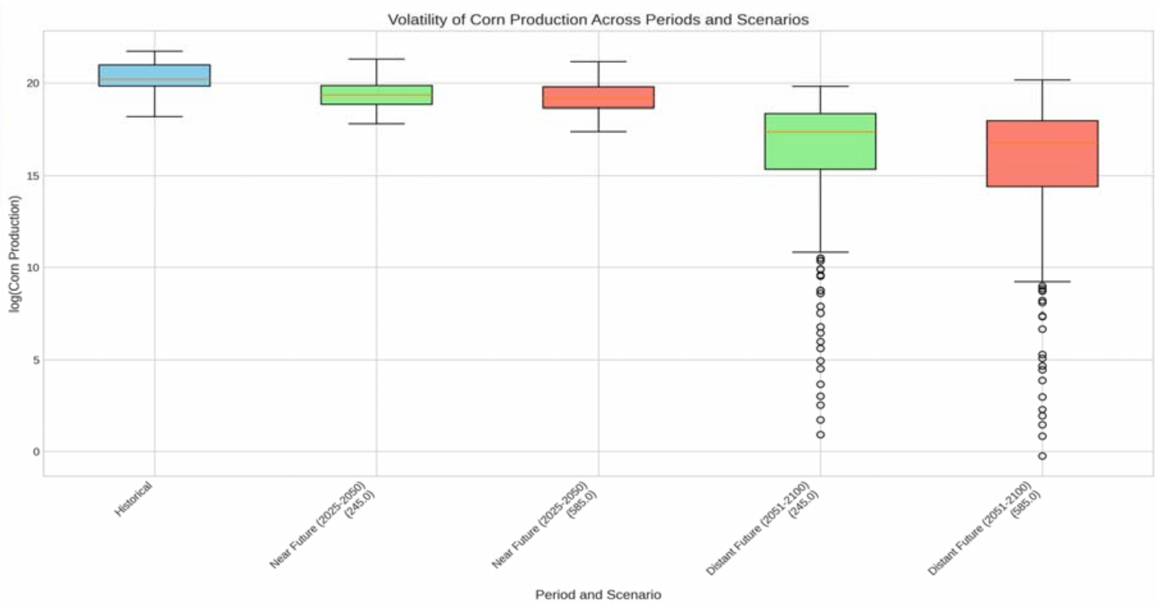
19

Historical and Future Soybean Exports from 2000-2100

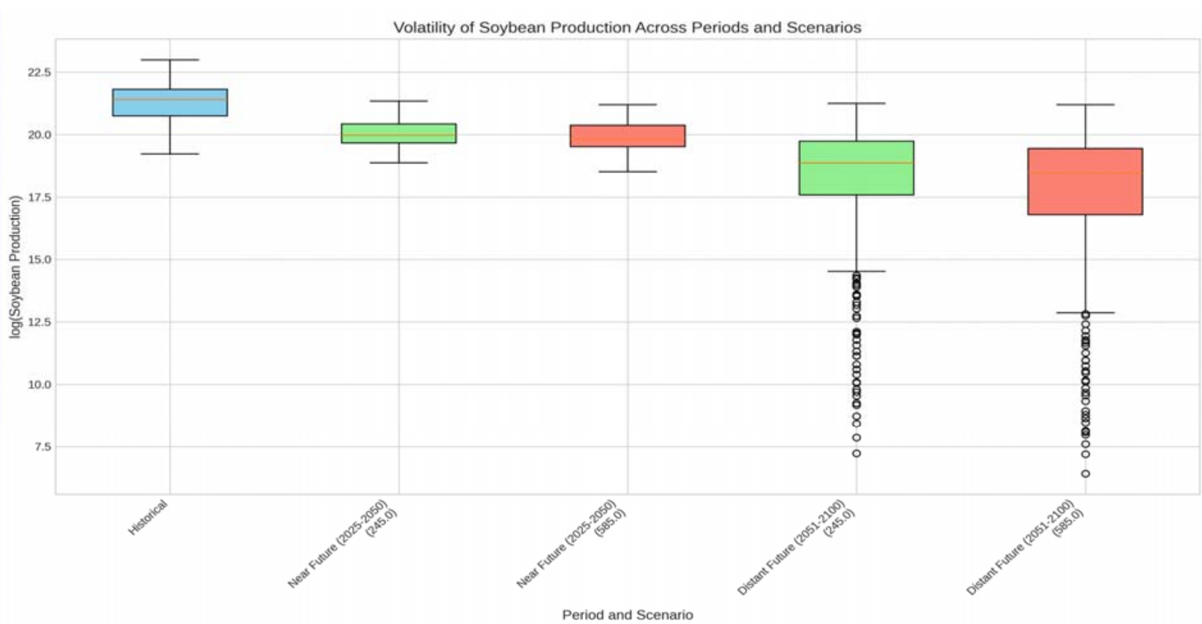


