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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

National Autonomous University of Nicaragua

Research Article

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Posted Date: October 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11355274/v1>

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Additional Declarations: The authors declare no competing interests.

Cereal crop yields in Spain and their relationship with climate and solar activity

Pablo Sierra-Figueredo¹ 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 shaped by technological and management improvements, while interannual variability is strongly influenced by climatic conditions. This study examines whether low-frequency variability associated with solar activity is detectable in long-term cereal yield records from Spain. Annual yield series for oats, barley, rye, and wheat covering 1961–2021 were normalized and analyzed alongside annual sunspot numbers. Long-term trends were separated from residual variability, and fast Fourier transform (FFT) spectral analysis and cross-correlation functions were used to investigate variability across different timescales. The results show substantial long-term increases in cereal yields, together with dominant interannual variability at approximately 2–4 years and a broader quasi-decadal component within the 8–14-year range. Some spectral features overlap with the characteristic timescales of solar activity, suggesting a possible temporal association. However, the observed similarities do not establish a causal relationship or demonstrate a physical mechanism linking solar variability to agricultural

production. A conceptual framework involving atmospheric circulation and hydroclimatic variability is proposed as a potential pathway through which low-frequency environmental signals could affect cereal yields. This mechanism remains to be tested using explicit climatic and hydrological variables. The findings therefore support further investigation of multiscale variability in agricultural productivity while emphasizing the need for robust statistical validation and independent evidence before attributing crop yield fluctuations to solar forcing.

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; and Pellegrini et al.,). Although long-term yield increases since the mid-twentieth century are largely explained by genetic improvement, fertilizer application, mechanization, and irrigation expansion (Spiertz, 2014; 2022; Vitali et al., 2019), residual interannual variability remains heavily driven by climate dynamics (Kukal & Irmak, 2018; Sierra et al., 2015).

It have been hypothesized that external climate forcing sources, including solar activity (Harrison Virden, 1976; Melnik & Drebot, 2019; Pustilnik & Yom Din, 2013), contribute to low-frequency variability in regional climate systems (Sierra et al., 2019, 2022, 2025a, 2025b; Sierra-Figueredo et al., 2021, 2022; Tripathi et al., 2022; 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). Furthermore, potential ecological mechanisms such as insect-mediated pollination cannot be dismissed within the broader chain of phenomena influencing crop yield dynamics (Miñarro et al., 2018; Sierra et al., 2015), as prior empirical evidence demonstrates a clear association between geomagnetic activity cycles and apicultural productivity over a span of two decades (Sierra et al., 2015).

Rather than assuming a direct biophysical impulse, 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.

2. Materials and Data Sources

2.1 Agricultural yield data

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, 2026; 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, as illustrated in Fig. 1.

