

# How Drought Shocks Alfalfa Production and Export Markets? Evidence from U.S. Alfalfa Spatial Diagnostics and Panel Analysis

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## Context

- ▶ Alfalfa is grown on about 6.8 million acres of cropland in the 11 Western States (AZ, CA, CO, ID, MT, NM, NV, OR, UT, WY) each year (USDA-NASS, 2019),
- ▶ Around 1/3 of U.S. alfalfa acreage was in drought-affected areas in 2025 (NOAA–NIDIS), annually use more irrigation water than some other crops.
- ▶ Alfalfa's biological characters (land rotation, drought tolerant, deeper roots, land intensive) and strategic importance on dairy and meat lead it became 3rd. valuable field crop in U.S.

Table: U.S. agriculture affected by drought (2025)

Commodity	% Area Affected
Alfalfa hay acreage	32
Hay inventory	33
Milk cow inventory	39
Cattle inventory	25

## Motivation

- ▶ Environment/water policy scientists argue alfalfa delivers relatively low water-use efficiency returns per unit of water (dollars/jobs per drop). When this hay is exported, the region is essentially exporting its scarce water.
- ▶ Agronomists argue that alfalfa can survive "deficit irrigation" (reducing ET without killing the plant), producers can readily idle (fallow) stands or reduce irrigation when water becomes scarce.
- ▶ But irrigation is necessary for export alfalfa, and complex water rights make alfalfa arguments and rigid in Western States.

Alfalfa, Drought, Water Regulation, and Export

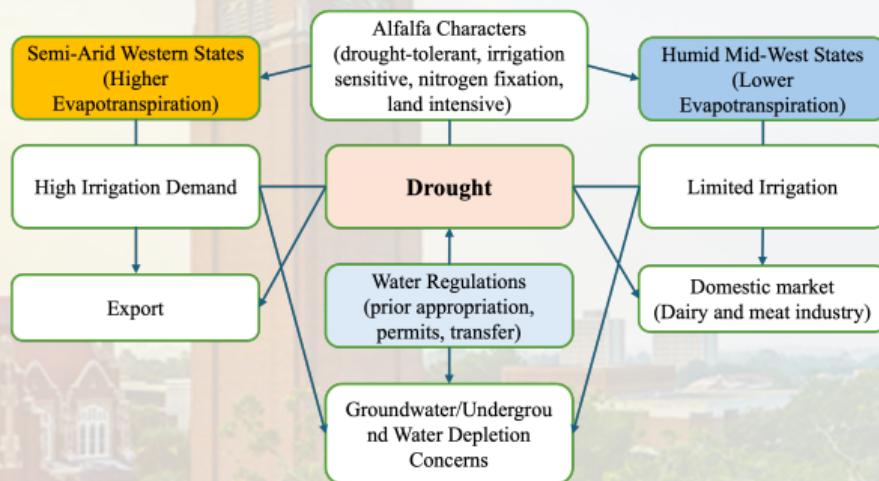


Figure 1: Alfalfa, drought, water regulation, and export

Note: These institutional features can make alfalfa production more rigid in practice, intensifying debates over its role in water-scarce western states.

# Alfalfa systems: West vs Midwest

## ► Western states (CA, AZ, WA, ID, NV)

- High irrigation dependence (often > 50% irrigated alfalfa area).
- About 20% of hay output exported; strong link to global markets.
- Highly exposed to multi-year drought and water allocation cuts.

## ► Upper Midwest (WI, MN, SD, NE, KS)

- Largely rain-fed alfalfa.
- Integrated into local dairy systems; minimal exports.

