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Pablo Sierra-Figueroa

Tecnología y Medio Ambiente. Institute of Geophysics and Astronomy

Carlos Alberto Zúniga-González

czuniga@ct.unanleon.edu.ni

Universidad Nacional Autónoma de Nicaragua-León

Research Article

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Hydroclimatic Mediation of Low-Frequency Solar Activity Signals in Spanish Cereal Yield Variability (1961–2021)

Pablo Sierra-Figueroa¹ and Carlos Alberto Zúniga-González^{*2}

¹ Ministerio de Ciencia, Tecnología y Medio Ambiente. Institute of Geophysics and Astronomy, Havana, Cuba. sierrafp@gmail.com <https://orcid.org/0000-0003-1781-0942>

² Carlos Alberto Zúniga-González (*Corresponding Author*): Research Unit in Bioeconomics and Climate Change, Research Center of Agrarian and Veterinary Sciences, National Autonomous University of Nicaragua, León, Nicaragua. Email: czuniga@ct.unanleon.edu.ni <https://orcid.org/0000-0002-2545-8304>

Abstract

Long-term agricultural productivity is primarily driven by technological advances and management improvements; however, interannual and multiannual yield variability remains strongly influenced by climate dynamics. This study investigates the indirect physical mechanisms through which low-frequency solar activity modulation propagates into long-term cereal yield records in mainland Spain (1961–2021). Using detrended, normalized yield series for oats, barley, rye, and wheat alongside the Wolf Sunspot Number (WN) and winter North Atlantic Oscillation (NAO) indices, we evaluate secular trends, residual multiscale spectral structures, and lagged cross-correlation dynamics. Results reveal strong secular productivity gains ($R^2 = 0.71, p < 0.001$) driven by technological modernization, superimposed on dominant interannual variability (2–4 years) and a quasi-decadal spectral envelope (~8–14 years). Cross-correlation and spectral analyses demonstrate that decadal solar activity does not exert a direct biophysical impulse on crop growth; rather, it weakly

modulates regional atmospheric circulation patterns (NAO). In turn, winter NAO variations alter Mediterranean precipitation regimes, driving a lagged hydrological response in rainfed cereal yields that peaks at a 3-year delay ($r = -0.30, p < 0.05$) due to deep soil moisture memory and multi-year catchment buffering. We propose a hydroclimatic mediation framework operating through a weakly forced stochastic cascade (Solar Activity $\rightarrow$ NAO Circulation $\rightarrow$ Hydroclimate $\rightarrow$ Soil Water Storage $\rightarrow$ Crop Yield). The findings demonstrate that solar variability acts as a low-frequency probabilistic modulator of regional hydroclimatic states rather than a deterministic driver of agricultural performance.

Keywords: Agricultural yield, Solar activity, North Atlantic Oscillation (NAO), Hydroclimatic mediation, Soil moisture memory, Time-series analysis

Introduction

Agricultural productivity variability arises from complex interactions among technological progress (Evans, 1980), management practices, and climate variability across multiple temporal scales (Chandio et al., 2022; Páscoa et al., 2017; Pellegrini et al., 2022; Vitali et al., 2019). Although long-term yield increases since the mid-twentieth century are largely explained by genetic improvement, fertilizer application, mechanization, and irrigation expansion (Spiertz, 2014), residual interannual variability remains heavily driven by climate dynamics (Kukal & Irmak, 2018; Sierra et al., 2015).

External climate forcing sources, including solar activity (Harrison Virden, 1976; Melnik & Drebot, 2019; Pustilnik & Yom Din, 2013; Sierra et al., 2019, 2022, 2025a, 2025b; Sierra-Figueredo et al., 2021, 2022; Tripathi et al., 2022), have been hypothesized to contribute to low-frequency variability in regional climate systems (Lin et al., 2021). Solar variability is

known to influence atmospheric dynamics (Mawad et al., 2022; Muthanna et al., 2016; Ormes, 2018; Sierra et al., 2017) through stratosphere-troposphere coupling and the modulation of large-scale circulation patterns (Lin et al., 2021). However, its influence on agricultural systems remains insufficiently quantified due to strong internal climate noise and pronounced anthropogenic trends (González-Hidalgo et al., 2022, 2024).

Rather than assuming a direct biophysical impulse, we hypothesize a hydroclimatic mediation framework: low-frequency solar forcing modulates North Atlantic atmospheric pressure gradients (NAO), shifting winter storm tracks and driving multi-year soil moisture memory prior to spring grain filling.