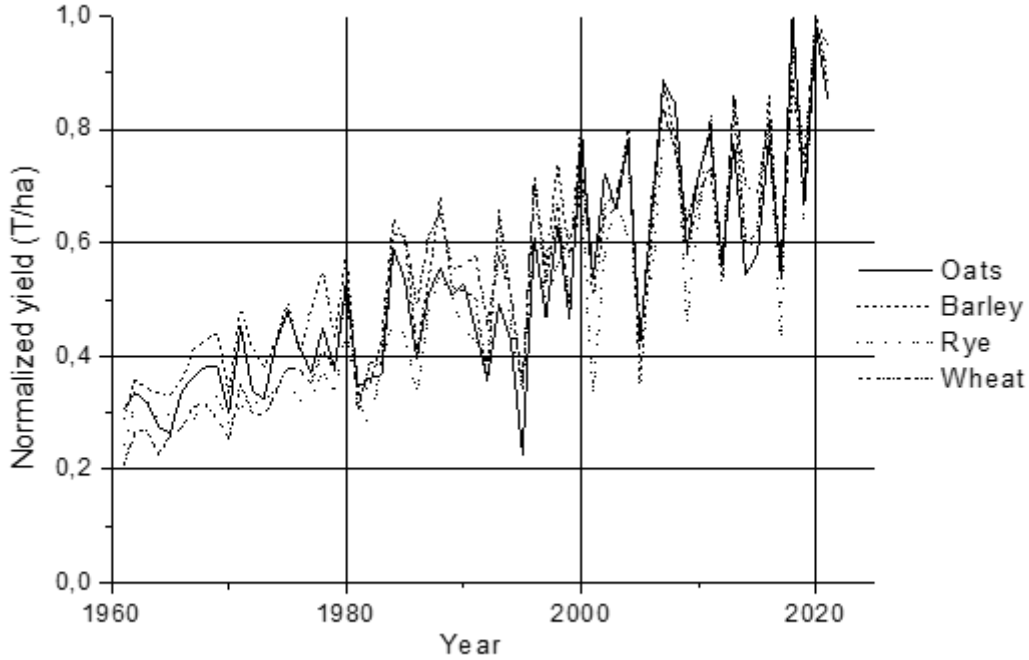


Fig. 1 Annual yield graphs (normalized) over 60 years for the four cereal crops across Spain. Normalization was performed by dividing each series by its maximum value, resulting in values ranging from 0 to 1 for each series (Microcal Origin 6.0). Given the similarity in the trends of the four series, their average was calculated for trend analysis.

The normalized quadratic trend (N) fitted to the mean of the four series yielded the following expression [Eq 1] where Yield time series ($Y(t)$) were decomposed into a deterministic secular trend component ($Y_{\text{trend}}(t)$) and a stochastic residual component ($Y_{\text{residual}}(t)$):

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

A quadratic trend model was fitted to the ensemble mean of the four normalized cereal yields (Eq 2), as shown in Fig. 2:

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

The detrended series (sT) were subsequently filtered using a 5-year moving average window to generate the normalized, detrended, and filtered series (NFsT) for spectral analysis. Augmented Dickey-Fuller (ADF) tests performed on the NFsT series confirmed stationarity (ADF=−6.03,p<0.0001). Consequently, Fast Fourier Transform (FFT) power spectral density calculations (Randall, 2008; Reddy, 1998) and cross-correlation functions were consistently based on this filtered NFsT series.

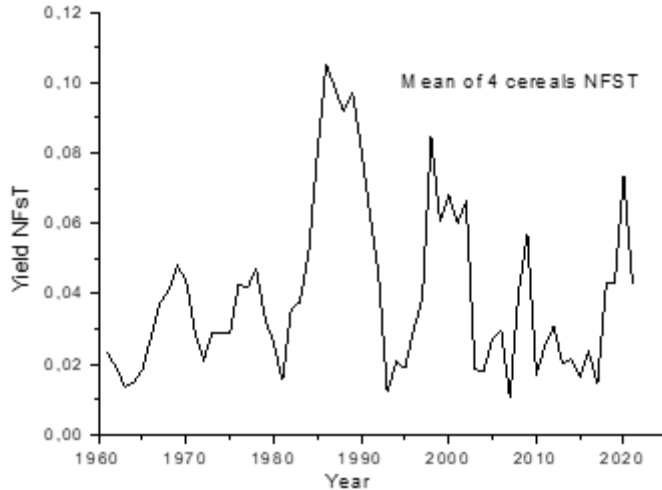


Fig. 2 Mean yield of the four cereals, normalized, filtered, and with the fitted quadratic trend removed (NFsT). Fig. 1 demonstrates the strong similarity among the four graphs; therefore, the meaning is assumed to be representative of them.

2.2 Solar activity indicator

Solar activity (Arlt & Vaquero, 2020; Clette et al., 2007, 2014; Makarov, 1994; Wilson, 1994) was represented by the annual Wolf Sunspot Number (WN) obtained from the WDC-SILSO dataset. The Wolf Number captures the primary 10–12 year solar activity cycle (Fig. 3).