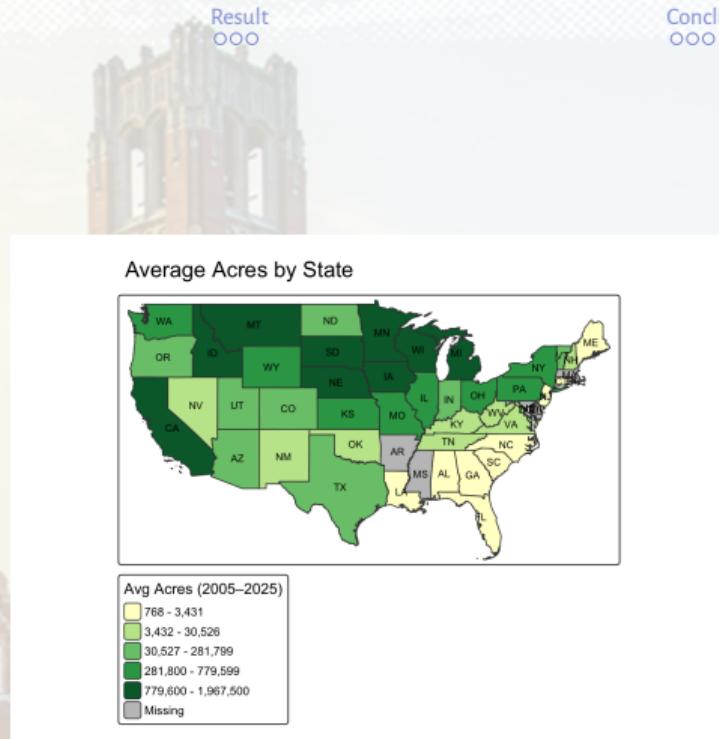


Figure 2: Average annual alfalfa acreage by state

# Research questions and contribution

## Research questions

- ▶ How does drought, measured by SPEI, affect state-level alfalfa:
  - ▶ yields (tons/acre),
  - ▶ export value (thousand USD)?
- ▶ How strongly are drought and export activity coupled in space?
- ▶ Do drought impacts differ between irrigation-intensive western states and rain-fed Midwest states, do irrigation buffer drought impacts?

## Contribution

- ▶ Combine geospatial analysis, time-series modeling, variogram-based spatial diagnostics, fixed effects, and GAM.
- ▶ Provide a spatially explicit assessment of biophysical and economic drought impacts in the U.S. alfalfa sector.

## Data overview

- ▶ **Drought:** Standardized Precipitation–Evapotranspiration Index (SPEI), 12-month accumulation, 2005–2025 (NOAA).
- ▶ **Alfalfa production:** State-level harvested area, production, and value (USDA NASS QuickStats, Census).
- ▶ **Irrigation:** Share of hay acreage irrigated by state (Census of Agriculture), used to classify irrigation dependence.
- ▶ **Trade:** State-level alfalfa export value and export rate (USDA GATS, literature).
- ▶ **Data quality:** Use coefficient of variation (CV) to construct precision weights ( $1/CV^2$ ) for regression analysis.

$$CV = \frac{SE}{\text{Estimate}} \times 100$$

## Key spatial patterns

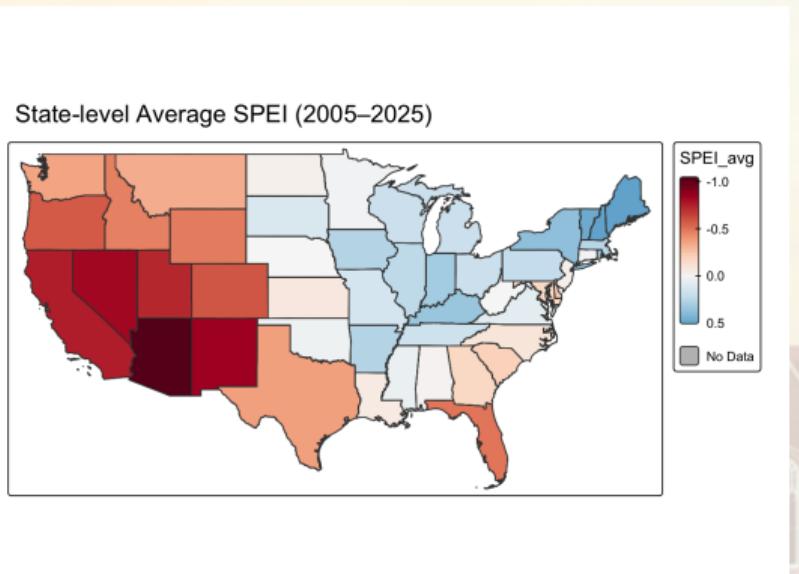


Figure 3: Average SPEI, 2005–2025

Notes: States west of the Rockies exhibit much more negative (drier) SPEI.

