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

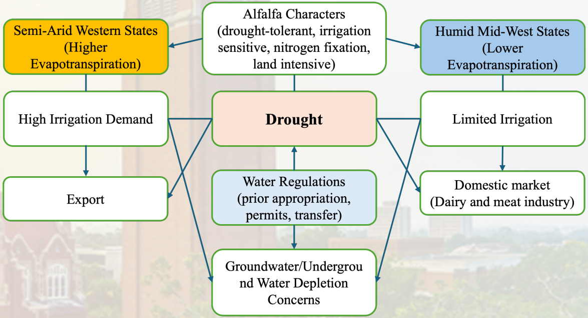

Figure 1: Alfalfa, drought, water regulation, and export

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.

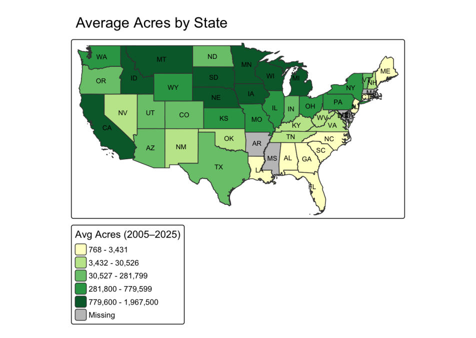

Figure 2: Average annual alfalfa acreage by state

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 weights ($1/CV^2$) for WLS regression.

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

Key spatial patterns

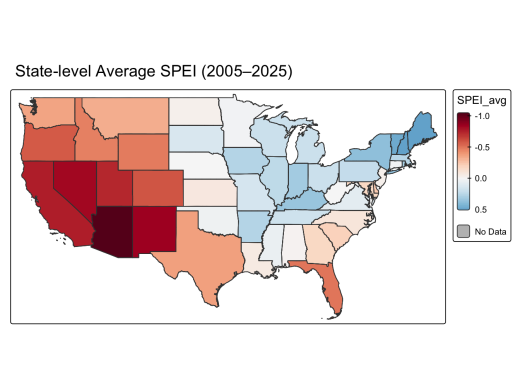

Figure 3: Average SPEI, 2005–2025

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

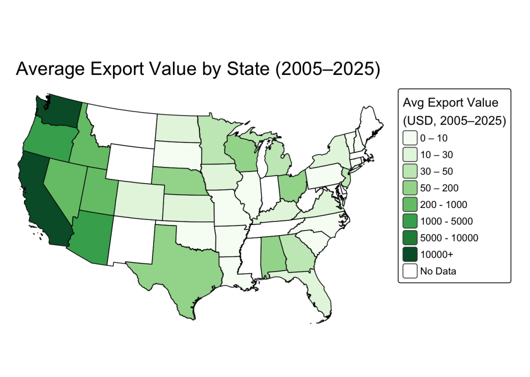

Figure 4: Average alfalfa export value

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.

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

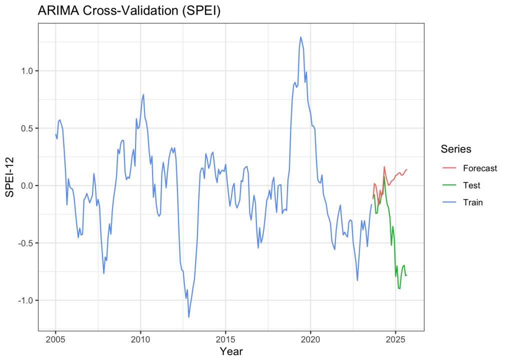

Figure 5: ARIMA Cross-validation (SPEI)

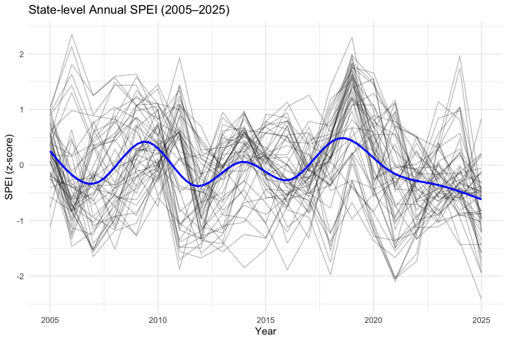

Figure 6: National SPEI trend

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

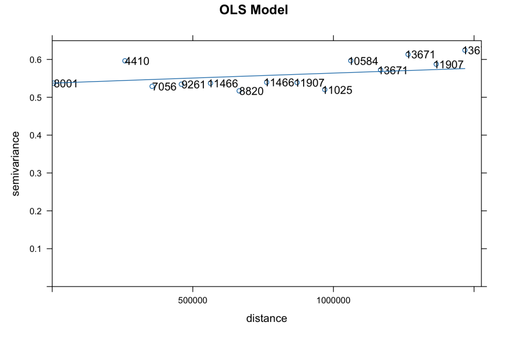

Figure 7: Spatial correlation in export

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

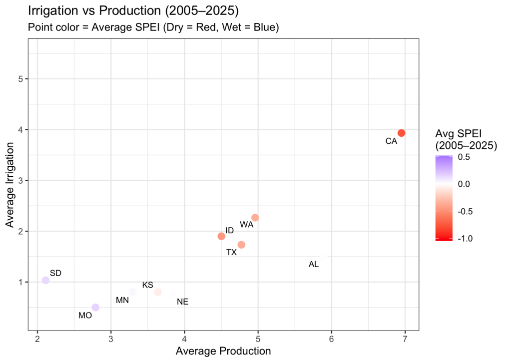

Figure 8: Irrigation, yield, and SPEI

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

Table 3: Fixed-effects and WLS yield model (SPEI and irrigation)