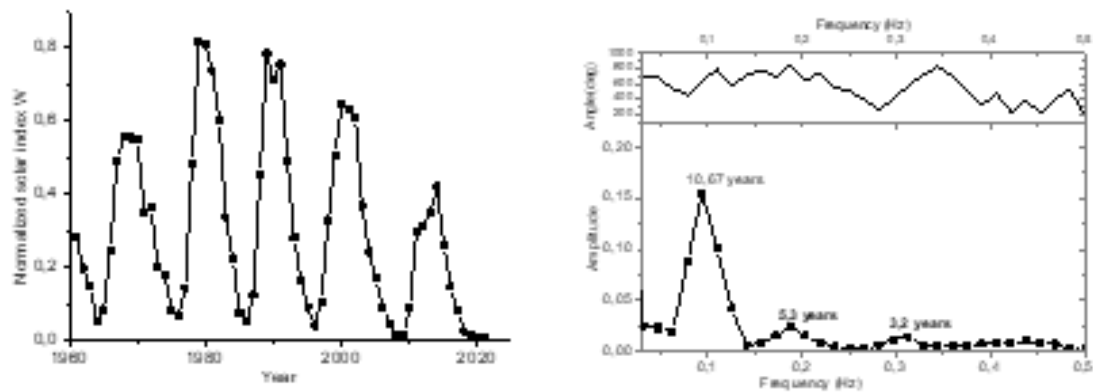


Fig. 3 Annual average (normalized) of the Wolf Number (WN) from 1960 to 2021 (left) and its periodogram obtained via FFT (right), showing the prominent peaks that spectrally characterize solar activity.

2.3 Methods

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.

Building upon this framework, the detrended series (s_T) were subsequently filtered using a 5-year moving average window to generate normalized, detrended, and filtered series

(*NFsT*). Fast Fourier Transform (FFT) power spectral density calculations (Randall, 2008; Reddy, 1998) and cross-correlation functions were then executed using Microcal Origin 6.0 to evaluate the multi-scale spectral properties and lagged system responses.

The coupled system was modeled as a weakly forced stochastic cascade:

Solar forcing → *Atmospheric circulation* → *Hydroclimate* → *Soil moisture* → *Yield variability*

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.

3. Results

3.1 Long-term productivity trends

All four cereals show strong long-term increases, particularly after 1980 and again after approximately 2000. This pattern is consistent with the phases of agricultural modernization (Clar Ernesto and Ayuda María I. 2023) during the study period. **Fig. 1** shows that the long-term yield trend is quasi-monotonically increasing, whereas **Fig. 4C** reveals multi-year cyclical behavior in the short term; this behavior mirrors and is in phase with the annual average precipitation shown in **Fig. 4A**, exhibiting fluctuations on the order of 10 to 12 years

that closely align with solar activity cycles (**Fig.. 4B**), albeit with a marked phase lag in some instances. This implies that the years around 1980 and 2008 were generally characterized by wet seasons in Spain, whereas 1994 and the surrounding years saw a dry season—a contrast that does not appear to have had a notable impact on the yield curve.