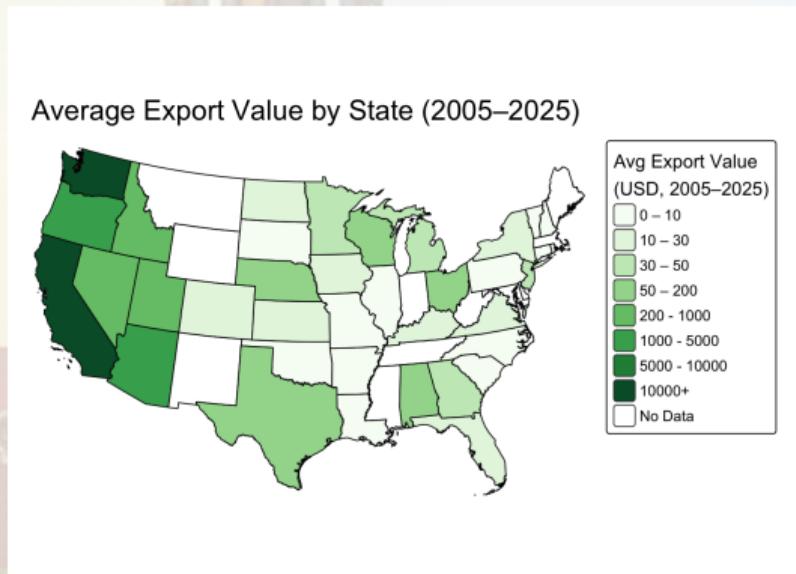


Figure 4: Average alfalfa export value

Note: Export activity is highly concentrated in western states.

## Methods: SPEI time-series modeling: Decomposition and forecasting

- Log-transform to obtain an additive representation: Fit ARIMA to model dynamics and forecast drought conditions.

$$\log(\text{SPEI}_t) = \log(\text{trend}_t) + \log(\text{seasonality}_t) + \varepsilon_t$$

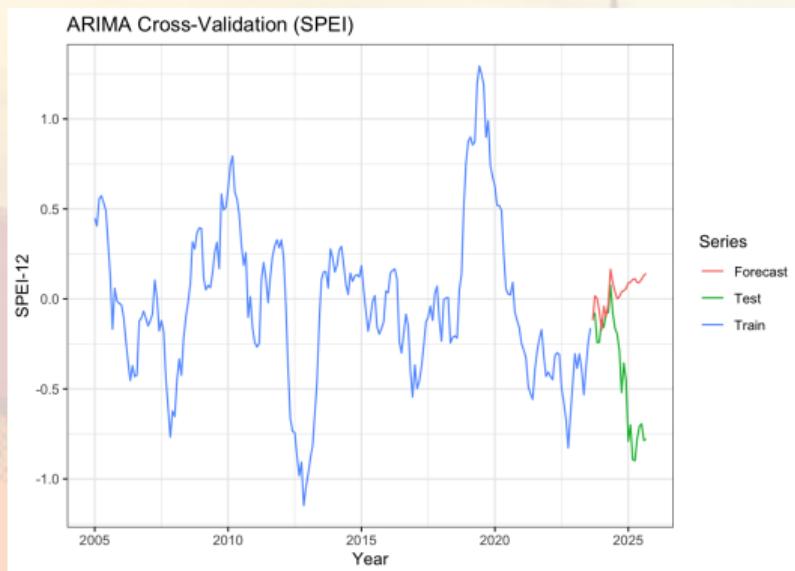


Figure 5: Cross-validation for national SPEI

# Methods: spatial correlation

## Semivariogram and cross-variogram

- ▶ Empirical semivariograms for SPEI and export value show strong positive spatial autocorrelation.
- ▶ Linear model of coregionalization (LMC) fitted for both variables and their cross-variogram.
- ▶ Spatial range  $\approx 500$  km for both drought and export value.
- ▶ Cross-variogram indicates near-zero spatial covariance between SPEI and export value.

