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

Motivation and relevance

Alfalfa is the third valuable field crop in U.S. and serves as the foundation feed in dairy and beef cattle production systems, yet production and marketing are geographically bifurcated. In the arid West, alfalfa systems are frequently irrigation-dependent and export-oriented, while in the Midwest alfalfa is predominantly rain-fed and integrated into local dairy forage rations. This institutional and market segmentation creates a central policy question: as drought risk intensifies, are yield and acreage impacts transmitted into export performance, or do irrigation capacity, water institutions, and logistics decouple exports from climate shocks?

This project quantifies (i) how drought affects alfalfa productivity and harvested area, (ii) whether drought effects differ systematically across irrigation-dependent versus rain-fed states, and (iii) whether drought is reflected in export value once one accounts for persistent spatial advantages (e.g., proximity to ports, established hay processing and shipping networks) and macro market conditions. The analysis speaks directly to drought adaptation investments (irrigation efficiency, risk management, forage reserves), to the "exporting water" debate in western basins, and to feed supply resilience for dairy and beef industries.

Data

We assemble a state–year panel for 2005–2025 that links drought severity measured by the 12-month Standardized Precipitation–Evapotranspiration Index (SPEI), alfalfa outcomes (yield, harvested acreage, and production value from USDA statistics), state-level alfalfa hay export value compiled from U.S. trade accounting, and irrigation dependence proxied by each state's irrigation share constructed from available irrigation and hay acreage information. This structure supports within-state identification of drought impacts while controlling for persistent cross-state heterogeneity in climate normals, soils, water institutions, and baseline export orientation. Because exports are highly concentrated in a subset of western states, we pair fixed-effects identification with explicit spatial diagnostics to distinguish spatially persistent comparative advantage from drought-driven temporal variation.

Empirical approach

(1) Drought characterization and signal extraction. We treat SPEI as a climate-risk time series and summarize national and state-level dynamics to distinguish long-run drift from seasonal and irregular shocks. Time-series diagnostics and forecasting exercises (including ARIMA-based benchmarks and flexible nonlinear prediction using decomposed components) are used as a robustness check that SPEI contains meaningful systematic variation rather than pure noise at the annual horizon relevant for a perennial forage crop.

(2) Spatial diagnostics. We quantify spatial autocorrelation in drought and export performance using semivariogram-based diagnostics and a cross-variogram between SPEI and export value. The objective is to determine whether drought exposure and export outcomes share a common spatial structure, or whether each is spatially clustered for different reasons. This step informs model specification and interpretation: if export value is spatially structured primarily by logistics and market access, then a purely climatic explanation for export variation is inappropriate.

(3) Panel econometrics for yields, area, and exports. We estimate two-way fixed-effects models to identify within-state drought effects:

$$Y_{st} = \beta_1 \, SPEI_{st} + \beta_2 \, Irrig_{st} + \mu_s + \lambda_t + \varepsilon_{st},$$

with analogous specifications for harvested area. Here, μ_s absorbs time-invariant state heterogeneity and λ_t captures common year shocks (national prices, policy shifts, macro conditions). Standard errors are clustered by state to allow serial correlation in shocks.

For exports, we estimate fixed-effects models that add market controls (e.g., price proxies) and compare them to flexible specifications that allow strong spatial structure:

$$EV_{st} = \gamma_1 \, SPEI_{st} + \gamma_2 \, Irrig_{st} + \mu_s + \lambda_t + u_{st}.$$

To capture persistent geographic advantages not fully explained by observables, we also fit a generalized additive model (GAM) for export value that includes smooth nonlinear effects and spatial smooth in latitude/longitude. This provides an interpretable decomposition of export variation into market forces, drought, and latent spatial structure (ports/logistics/industry clustering).

Key findings (current estimates)

Export value is not directly explained by drought once persistent heterogeneity is controlled. In pooled specifications, drought appears strongly related to export value, but this relationship dissipates when state and year fixed effects are included. This pattern is consistent with a cross-sectional confound: the most arid states also tend to be the largest exporters due to long-run specialization and logistics, so climate aridity and export orientation are mechanically correlated in levels. Within-state year-to-year drought variation does not map cleanly into export revenue once those persistent features are removed.

Exports are spatially structured for non-climatic reasons. Spatial diagnostics indicate that both SPEI and export value are individually spatially autocorrelated, but their *shared* spatial covariance is minimal (near-zero cross-variogram signal). This supports the interpretation that export geography is driven primarily by port access, hay processing/shipping networks, and industry clustering, rather than by the spatial pattern of drought exposure.

A transmission channel emerges when focusing on exogenous yield shifts. Instrumental-variable estimates imply a positive and statistically significant effect of instrumented yield on export value: when moisture conditions exogenously raise yield, export value increases, consistent with a drought $\rightarrow$ production $\rightarrow$ export. Drought clearly harms production, but exports can remain stable in reduced-form fixed-effects regressions because trade and irrigation policy buffers and reallocation mechanisms dampen the direct mapping from drought to export revenue.

Discussion prompts for the session

We will generate productive discussion at the AAEA annual meeting on topics of broad interest to agricultural and environmental economists, while also engaging the growing interdisciplinary community working at the interface of geocomputation, spatial analysis, and applied economic inference. This research uses U.S. alfalfa to show how drought risk in an irrigation-dependent forage system translates into economic outcomes at the agriculture–environment nexus. We motivate discussion on when climate signals should appear in export performance, and how irrigation and water-rights regimes buffer or amplify impacts.

Keywords: Alfalfa; Drought; SPEI; Irrigation; Spatial Analysis; Exports.