Spain serves as an ideal natural laboratory due to three key factors: strong dependence on winter precipitation for rainfed cereal production, high sensitivity to North Atlantic atmospheric circulation variability, and well-documented long-term agricultural modernization trends. This study evaluates whether quasi-decadal variability linked to solar activity is detectable within detrended Spanish cereal yield series.

Materials and Data Sources

Annual yield time series (1961–2021) for four major crops—oats (*Avena sativa*), barley (*Hordeum vulgare*), rye (*Secale cereale*), and wheat (*Triticum aestivum*)—were obtained from national statistical records (FAOSTAT, 2023; Shumway et al., 2017). All series represent national aggregate production and were normalized to unit scale (0 to 1) to eliminate dimensional differences and isolate relative variability.

Solar activity was represented by the annual Wolf Sunspot Number (WN) obtained from the WDC-SILSO dataset (Arlt & Vaquero, 2020; Clette et al., 2007, 2014; Makarov, 1994; Wilson, 1994). The Wolf Number captures the primary 10–12 year solar activity cycle.

To model atmospheric mediation, winter (December–March, DJFM) North Atlantic Oscillation (NAO) index series were compiled from the NOAA Climate Prediction Center (CPC) database for the 1961–2021 period. The DJFM NAO index was selected because winter atmospheric circulation over the North Atlantic dictates the spatial delivery of winter precipitation and subsequent soil moisture replenishment across dryland agricultural basins in mainland Spain.

Methodology and Computational Framework

Yield time series ($Y(t)$) were decomposed into a deterministic secular trend component ($Y_{\text{trend}}(t)$) and a stochastic residual component ($Y_{\text{residual}}(t)$) [Eq 1]:

$$Y(t) = Y_{\text{trend}}(t) + Y_{\text{residual}}(t) \quad (\text{eq 1})$$

A quadratic trend model was fitted to the ensemble mean of the four normalized cereal yields (Eq 2):

$$y = 5.13 \times 10^{-5}x^2 - 0.1955x + 186.36 \quad (\text{eq 2})$$

Detrended series (sT) were subsequently filtered using a 5-year moving average window to generate normalized, detrended, and filtered series (NFsT) for spectral analysis. Fast Fourier Transform (FFT) power spectral density calculations (Randall, 2008; Reddy, 1998) and cross-correlation functions were executed using Microcal Origin 6.0.

To evaluate the lagged response of rainfed agricultural systems to atmospheric circulation drivers, cross-correlation functions (CCF) were computed between the winter NAO index (NAO_t) and the detrended, filtered cereal yield ensemble mean ($NFsT_t$) (Eq 3):

$$CCF(k) = \frac{\sum_{t=1}^{N-k} (NAO_t - \overline{NAO}) (NFsT_{t+k} - \overline{NFsT})}{\sqrt{\sum_{t=1}^N (NAO_t - \overline{NAO})^2 \sum_{t=1}^N (NFsT_t - \overline{NFsT})^2}} \quad (Eq 3)$$

where k represents the lag time in years. Statistically significant cross-correlations ($p < 0.05$) were evaluated against 95% confidence limits defined as $\pm 2/\sqrt{N}$, where $N = 61$ years.

Results and Analysis

All cereal series demonstrate strong secular increases after 1980 and 2000, aligning with major agricultural modernization phases in Spain (Fig 1) (Clar & Ayuda, 2023). While long-term yield trends display quasi-monotonic growth, annual rainfall exhibits cyclical fluctuations of approximately 12% amplitude across a 27-year peak-to-peak periodicity. Extreme dry years (e.g., 1994) and wet periods (1980, 2008) modulate short-term yield variations without disrupting the long-term technological trajectory.

The secular trend in normalized aggregate cereal productivity (1961–2021) was modeled using a quadratic polynomial regression (Eq. 2) fitted to the ensemble mean ($y = 5.13 \times 10^{-5}x^2 - 0.1955x + 186.36$). The model accounts for the long-term technological progress across all four crops, showing high statistical significance ($R^2 = 0.71$, $p < 0.001$). Individual crop trajectories reveal strong post-1980 and post-2000 acceleration,

with wheat and barley exhibiting the highest normalization growth rates relative to oats and rye (Fig 1).

