Study of agricultural yield gaps using the WOFOST model: impact of La Niña on soybean production in Argentina

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Abstract. This study analyzes yield gaps in Argentina under highly variable climatic conditions, where water availability plays a key role in agricultural productivity. A high-resolution georeferenced database is used to integrate satellite, climate, and soil data into a 10 × 10 km grid covering the entire country. Using the WOFOST crop simulation model, soybean production is simulated for the period 2010–2025. The proposed approach captures differences between irrigated and rainfed systems, and the impact of extreme climatic events within a unified framework. Preliminary results show that yield gaps are strongly driven by water availability and vary significantly across years.

Keywords: Yield gap, WOFOST, Soybean, Argentina, La Niña

Estudio de brechas de rendimiento agrícola usando el modelo WOFOST: impacto de La Niña sobre la producción de soja en Argentina

Abstract. Este trabajo analiza las brechas de rendimiento en Argentina bajo condiciones climáticas altamente variables, donde la disponibilidad de agua juega un rol clave en la productividad agrícola. Se utiliza una base de datos georreferenciada de alta resolución que integra información satelital, climática y de suelo en una grilla de 10 × 10 km que cubre todo el país. El modelo biológico de cultivos WOFOST simula la producción de soja para el período 2010–2025. El enfoque propuesto captura las diferencias entre sistemas bajo riego y de secano, y el impacto de eventos climáticos extremos dentro de un mismo marco de análisis. Los resultados preliminares muestran que las brechas de rendimiento dependen fuertemente de la disponibilidad de agua y varían significativamente entre años.

Keywords: Brecha de rendimiento, WOFOST, Soja, Argentina, La Niña

1 Introduction

In general, there is a significant difference between actual crop yields and the potential yields that could be achieved under optimal conditions. This difference, known as the yield gap, is strongly influenced by climatic, soil, and agronomic management factors. This gap serves as a strategic tool to evaluate the country's productive capacity, enabling the identification of improvement opportunities in current systems to ensure national food and economic security.

In Argentina, agricultural production exhibits high interannual variability, mostly associated with climatic phenomena such as El Niño and La Niña. These variations directly affect yields and make it necessary to consider climate as a key factor in production analysis. However, many studies analyze yields at a general level, without considering the differences within each region. Additionally, they often fail to distinguish between irrigated and rainfed areas, even though these management differences have a significant impact on yields.

In this context, this study aims to analyze the yield gap in Argentina by incorporating both climatic variability and differences in production management. The objective is to examine how these conditions affect production over time and across different regions.

2 Metodological Approach

2.1 WOFOST: Crop Simulation Model

The PCSE (Python Crop Simulation Environment) package is used to simulate crop growth. PCSE is a Python-based library that implements several agricultural simulation models (de Wit, 2024). The WOFOST model is used to simulate crop growth, development, and yield under different environmental conditions (de Wit et al., 2020). Two simulation modes were run: potential production and water-limited production. In **potential production** (Y_p), crop growth is determined by meteorological conditions, atmospheric CO_2, and crop characteristics, with water and nutrient supply assumed unlimited and biotic stresses excluded. **Water-limited production** (Y_w), by contrast, explicitly simulates the soil water balance. Initial soil water content was set to 50% of available water capacity (field capacity minus wilting point) for each soil profile (de Wit et al., 2017). Under this mode, rainfall, soil water storage, and crop water use determine the amount of water available to the crop.

Following previous studies that calibrated the model for Argentina (de Wit et al., 2017), an adapted version of WOFOST for soybean is used. These studies developed a hybrid scheme ("WOFOST-Soybean") that replaces sequential phenological development with a parallel approach and incorporates mathematical functions to simulate the crop's high sensitivity to photoperiodGrowth parameters were also recalibrated to correct unrealistic levels of low biomass and excessive leaf area index.

All simulations represented a single soybean growing season from November to April, spanning two calendar years. Following the regional soybean calendar proposed in the Argentine adaptation of WOFOST (de Wit et al., 2017), crop emergence was assigned according to the maturity group of each cultivar. Since all five grid cells analyzed in this study belong to maturity group VI, crop emergence was fixed on November 15. A maximum crop cycle length of 180 days was allowed, though the actual duration varied with simulated temperature and photoperiod conditions.