20

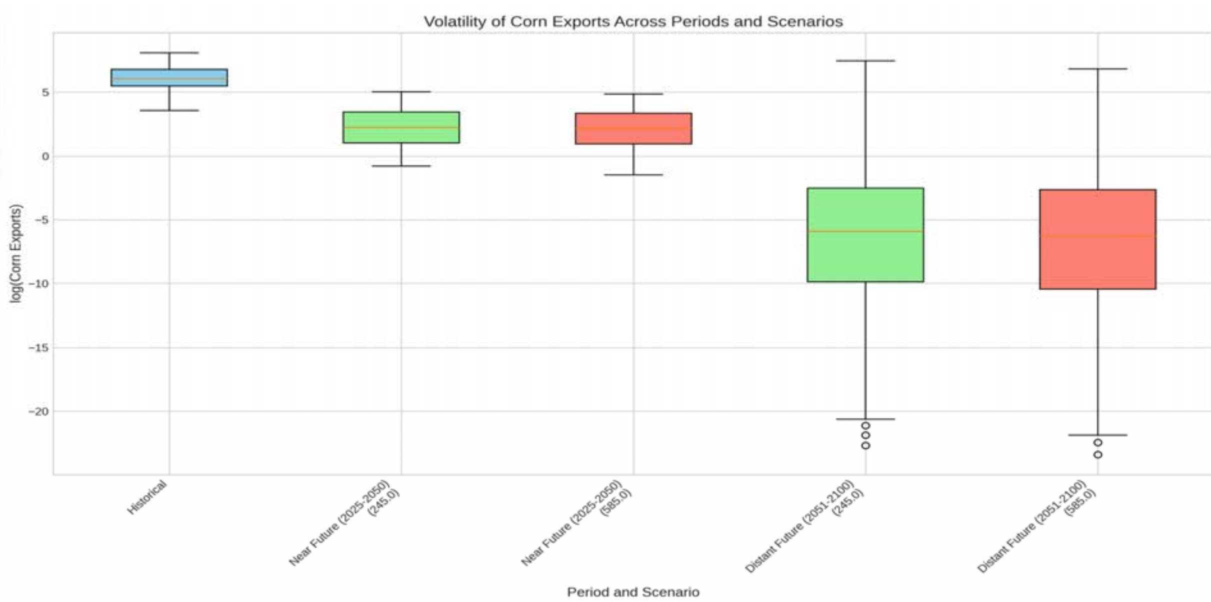
Volatility in Corn Production from 2000-2100 under SSPs