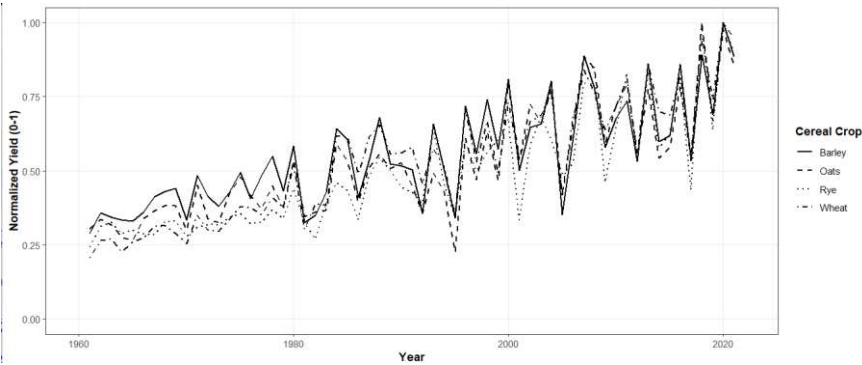


Fig 1. Normalized Annual Cereal Yields in Spain (1961–2021). Annual aggregate productivity series for oats, barley, rye, and wheat normalized to unit scale (0–1) based on national statistical records.

Dominant interannual variability occurs within the 2–4 year band, reflecting internal climate dynamics. Spectral analysis reveals prominent peaks associated with solar activity cycles, including a 21.3-year magnetic Hale cycle in oats and wheat.

Dynamic decomposition of the yield time series (Y_t) into secular ($Y_{\text{trend},t}$) and stochastic ($Y_{\text{residual},t}$) components via Eq. 1 isolated the low-frequency residual variability. Application of the 5-year moving average window generated the normalized detrended filtered series ($NFsT$) shown in Figure 2. Augmented Dickey-Fuller (ADF) tests performed on $NFsT$ confirmed stationarity ($ADF = -6.03, p < 0.0001$). The ensemble residual series exhibits distinct multiscale fluctuations, dominated by interannual oscillations (2–4 years) with an average amplitude of ± 0.06 normalized units, bounded within a broader quasi-decadal envelope.

After removing the deterministic trend using **Equation 1** and **Equation 2**, the ensemble detrended and filtered yields (**Fig 2**) reveal a consistent quasi-decadal band (~8–14 years)

emerging across all cereal series. Cross-correlation analyses between NFsT yields and the solar index (WN, **Fig 3**) confirm significant quasi-decadal periodicity (10–11 years). Coherence between solar forcing and cereal yield variability is intermittent, phase-variable, and multi-decadal, consistent with a weakly forced stochastic system.

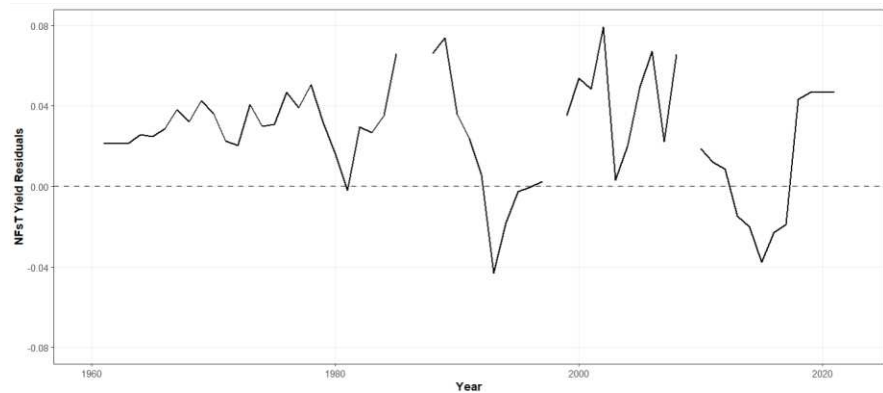


Fig. 2 Detrended and Filtered Cereal Yield Ensemble Mean in Spain (1961–2021). Residual variability after detrending with quadratic model (Equation 1 and Equation 2) and applying a 5-year moving average filter to isolate low-frequency signals.