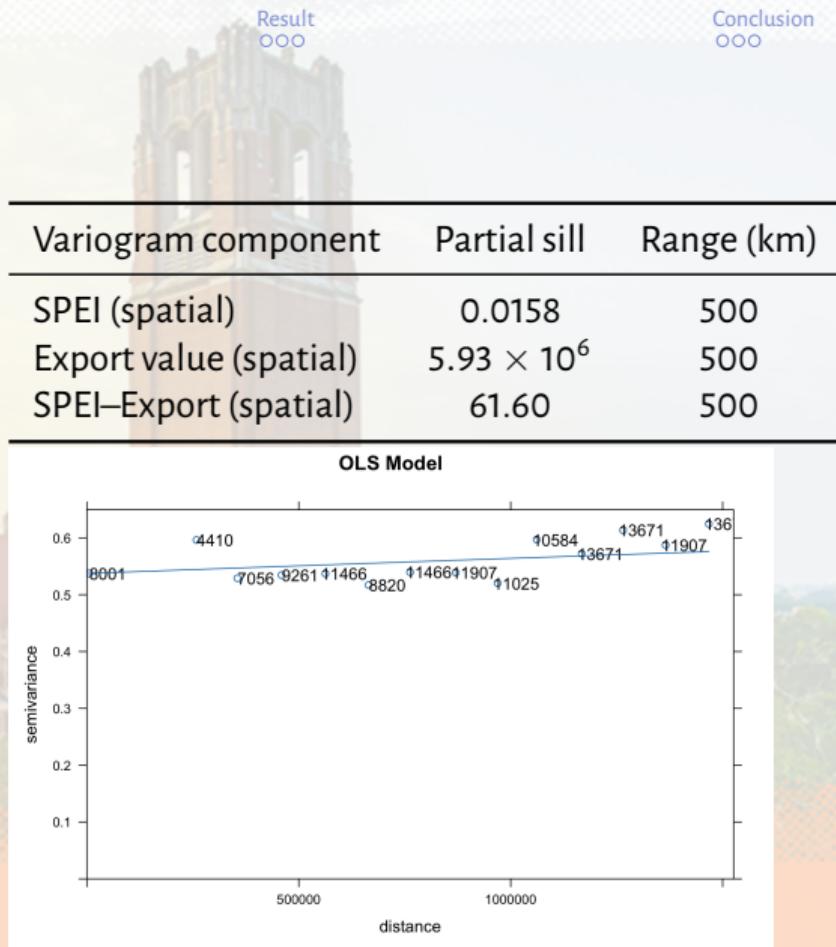


Figure 6: Spatial correlation in export

# Methods: econometric regression models

## Two-way fixed effects

$$Y_{st} = \beta_1 S_{st} + \beta_2 I_{st} + \mu_s + \lambda_t + \varepsilon_{st}$$

$$EV_{st} = \gamma_1 S_{st} + \gamma_2 I_{st} + \gamma_3 P_t + \mu_s + \lambda_t + u_{st}$$

- ▶  $Y_{st}$ : yield (tons/acre);  $EV_{st}$ : export value.
- ▶  $S_{st}$ : SPEI;  $I_{st}$ : irrigation share;  $P_t$ : alfalfa price.
- ▶ State and year fixed effects control for time-invariant heterogeneity and common shocks.
- ▶ Standard errors clustered by state.

## Spatial GAM for export value

$$EV_{st} = \theta_1 S_{st} + \theta_2 Y_{st} + f_1(\text{Price}_{st}) + f_2(\text{lon}_s, \text{lat}_s) + \epsilon_{st}$$

- ▶  $f_1(\cdot)$ : nonlinear price effect.
- ▶  $f_2(\cdot)$ : spatial smooth (captures port access, clustering).