Volatility in Soybean Production from 2000-2100 under SSPs

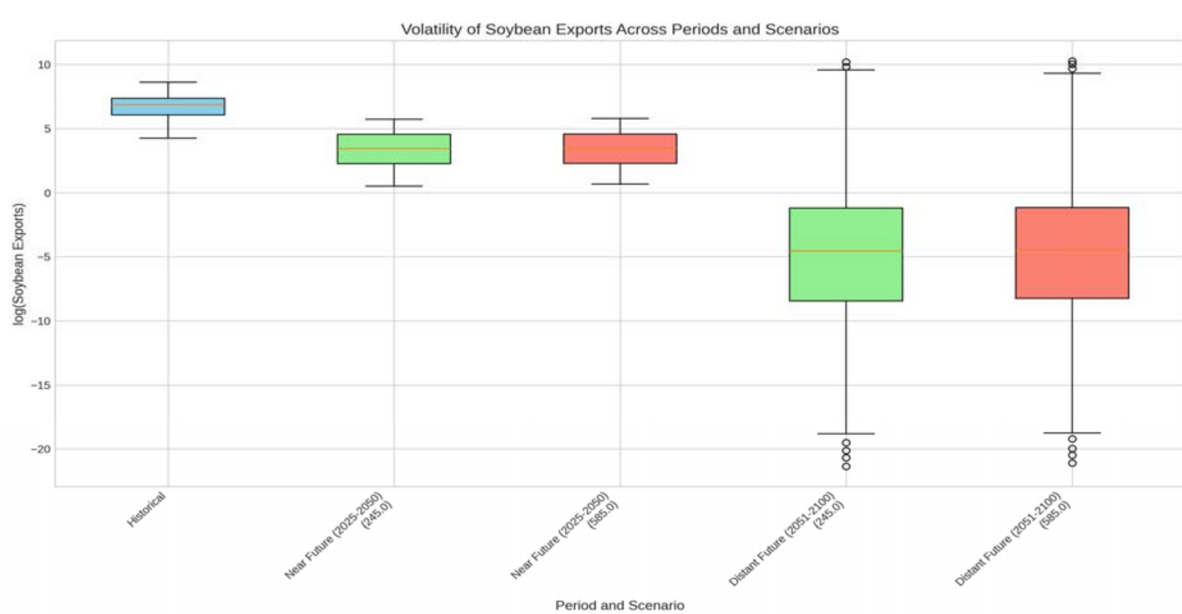


Volatility in Corn Exports from 2000-2100 under SSPs



19

Volatility in Soybean Exports from 2000-2100 under SSPs



20

Preliminary Insights Summary

1. **Historical Effects of Heating Temperature (2000-2022)**

   – HDD significantly reduces both crop production and export volumes for corn and soybeans.
   – Exports absorption of production shocks varies by state and crops.

2. **Future Climate Projections (2023–2100)**

- Future projections align with historical impacts but vary significantly by state
  – Hotter states (e.g., Kansas, Missouri, Nebraska): Steep declines in production and exports
  – Cooler states (e.g., Michigan, Ohio): Moderate but persistent disruptions

Questions?

Appendix

Methodology

1. $Y_{it}^{c} = \beta_0 + \beta_1\, GDD_{0-28} + \beta_2\, HDD_{29-inf} + \beta_3\, Prec_{it} + Z_{it}\delta + s_i + \delta_t + \varepsilon_{it}$ (1)

2. $P_{it}^{c} = \beta_0 + \beta_1\, GDD_{0-28} + \beta_2\, HDD_{29-inf} + \beta_3\, Prec_{it} + Z_{it}\delta + s_i + \delta_t + \varepsilon_{it}$ (2)

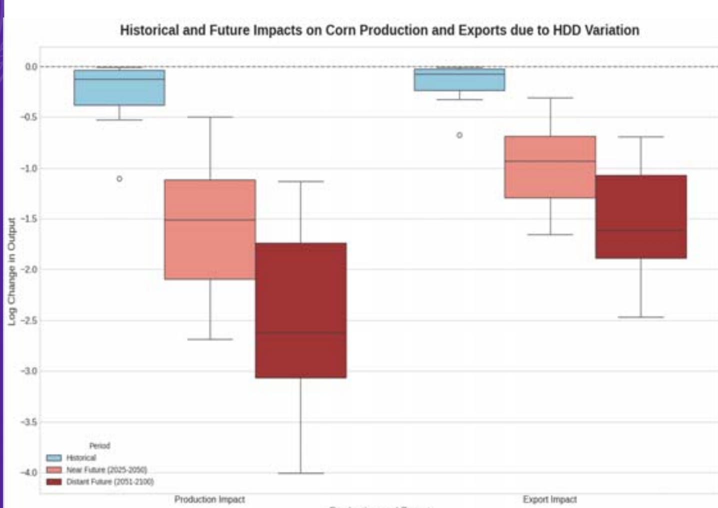
3. $X_{it}^{c} = \beta_0 + \beta_1\, GDD_{0-28} + \beta_2\, HDD_{29-inf} + \beta_3\, Prec_{it} + Z_{it}\delta + s_i + \delta_t + \varepsilon_{it}$ (3)

Where $\boldsymbol{Y_{it}^{c}, P_{it}^{c}, X_{it}^{c}}$ denote log of yield, production and exports, respectively of crop c (corn or soybean) from exporter state ***i*** in year ***t***.