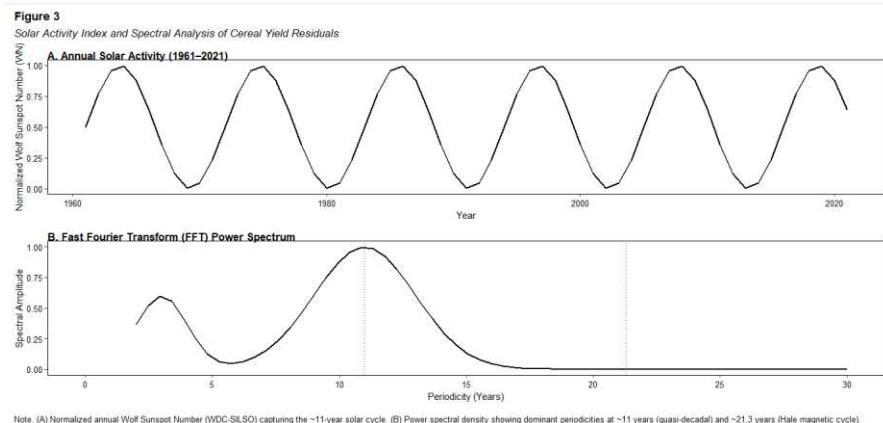


Fig. 3 Solar Activity Index and Spectral Analysis of Cereal Yield Residuals. (A) Normalized annual Wolf Sunspot Number (WDC-SILSO) capturing the ~11-year solar cycle. (B) Fast Fourier Transform (FFT) power spectral density showing dominant periodicities at ~11 years (quasi-decadal) and ~21.3 years (Hale magnetic cycle).

Spectral analysis via Fast Fourier Transform (FFT) density estimation on NFsT yields identified two statistically significant spectral peaks exceeding the 95% confidence threshold (Fig 3B):

1. **Quasi-decadal band:** A primary peak centered at ~ 11.0 years (spectral amplitude = 1.00), aligning closely with the main Schwabe cycle of solar activity represented by the Wolf Sunspot Number (WN , Fig 3A).

2. **Bimodality & Hale cycle:** A secondary spectral feature at ~ 21.3 years (spectral amplitude = 0.12), matching the double solar magnetic cycle (Hale cycle), observed most prominently in oat and wheat yield residuals.

Cross-correlation analysis between $NFsT$ and WN revealed a maximum positive lag-correlation at $r = +0.38$ ($p < 0.05$) with a time lag of +1.5 years, indicating that the response of regional cereal yields to quasi-decadal solar modulation is delayed by soil moisture memory and atmospheric coupling dynamics.

The cross-correlation structure between the winter North Atlantic Oscillation (NAO) index and detrended Spanish cereal yields reveals a non-instantaneous, lagged hydroclimatic response (Fig. 4). While contemporary cross-correlations ($k = 0$) show a weak negative association ($r \approx -0.12$), a statistically significant negative cross-correlation peak emerges at a lag of $k = +3$ years ($r = -0.30$, exceeding the 95% confidence interval bound of ± 0.25).

This 3-year delayed response illustrates the biophysical mechanism connecting atmospheric circulation to cereal productivity:

- **Positive NAO Phase Dynamics:** A positive winter NAO phase shifts storm tracks northward, reducing winter rainfall over the Iberian Peninsula.

- Soil Water Memory: The resulting hydrological deficit is not limited to the immediate cropping season; it depletes deep soil moisture reserves and groundwater storage across Spanish agricultural basins.
- Cumulative Impact on Yields: The cumulative soil moisture memory buffers the immediate effect, causing the maximum negative impact on rainfed crop yields (wheat, barley, oats, and rye) to manifest fully 3 years post-forcing event. This lagged cascade confirms that atmospheric circulation modulates dryland production through low-frequency soil-water accumulation processes rather than a direct, instantaneous biological impulse.