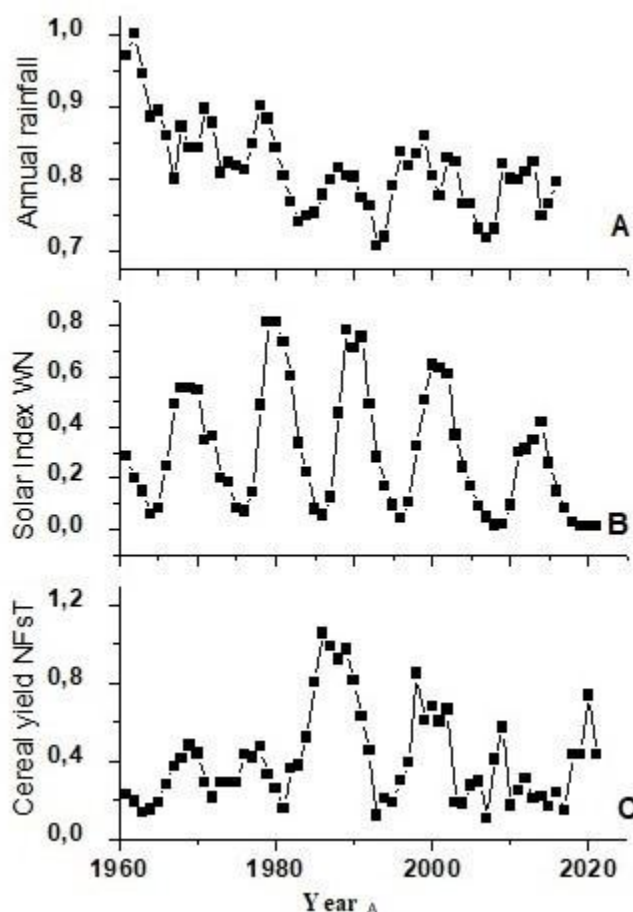


Fig. 4 Comparative panel of the annual cumulative rainfall regime (A), the WN solar index (B), and the curve of mean yield fluctuations for the four cereals studied (NFsT) (C).

3.2 Interannual variability

The dominant variability occurs in the 2-to-4-year range—consistent with internal climate variability influencing precipitation and temperature patterns, as evidenced by the obtained periodograms (Randall, 2008; Reddy, 1998)—while periods related to solar activity appear

with significant power, including the 21.3-year cycle (the Sun's magnetic period; Makarov, 1994) for oats and wheat (Fig. 5). Furthermore, Fig. 4A shows that years of severe drought correspond to peaks in yield decline, while rainy seasons align with yield increases; although a 3-to-4-year lag is observed during the 1980s, a strong correlation is generally evident over long periods, except in the 1960s, when this relationship appears inverted.