- $\boldsymbol{GDD_{0-28}}$: Indicators for growing degree days in the 0–28°C
- $\boldsymbol{HDD_{29-above}}$: indicators for heating degree days above-28°C ranges
- $\boldsymbol{Prec_{it}}$: Precipitation for state i in year t.
- $\boldsymbol{Z_{it}}$: Controls for confounders, including freezing and state-specific quadratic time trends.
- $\boldsymbol{s_i}$ and $\boldsymbol{\delta_t}$: State and year fixed effects to capture unobserved heterogeneity.
- $\boldsymbol{\varepsilon_{it}}$: is error term

Midwest Aggregate Historical and Future Impact on Corn Production and Exports due to HDD Variation (2023–2100)

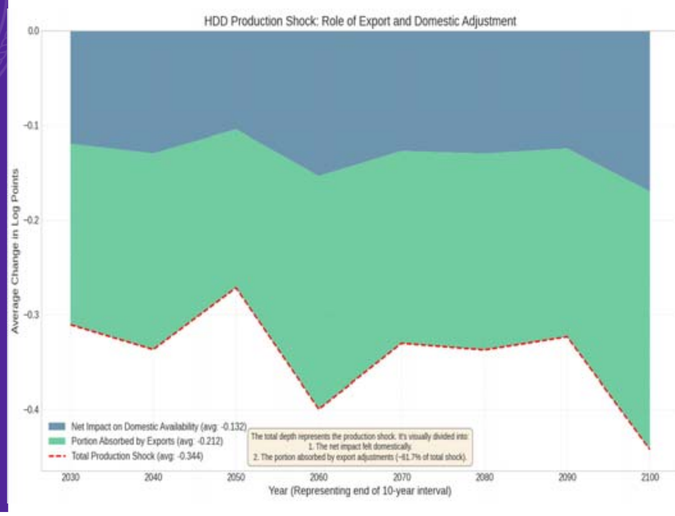
Corn



- **Growing Negative Impacts**
  - Both corn production and exports face increasingly negative impacts from HDD over time
  - Future shocks projected to be far more severe than historical ones
- **Production takes the Brunt**
  - Production impacts are consistently more severe than export impacts across all periods
  - Domestic adjustments are key in buffering the supply shock
- **Future Volatility and Trade Risk**
  - Production suffers more, raising uncertainty for both U.S. corn supply and export stability.

Midwest Aggregate Projected HDD Exposure (2023–2100)

Corn

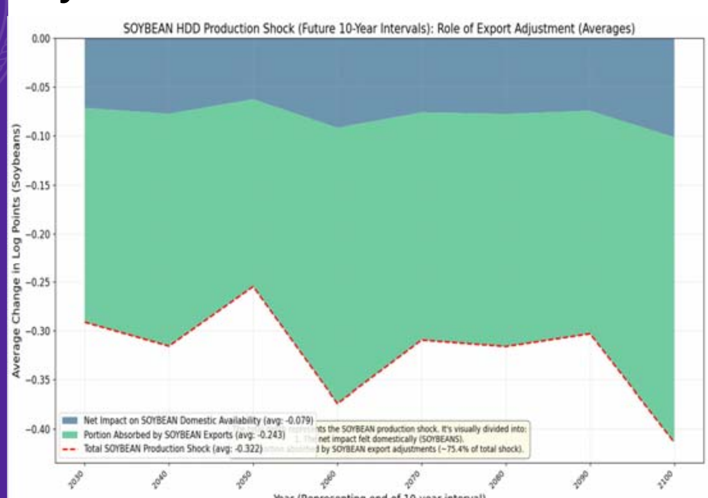


- **Projected Production Declines**
  - Anticipate significant future corn production losses due to HDD
- **Exports Absorb Major Share**
  - Larger proportion (**61.7%**) of these future production losses is projected to be absorbed by reduced exports
  - Weak domestic buffering capacity
- **Implications for Trade Stability**
  - Greater volatility in future corn export volumes
  - Can impact global trade competitiveness

23

Midwest Aggregate Projected HDD Exposure (2023–2100)