## Results: drought and production

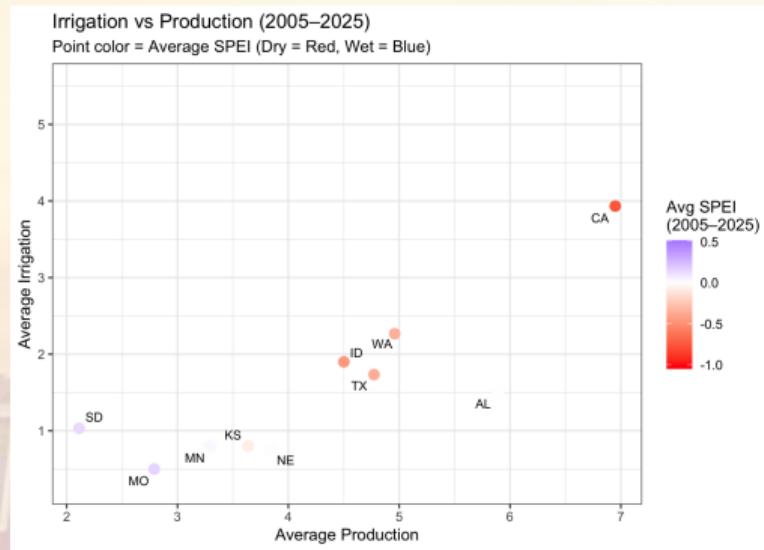


Figure 7: Irrigation, yield, and SPEI

Note: Western states: high yields, high irrigation, more negative SPEI. Midwest: rain-fed, moderate yields.

Table Fixed-effects and WLS yield model (SPEI and irrigation)

	Yield (tons/acre)		
SPEI	0.103 <sup>†</sup> (0.053)	0.103* (0.047)	0.103** (0.039)
Irrigation	0.078	0.078	0.078
FE	State	S+Y	S+Y
Obs.	361	361	361

- ▶ Higher SPEI (wetter conditions) significantly increase yield.
- ▶ Drought reduces both yield and harvested area; effects are strongest in irrigation-dependent West.

## Results: export value and spatial structure

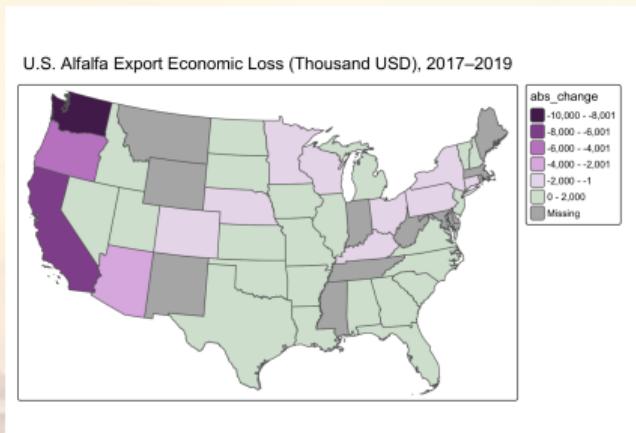


Table Export value models (summary)

	FE	OLS	GAM	2SLS
Dep. var.	EV	EV	EV	EV
SPEI	ns	—***	ns	343*
Irrig.	ns	ns	ns	ns
Nonlin. price	No	No	Yes ( $p \approx 0.03$ )	No
Spatial smooth	No	No	Yes ( $p < 10^{-16}$ )	No
Adj. $R^2$	0.86	0.04	0.81	0.89

Figure 8: Export value loss, 2017–2019 *Note:* Largest losses in drought-affected western states (CA, AZ, NV).

- ▶ Pooled OLS suggests strong negative drought–export link.
- ▶ Two-way FE and GAM show no robust within-state effect of SPEI on export value.
- ▶ Export value driven by spatial clustering and nonlinear price dynamics.