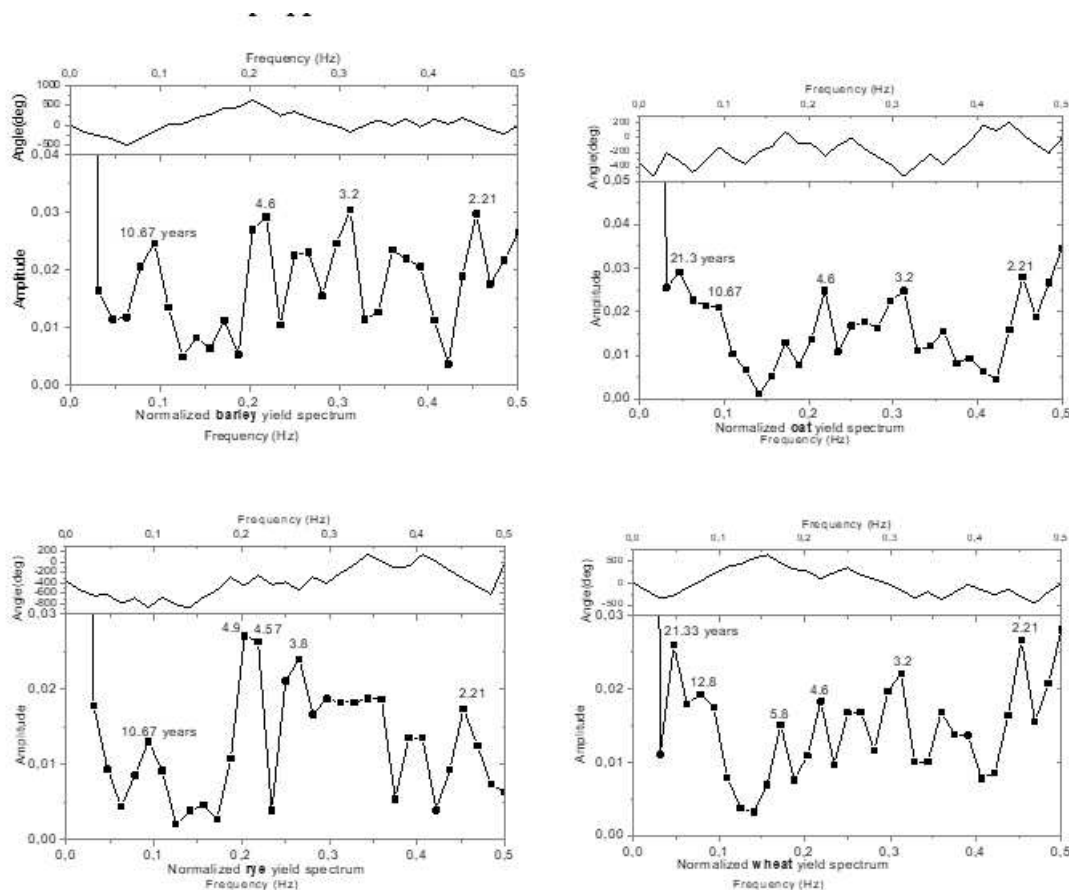


Fig. 5 Periods (T) present in the normalized (N), detrended yield time series of the four cereals studied, obtained via FFT calculation (Microcal Origin 6.0). The most prominent peaks are labeled with the corresponding number of years. ($T = 1/f$)

4.3 Quasi-decadal variability

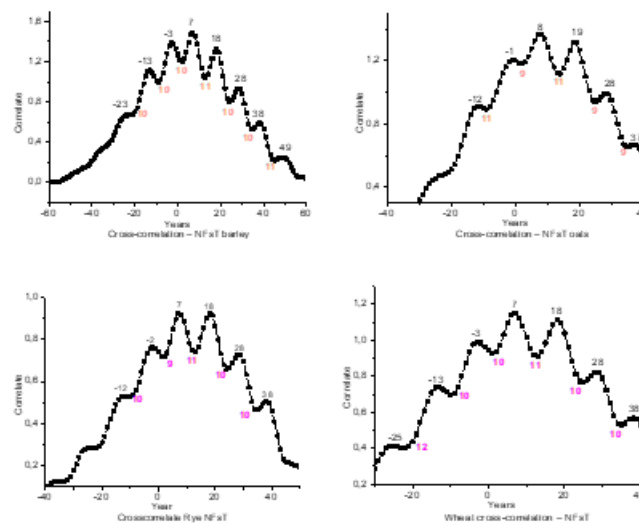
172 The temporal coherence between solar activity and agricultural yield variability displays
 173 three distinct structural properties:

174 Intermittency: The coupling is non-continuous, appearing prominently during specific
 175 epochs while remaining subdued in others.

176 Phase variability: The alignment between signals exhibits non-stationary phase shifts across
 177 decades.

178 Episodic intensification: Signal strength increases markedly during specific multi-year
 179 intervals rather than maintaining uniform amplitude.

180 This complex behavior is fully consistent with a weakly forced stochastic system operating
 181 under the strong imprint of internal climate variability. These dynamic patterns are explicitly
 182 detailed in Fig. 7, which illustrates the cross-correlation results (executed via Microcal Origin
 183 6.0) between the normalized, detrended, and filtered cereal yield series (NFsT) and the Wolf
 184 Number (WN) solar activity time series.