Soybean

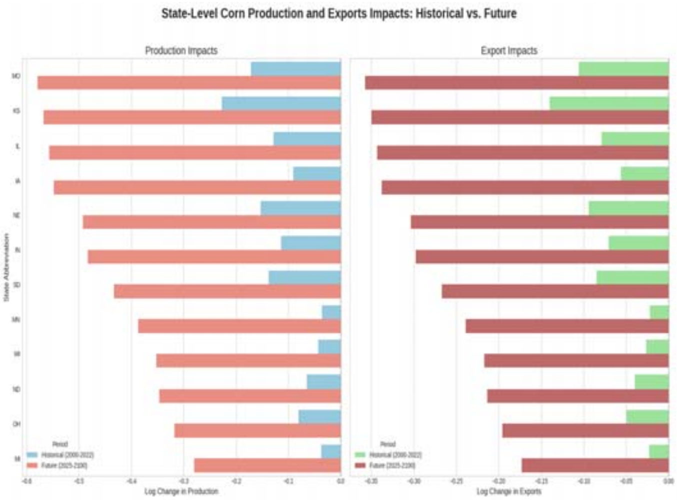


- **Projected Production Declines**
  - Anticipate significant future corn production losses due to HDD
- **Exports Absorb Major Share**
  - Larger proportion **(75.4%)** of these future production losses is projected to be absorbed by exports
  - Weaker domestic buffering capacity
- **Implications for Trade Stability**
  - Significant volatility in future export volumes
  - Severely impacting global trade competitiveness

24

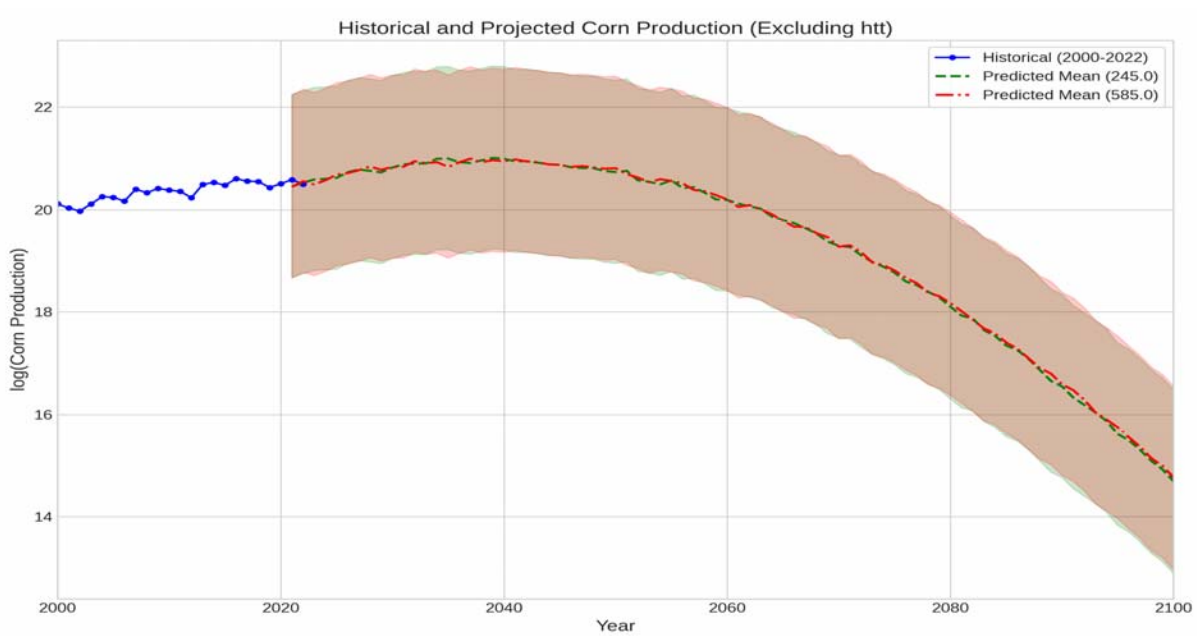
State Level Historical and Future impact on Corn Production and Exports due to HDD Variation (2025–2100)