# Drought–export decoupling

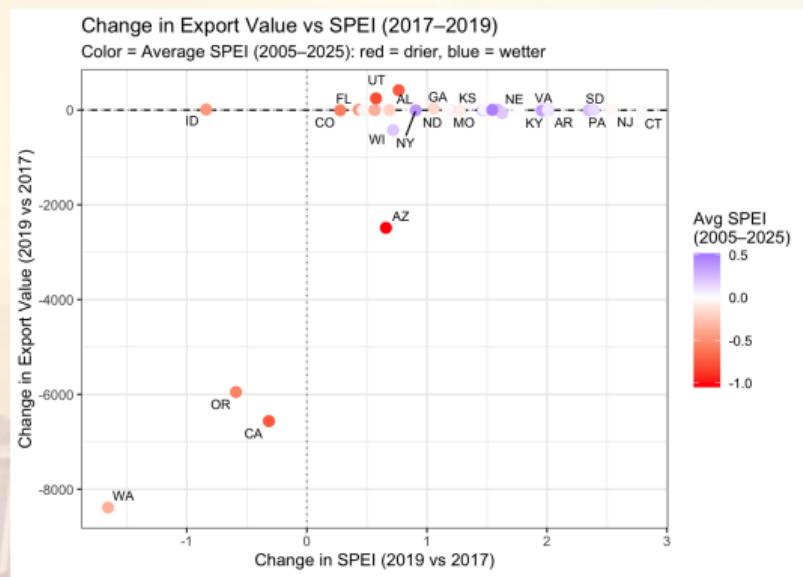


Figure 9: Change in SPEI vs export value

- ▶ No clear systematic relationship between changes in SPEI and changes in export value.
- ▶ Drought-affected western states often maintain export volumes via storage and reallocation from domestic markets.

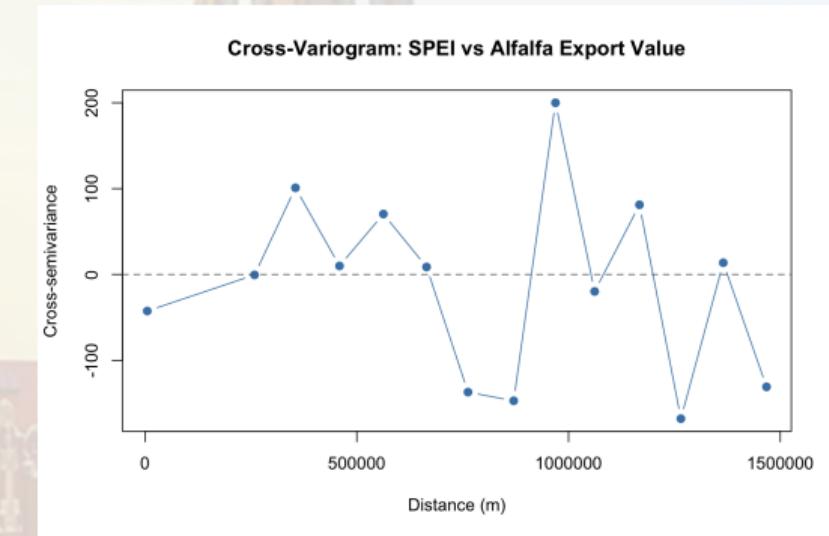


Figure 9: Cross-validation: SPEI vs export

## Discussion and policy implications

- ▶ **Biophysical:** Drought significantly lowers yields and area, especially in irrigation-intensive western systems.
- ▶ **Economic:** Export value is buffered by market prioritization, storage, and infrastructure.
- ▶ **Regional differentiation**
  - ▶ West: focus on water allocations, irrigation efficiency, storage, and export logistics.
  - ▶ Midwest: focus on feed-cost risk management, insurance, and maintaining local forage supply.
- ▶ **Trade and climate:** Open, flexible trade can dampen price spikes under climate shocks, but also risks shifting land-use and emissions abroad.

# Conclusion and next steps

## Main messages

- ▶ Drought poses a major threat to the U.S. alfalfa forage base, with strong spatial heterogeneity.
- ▶ Irrigation dependence amplifies vulnerability in the West; rain-fed Midwest shows smaller area adjustments.
- ▶ Export outcomes are more shaped by geography and prices than by year-to-year drought severity.

## Next steps

- ▶ Explicitly model acreage dynamics and drought-induced land reallocation.
- ▶ Integrate trade policy scenarios and land-use spillovers into welfare analysis.
- ▶ Extend spatial modeling to county scale and to other forage crops.

Thank You for Your Attention

## Questions or Comments?

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Data and Code:

[github.com/liyoumin/Geospatial-AgEcon](https://github.com/liyoumin/Geospatial-AgEcon)

*Thank you for your time and feedback!*