4. Discussion

4.1. Interpretation within climate system dynamics

The potential association between solar activity and agricultural yield variability in Spain should be interpreted within the broader framework of climate system dynamics. Rather than exerting a direct influence on crop production, solar variability may be associated with changes in atmospheric circulation patterns that modulate precipitation distribution, temperature conditions, and the occurrence of droughts across the Iberian Peninsula. In this context, the identification of temporal synchronization between solar activity and agricultural performance would represent a potential statistical relationship whose physical interpretation requires further investigation. Previous research has explored associations between solar variability and hydrometeorological processes, including precipitation variability and extreme hydrological events, although the strength and mechanisms of these relationships remain dependent on the climatic region and the variables considered (Muthanna et al., 2016; Lin et al., 2021).

The relevance of this potential connection is particularly evident in the Mediterranean climate, where agricultural production is strongly influenced by precipitation variability and the recurrence of drought conditions. Long-term precipitation records for mainland Spain reveal substantial temporal and seasonal variability, providing an important climatic context for interpreting fluctuations in agricultural productivity (González-Hidalgo et al., 2022, 2024). Furthermore, the analysis conducted by Páscoa et al. (2017) demonstrated the importance of drought in explaining interannual wheat yield variability across the Iberian Peninsula. Consequently, any apparent correspondence between solar cycles and

agricultural yields should be evaluated in relation to the climatic processes that directly affect crop growth, rather than interpreted as evidence of a direct solar effect. Research examining solar activity and agricultural production in other geographical contexts has also reported potential temporal associations between solar variability and crop performance (Harrison Virden, 1976; Melnik and Drebot, 2019; Sierra et al., 2025a). However, these findings do not establish a universal relationship or demonstrate that solar activity independently determines agricultural outcomes. Instead, they support the need to investigate whether low-frequency solar variability may coincide with climatic oscillations or other environmental processes that influence agricultural production. Establishing such a mechanism would require explicit examination of the intermediate atmospheric and hydrological variables involved.

4.2. Role of soil moisture memory

Soil moisture provides a plausible mechanism through which climatic variability may be translated into agricultural yield fluctuations over time. In Mediterranean agroecosystems, soil water availability reflects not only current precipitation but also antecedent rainfall, evaporative demand, soil properties, vegetation cover, and agricultural water management. These interacting processes can generate hydrological memory, whereby water deficits or surpluses persist beyond the meteorological conditions that initially produced them. Consequently, the effects of climatic variability on crop development may extend across successive growth stages, influencing biomass accumulation, reproductive development, and final yield.

Evidence from the Iberian Peninsula supports the importance of drought conditions in explaining interannual wheat yield variability, highlighting the close relationship between water availability and agricultural performance (Páscoa et al., 2017). Similarly, studies in other agricultural regions have demonstrated that crop responses depend on drought characteristics and their interaction with production conditions, including fertilization practices (Pellegrini et al., 2022). These findings suggest that the effects of climatic variability on yields cannot be fully understood through contemporaneous precipitation alone, since the timing, duration, and persistence of water deficits may be equally important.

Within this framework, soil moisture memory offers a plausible, although not yet demonstrated, explanation for the persistence of low-frequency signals in agricultural time series. If solar activity were associated with recurring climatic variations, their effects on precipitation and evaporative demand could potentially influence soil water availability and, subsequently, crop performance. Nevertheless, this interpretation remains hypothetical in the absence of explicit soil moisture, drought, and water-balance variables. Therefore, future investigations should examine whether soil moisture acts as an intermediary between climatic variability and agricultural yields and whether its persistence contributes to any observed synchronization between solar activity and crop production.

4.3. Non-stationary coupling between solar activity and agricultural yield

The relationship between solar activity and agricultural performance should not necessarily be expected to remain constant throughout the study period. Agricultural yields emerge from the interaction of climatic conditions, crop physiology, technological development, management practices, and socioeconomic factors. Accordingly, any statistical association

between solar variability and agricultural production may change over time as the relative importance of these determinants evolves. Such non-stationarity is particularly relevant when analysing long-term agricultural records, because a relationship identified during one period may weaken, strengthen, or disappear under different environmental and production conditions.