Corn

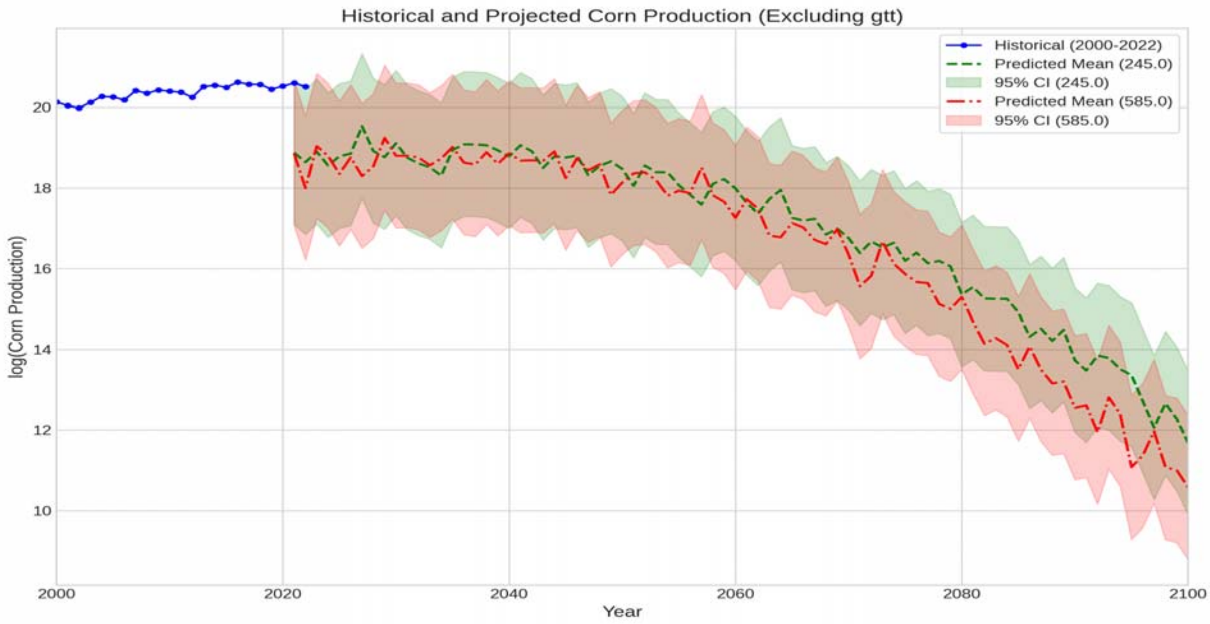


- **Future Declines**
  - Significant future declines in both production and exports
  - Future shocks projected to be far more severe than historical ones
- **Intensified Production Shocks**
  - KS and MO face larger production losses
  - Indicate concentrated climate risk in key provinces
- **Export Vulnerability Varies by State**
  - Severe export reductions
  - Highlight specific areas of trade vulnerability

Historical and Future Corn Production from 2000-2100 (No HDD)

