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

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January 2026

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Context

► Drought alters nutrient, water cycles and threatens forage-based livestock systems.
► Around 1/3 of U.S. alfalfa acreage was in drought-affected areas in 2025 (NOAA–NIDIS).
► Western alfalfa is irrigation-intensive and export-oriented; Midwest alfalfa is mostly rain-fed and used locally.
► Alfalfa's biological characters (land rotation, anti-drought, 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.

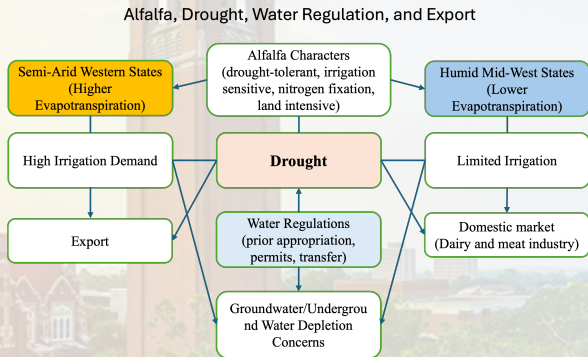Alfalfa, Drought, Water Regulation, and Export

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.

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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.
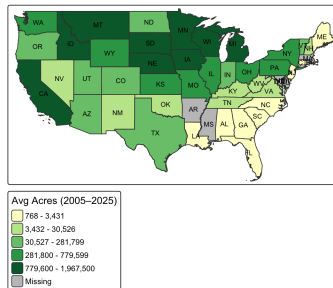 - Integrated into local dairy systems; minimal exports.

Figure 2: Average annual alfalfa acreage by state

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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.

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

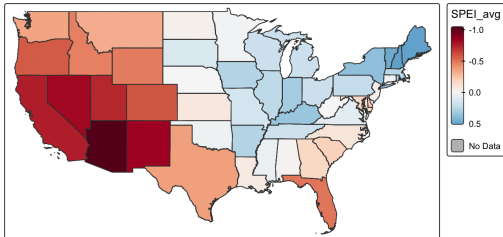# Key spatial patterns

State-level Average SPEI (2005–2025)

Figure 3: Average SPEI, 2005–2025

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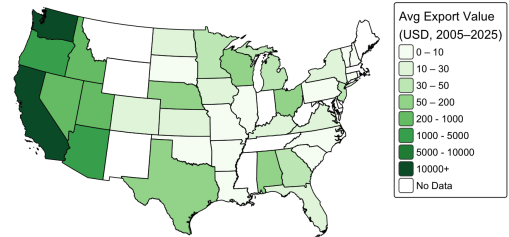

Average Export Value by State (2005–2025)

Figure 4: Average alfalfa export value

Note: Export activity is highly concentrated in western states.

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Methods: SPEI time-series modeling: Decomposition and forecasting

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

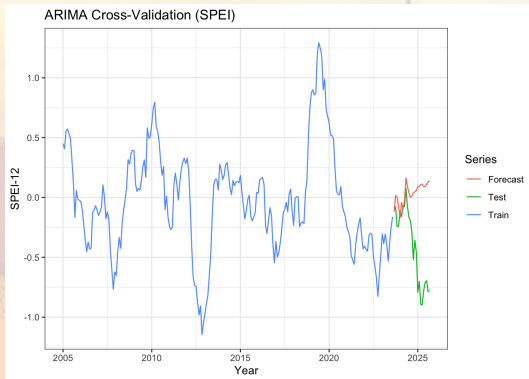$$\log(\text{SPEI}_t) = \log(\text{trend}_t) + \log(\text{seasonality}_t) + \varepsilon_t$$

Figure 5: Cross-validation for national SPEI

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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 ≈ 500 km for both drought and export value.

▶ Cross-variogram indicates near-zero spatial covariance between SPEI and export value.

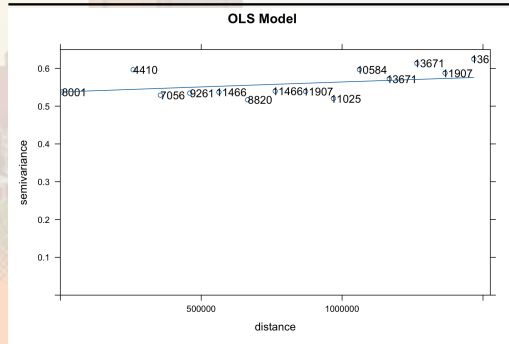| Variogram component	Partial sill	Range (km)
SPEI (spatial)	0.0158	500
Export value (spatial)	5.93×10^6	500
SPEI–Export (spatial)	61.60	500

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).
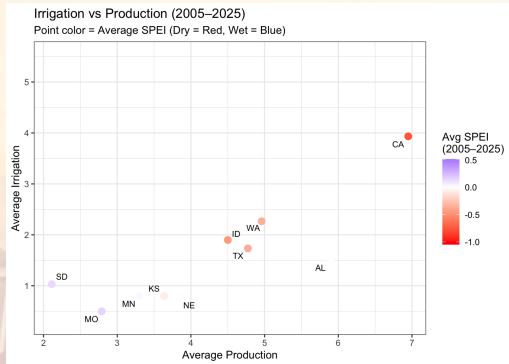
Results: drought and production

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	$0.103^{\dagger}$	0.103^{*}	0.103^{**}
	(0.053)	(0.047)	(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.

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Results: export value and spatial structure

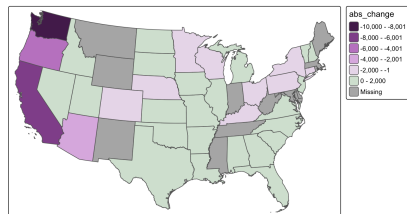U.S. Alfalfa Export Economic Loss (Thousand USD), 2017–2019

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

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

► 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.
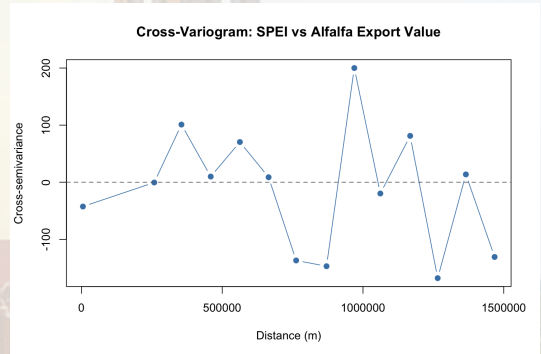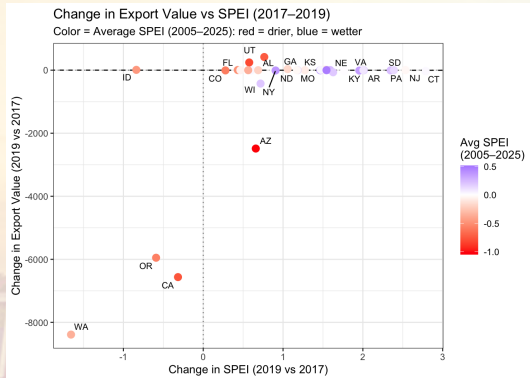
Drought–export decoupling

Figure 9: Change in SPEI vs export value

Figure 9: Cross-validation: SPEI vs export

▶ 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.

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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.

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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.

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Thank You for Your Attention

Questions or Comments?

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Data and Code:
github.com/liyoumin/Geospatial-AgEcon

Thank you for your time and feedback!