One important source of non-stationarity is internal climate variability, which can alter the relationship between large-scale atmospheric circulation, regional precipitation, and agricultural water availability. In the western Mediterranean, documented changes in seasonal precipitation provide evidence that the climatic conditions affecting crop production are not temporally uniform (González-Hidalgo et al., 2024). In addition, anthropogenic climate change may modify temperature regimes, evaporative demand, drought frequency, and the distribution of precipitation, thereby changing the environmental context in which crops respond to climatic variability. The combined influence of climate change and agricultural production conditions has been examined in different geographical settings, illustrating the need to consider multiple interacting drivers of yield variability (Kukal and Irmak, 2018; Chandio et al., 2022; Vitali et al., 2019).

Agricultural modernization represents another important source of temporal change. In Spain, the transformation of rural economies and agricultural systems has altered production structures and farming practices over recent decades (Clar and Ayuda, 2023). Improvements in crop varieties, fertilization, mechanization, irrigation infrastructure, and other management practices can modify the sensitivity of yields to climatic fluctuations (Evans, 1980; Spiertz, 2014). Irrigation, in particular, may buffer the effects of precipitation deficits where sufficient water resources are available, although its effectiveness depends

on water availability, infrastructure, and management. Consequently, the same climatic anomaly may produce different agricultural outcomes depending on the technological and institutional context in which it occurs.

Biological factors may further contribute to this changing relationship. Crop yields depend on successful pollination, reproductive development, and the activity of pollinating insects, among other biological processes. Changes in pollinator abundance and diversity, together with environmental stress during critical developmental stages, may affect reproductive success and final production (Miñarro et al., 2018). These processes provide additional reasons why agricultural responses to climatic variability may differ among crops, regions, and periods. Thus, even if a recurring association between solar activity and crop yields were identified, its expression would likely depend on the combined effects of climate variability, agricultural adaptation, resource availability, and biological constraints.

Taken together, these considerations suggest that potential solar–agricultural synchronization should be interpreted as a context-dependent relationship rather than a stable or universal mechanism. Previous investigations into the possible synchronization of solar activity and agricultural performance provide a basis for further comparative research (Sierra et al., 2025a; Sierra et al., 2025b). Nevertheless, determining whether such synchronization reflects a persistent physical connection, indirect climatic mediation, or coincidental correspondence between low-frequency time series requires additional statistical and mechanistic evidence.

4.5. Limitations

Several limitations should be considered when interpreting the results of this study. First, the use of nationally aggregated agricultural yield data may obscure substantial regional differences in climatic conditions, soil characteristics, crop distribution, and agricultural management. Spain encompasses contrasting climatic and agroecological environments, meaning that national averages may combine regions with different, or even opposing, responses to the same climatic fluctuations. Although long-term agricultural statistics provide a valuable basis for identifying broad temporal patterns (FAOSTAT, 2026), regional or provincial analyses would be necessary to determine the spatial consistency of any observed association.

Second, the absence of explicit climate-mediating variables limits the ability to identify the physical processes underlying potential relationships between solar activity and agricultural yields. In particular, precipitation, temperature, soil moisture, drought indices, atmospheric circulation, and irrigation availability should be incorporated into future analyses. Long-term precipitation datasets for mainland Spain provide relevant resources for this purpose (González-Hidalgo et al., 2022, 2024). Including these variables would help determine whether any statistical association between solar activity and agricultural performance is mediated by climate variability or instead reflects other temporal processes.

Third, the use of sunspot number as a proxy for solar activity represents a simplification of the complex variability of the Sun and the broader space environment. Although sunspot records constitute an important resource for reconstructing historical solar variability, their interpretation requires attention to the homogenization and calibration of observations across different periods (Clette et al., 2007, 2014; Arlt and Vaquero, 2020). Furthermore, different solar and geomagnetic indicators represent distinct aspects of solar variability and

may not exhibit equivalent relationships with terrestrial environmental processes. Therefore, comparisons involving alternative solar indices could help assess the robustness of the observed patterns.