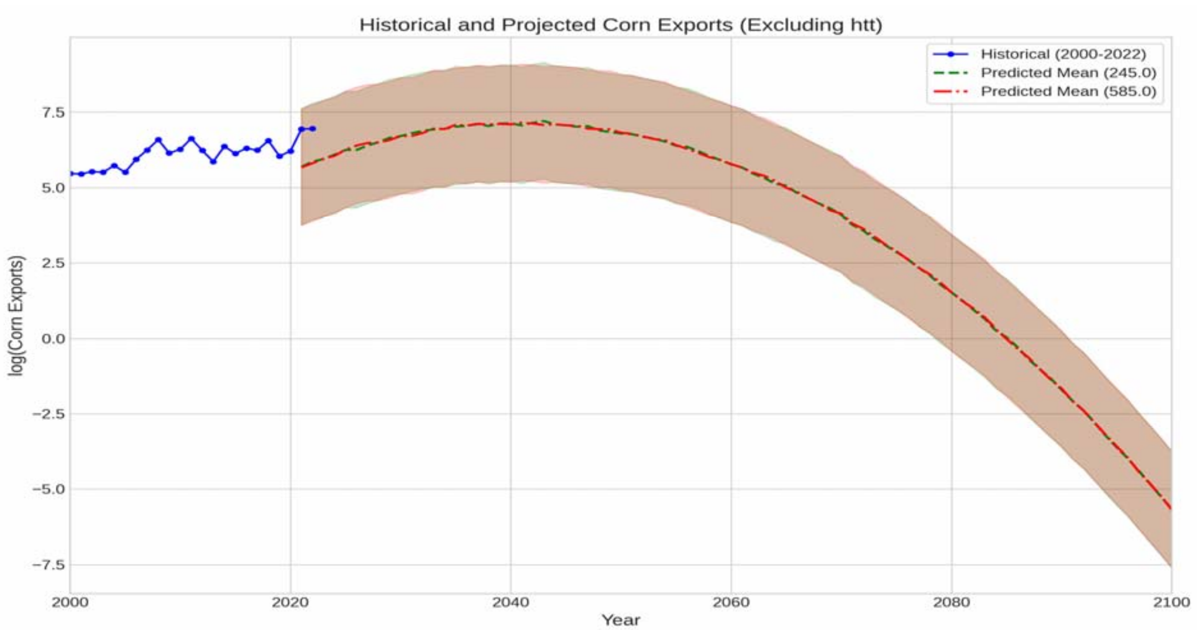


Historical and Future Corn Production from 2000-2100 (No GDD)



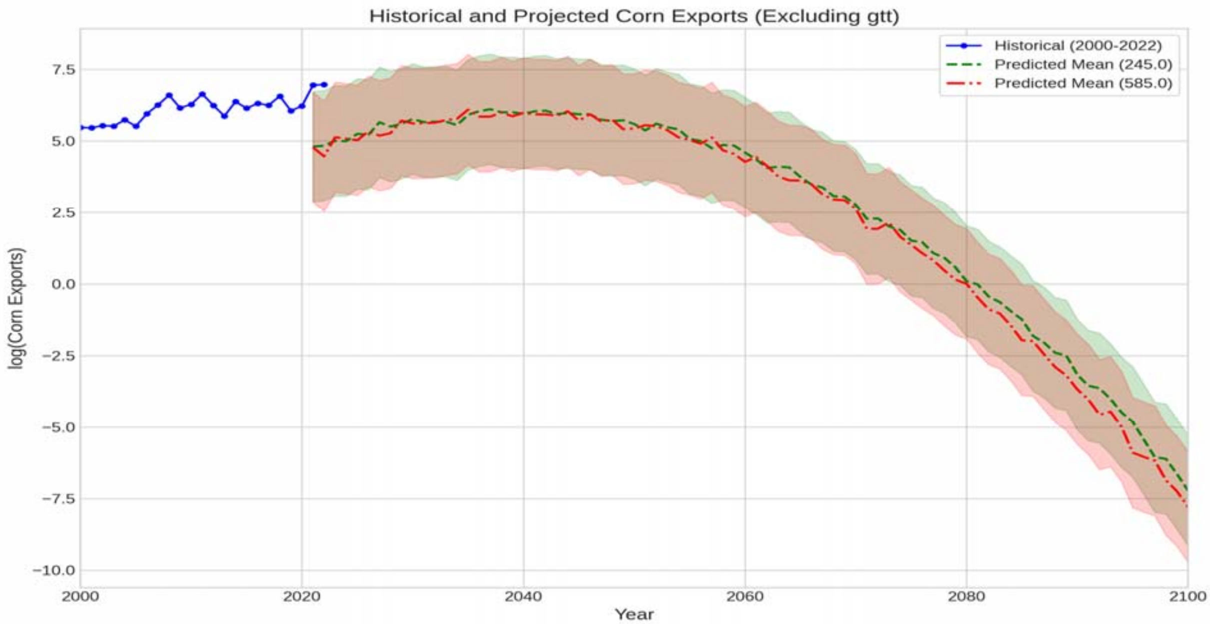
15

Historical and Future Corn Exports from 2000-2100 (No HDD)



15

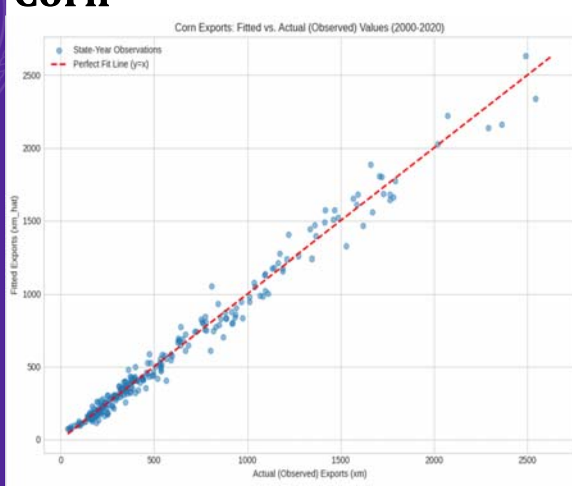
Historical and Future Corn Exports from 2000-2100 (No GDD)