	Yield (tons/acre)		
SPEI	0.103†	0.103*	0.103**
	(0.053)	(0.047)	(0.039)
Irrigation	0.075*	0.075*	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

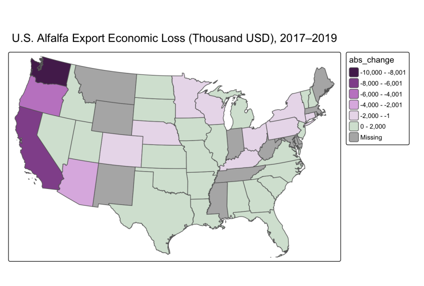

Figure 9: Export value loss, 2017–2019 *Note*:Largest losses in drought-affected western states (CA, AZ, NV).

Table 4: 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.

Results: Irrigation practice

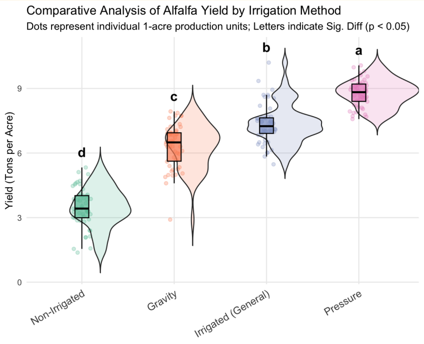

Figure 10: Irrigation practice buffer

Note:Largest losses in drought-affected western states (CA, AZ, NV). Each "violin shape" represent the results of a post-hoc statistical test (likely a Tukey HSD test).

Table 5: Alfalfa Yield Comparison by Irrigation Treatment

Treatment	**Mean Yield**	**SD**	**Yield Gain (%)**
Non-Irrigated	3.47	0.92	0.0
Gravity Irrigation	6.31	1.02	81.8
Irrigated (Combine)	7.35	0.93	112.0
Pressure Irrigation	8.78	0.62	153.0

Drought–export decoupling

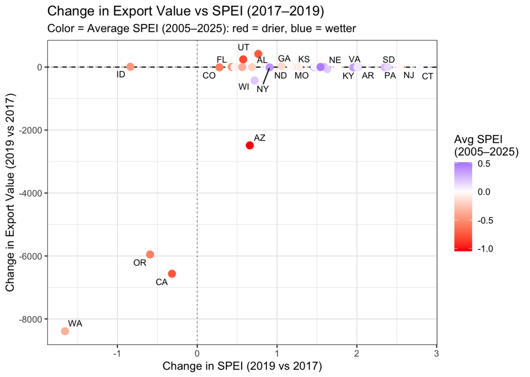

Figure 11: Change in SPEI vs export value

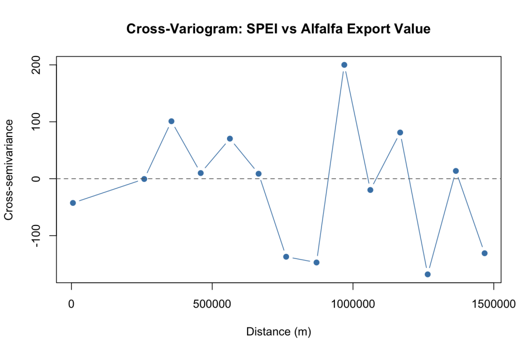

Figure 12: Cross-validation: SPEI vs export

- 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.

Discussion and policy implications

- **Biophysical**: Drought significantly lowers yields but irrigation buffer drought impacts especially in irrigation-intensive western systems.
- **Economic**: Export value is buffered by market prioritization, storage, and infrastructure.
- **Irrigation policy**: Precise irrigation practices and better water rights contracts (credits period, priority) are needed.

Limitations

- Acreage dynamics and drought-induced land reallocation.
- Irrigation data limitation (precise volume).
- Downscale state spatial modeling.

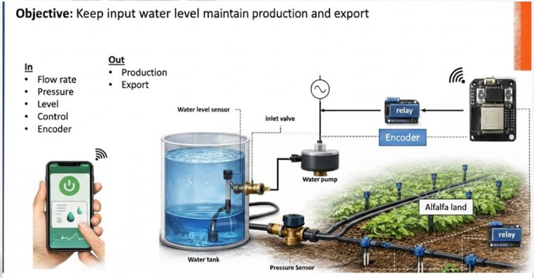

Figure 13: Precise irrigation practice: Internet of Things application in agricultural irrigation

Conclusion

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.
- **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.

Thank You for Your Attention

Questions or Comments?

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

Thank you for your time and feedback!