Finally, the application of linear spectral and correlation methods may not fully capture nonlinear relationships, time-varying associations, or interactions among multiple climatic and agricultural drivers. Spectral analysis is useful for identifying recurring periodic components in time series, but the presence of similar spectral peaks does not, by itself, establish synchronization, causality, or a shared physical mechanism (Randall, 2008; Reddy, 1998). Moreover, long-term trends and autocorrelation can affect the statistical interpretation of apparent periodicities. Future research should therefore incorporate appropriate time-series modelling and robustness tests, including the assessment of trends, serial dependence, and the statistical significance of detected periodic components (Shumway and Stoffer, 2017). Nonlinear and time-frequency approaches could provide additional insight into whether potential solar–agricultural associations persist across different periods and climatic conditions.

Overall, these limitations indicate that the results should be interpreted as an initial contribution to understanding possible temporal associations between solar variability and agricultural performance in Spain. Establishing a robust physical interpretation will require integrating solar indicators with regional climate observations, hydrological information, biological processes, and changes in agricultural management. Such an approach would help distinguish statistical synchronization from physically meaningful relationships and clarify the extent to which solar variability contributes, directly or indirectly, to long-term agricultural yield variability.

5. Conclusions

Cereal productivity in Spain exhibits a multi-scale temporal variability structure resulting from the interaction of technological progress, climatic fluctuations, and potential low-frequency environmental modulation. The long-term evolution of agricultural yields reflects the substantial influence of technological development and changes in agricultural management, while interannual variability remains strongly associated with fluctuations in climatic conditions, particularly those affecting water availability. In addition to these dominant components, the results suggest the presence of intermittent quasi-decadal modulation, indicating that lower-frequency signals may contribute to the temporal structure of agricultural productivity. However, the identification of such patterns does not, by itself, establish a causal relationship with a specific external forcing mechanism.

Within this framework, solar variability may represent a weak external modulator of the hydroclimatic conditions affecting cereal production. Its potential influence would most plausibly operate indirectly, through possible changes in atmospheric circulation and precipitation variability, with subsequent effects on soil moisture availability and the hydrological memory of agroecosystems. These processes could contribute to the persistence or modulation of climatic signals affecting crop development and final yield. Nevertheless, the magnitude and consistency of this potential contribution are likely to depend on regional climatic conditions, crop characteristics, irrigation availability, agricultural management, and other environmental and biological factors, including insect pollination.

The principal conclusion is that solar variability should not be regarded as a direct or dominant control of agricultural productivity in Spain. Rather, it may constitute one of

several potential sources of low-frequency environmental modulation whose effects, if present, are conditioned by the interactions among the climate system, soil water dynamics, biological processes, and agricultural production systems. Consequently, the observed temporal patterns should be interpreted as evidence of potential variability at multiple timescales rather than as definitive proof of a causal solar influence on cereal yields.

Future research integrating regional agricultural statistics, climatic and hydrological variables, biological indicators, and alternative measures of solar activity will be essential to evaluate the robustness of these associations and clarify the mechanisms involved. Such an integrated approach would help determine whether the detected quasi-decadal patterns represent persistent environmental signals, time-dependent statistical associations, or coincidental similarities among temporal processes. Ultimately, understanding the relative contribution of these interacting factors is essential for improving the interpretation of long-term cereal yield variability and strengthening the scientific basis for agricultural adaptation under changing climatic conditions.

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.

Funding: The authors declare that no external financial support was received for the research, preparation, or publication of this manuscript.

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 acknowledge the use of generative AI tools (such as language models) solely for editorial assistance, including English language polishing, grammatical review, and stylistic refinement. No AI tools were used in conception, data design, mathematical modeling, statistical analysis, or drawing of scientific conclusions. All factual content, data interpretation, and final text were critically reviewed and approved by the authors.

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