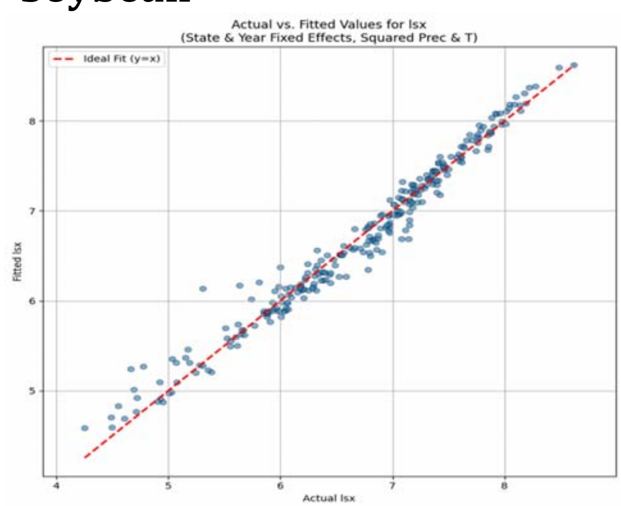
15

Corn and Soybean Actual vs Fitted Value (2000–2022)

Corn



Soybean



16

Midwest Aggregate Regression Results (2000-22)

Corn

Independent Variables	Dependent Variable		
	Yield	Production	Exports
GDD	0.000074	-0.000087	-0.000141
HDD	**-0.003882*****	**-0.00608*****	**-0.003753*****
Prec	-0.000312	-0.002045	-0.002221***
Freezing	-0.004781	-0.004528	0.007862
Constant	4.196894***	24.213725***	10.414897***
State FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	276	276	276
R-squared	0.845756	0.976271	0.974079
Adjusted R^2	0.821024	0.972466	0.969923

Soybean

Independent Variables	Dependent Variable		
	Yield	Production	Exports
GDD	0.000428**	0.000212	0.000161
HDD	**-0.004547*****	**-0.005728*****	**-0.004273*****
Prec	0.000894**	-0.000831	-0.001094
Freezing	-0.002067	-0.003354	-0.002623
Constant	1.376606	20.759701***	2.299994
State FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	276	276	276
R-squared	0.904721	0.978649	0.971341
Adjusted R^2	0.889444	0.975226	0.966746

State-wise HDD Standard Deviation(2000–2100)

Fips	State	Scode	PRISM SD_HDD	CMIP6 SD_HDD
17	Illinois	IL	21.05487	80.22064
18	Indiana	IN	18.74836	63.54706
19	Iowa	IA	14.97537	85.7358
20	Kansas	KS	37.34651	92.474
26	Michigan	MI	6.147604	33.88041
27	Minnesota	MN	5.86105	54.33461
29	Missouri	MO	28.21003	89.36668
31	Nebraska	NE	25.13691	70.3456
38	North Dakota	ND	10.59377	39.65521
39	Ohio	OH	13.25308	39.04494
46	South Dakota	SD	22.65115	58.25251
55	Wisconsin	WI	7.067014	50.55097

Future Extension of the Analysis

1. **Current Scope**

- Analysis to date uses NorESM2-MM under SSP2-4.5 to estimate climate-induced production shocks and the share absorbed by exports.

2. **Next Step: Multi-Model Ensemble**

- Expand projections using six CMIP6 GCMs under SSP2-4.5 and SSP5-8.5:
  - NorESM2-MM, CESM2 (NCAR), GFDL-ESM4 (NOAA)
  - HadGEM3-GC31-MM, EC-Earth3, MPI-ESM1-2-HR

3. **Why This Matters**

- Enables a more robust assessment of vulnerability to cumulative heat stress (HDD), while accounting for:
  - Model uncertainty
  - Scenario heterogeneity
  - State-level export risks under future climate pathways