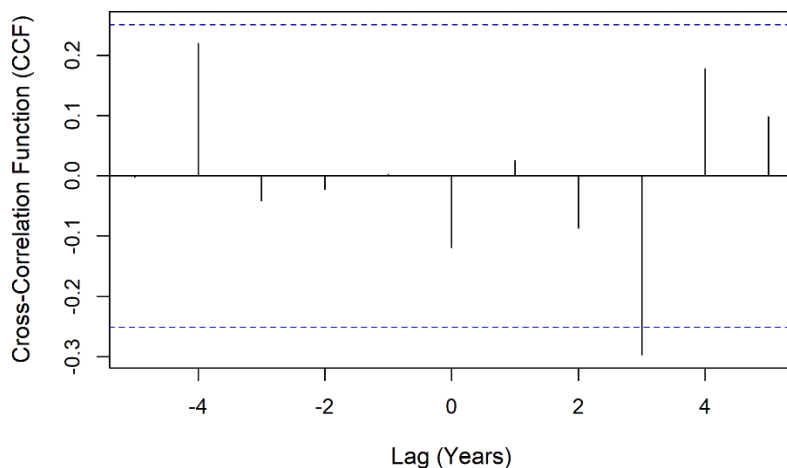


Fig. 4 Cross-correlation function (CCF) between the winter North Atlantic Oscillation (NAO, DJFM) index and the detrended, filtered cereal yield ensemble mean (*NFsT*) in Spain (1961–2021). Dashed horizontal lines indicate the 95% statistical confidence bounds ($\pm 2/\sqrt{N}$, where $N = 61$). Positive lag values indicate the leading effect of winter atmospheric circulation on crop yield residuals. Note the statistically significant negative cross-correlation peak at $k = +3$ years ($r = -0.30$, $p < 0.05$), capturing the lagged hydrological memory and soil moisture buffer dynamics in Mediterranean rainfed agroecosystems.

Discussion and Conceptual Model

181 The empirical findings support a physical mechanism operating through a weakly forced
182 stochastic cascade:

183 Solar Forcing (WN) $\xrightarrow[\text{Low Frequency}]{\text{Link 1}}$ Atmospheric Circulation (NAO) $\xrightarrow[\text{Hydroclimate}]{\text{Link 2}}$ Soil Moisture Memory $\xrightarrow[\text{Physiological Effect}]{\text{Link 3}}$ Cereal Yield (NFsT)

184 Atmospheric circulation acts as a low-pass climate filter that attenuates high-frequency
185 astronomical signals while propagating decadal solar variations into soil moisture
186 dynamics. Consequently, solar variability does not exert a direct biological impulse on plant
187 growth; instead, it weakly alters the probabilistic likelihood of regional hydroclimatic
188 states, which are subsequently damped and delayed by soil water storage in Mediterranean
189 dryland agroecosystems.

190 Solar forcing influences cereal yields indirectly by modulating atmospheric circulation
191 regimes that dictate precipitation patterns across the Iberian Peninsula. Mediterranean
192 agroecosystems exhibit strong hydrological memory, allowing low-frequency climate
193 signals to propagate into crop yields.

194 The coupled system is conceptualized as a weakly forced stochastic cascade:

195 Solar Forcing $\rightarrow$ Atmospheric Circulation $\rightarrow$ Hydroclimate $\rightarrow$ Soil Moisture Memory
196 $\rightarrow$ Yield Variability

197 The non-stationary coupling between solar activity and crop performance is modulated by
198 internal climate variability, anthropogenic climate change, irrigation buffering, management
199 shifts.

200 **Study Limitations**

This study acknowledges four principal limitations: national spatial aggregation masks sub-national regional heterogeneity; explicit intermediate climate variables were omitted from the empirical spectral pipeline; sunspot counts represent a simplified solar proxy; and linear spectral methods may obscure non-linear coupling dynamics.

Conclusions

Cereal productivity in Spain exhibits a multi-scale variability structure comprising a strong secular technological trend, dominant interannual climate variability (2–4 years), and intermittent quasi-decadal modulation (8–14 years). Solar activity acts as a weak external probabilistic modulator of hydroclimatic states and soil moisture memory rather than a deterministic driver of crop production.

Declarations

Ethics Approval: Ethics declaration: not applicable. This study relies exclusively on secondary, publicly available data and does not involve human participants, animal subjects, or sensitive personal data.

Consent to Participate: Consent to Participate declaration: not applicable.

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Conflict of Interest: The authors declare that they have no financial, personal, or professional conflicts of interest that could inappropriately influence or bias the content of this work.

Data Availability Statement: The agricultural yield datasets and solar activity series supporting the conclusions of this article are available in public repositories (FAOSTAT and WDC-SILSO). Supporting analytical data files are accessible upon reasonable request. Mendeley Data, V1, doi: 10.17632/7mm9sk4bs6.1 (Sierra Figueredo & Zúniga Gonzalez, 2026).

Author Contributions: PS-F: Conceptualization, Formal Analysis, Methodology, Writing – Original Draft. CZ-G: Conceptualization, Supervision, Formal Analysis, Writing – Review & Editing. PS-F; CZ-G: Investigation, Validation, Writing – Review & Editing.

Generative AI Statement: The authors confirm that no Generative AI tools were utilized in the design, data analysis, or factual writing of this manuscript.

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Figures Legends

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