This study develops an analysis based on a high-resolution georeferenced dataset for Argentine agriculture, organized into a regular grid of 10×10 km cells covering the entire national territory. To run the simulation, an original database SIMPLE-G-AR is constructed, integrating the following data sources: land use (NASA GFSAD30), water management and irrigation (NASA LGRIP30), soil properties (SoilGrids), and climatic variables (NASA POWER). Within each cell, irrigated and rainfed areas are identified based on land use information (Romero Gomez et al., 2026).

2.2 Agricultural Production under Water Stress

To assess the production gap, soybean simulations were run using PCSE and the collected data, covering the period from 2010 to 2025. This period includes multiple La Niña, El Niño, and neutral conditions. Each crop season was classified according to the Oceanic Niño Index (ONI), averaged over October–March to represent the ENSO conditions experienced during soybean development rather than the calendar year.

This approach makes it possible to integrate, within a single framework, spatial variability, differences in water management, and the effects of climatic variability on crop yields. Water availability is one of the main factors controlling crop growth, as it directly influences transpiration, photosynthesis, biomass accumulation, and ultimately grain yield. Water deficits are particularly detrimental when they occur during the critical reproductive stages of crop development.

To quantify the impact of water availability on soybean production, the yield gap (Y_g) was calculated as the difference between potential yield (Y_p) and water-limited yield (Y_w): $Y_g = Y_p - Y_w$

3 Preliminary Results

For the preliminary analysis, a set of grid cells previously used in earlier studies (de Wit et al., 2017) was selected. These are shown in Fig. 1, located in the central region of Argentina, mainly in the provinces of Córdoba and Santa Fe.

For grid cells containing both irrigated and rainfed soybean areas, a single representative yield was obtained as an area-weighted average of the simulated yields, using the proportion of soybean area under each management condition as weights.

Panel (a) in Fig. 1 shows the interannual variability of growing-season precipitation for the selected grid cells. Background colors identify the ENSO phase of each season: red for El Niño, blue for La Niña, and gray for neutral conditions.

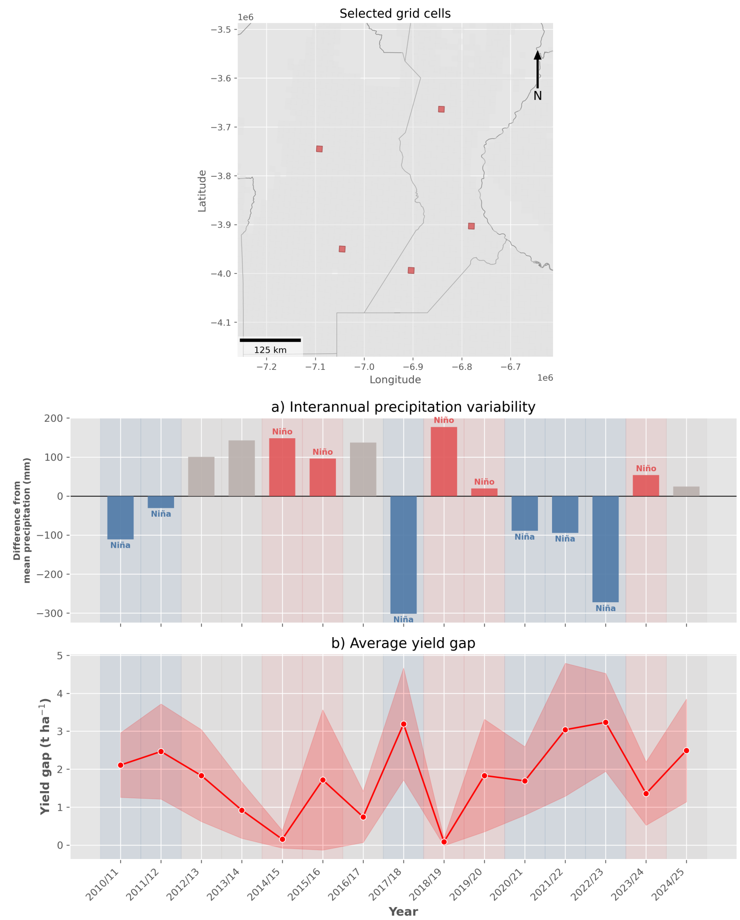

Fig. 1. Map: Location of the analyzed grid cells in the central region of Argentina. (a) Interannual variability of growing-season precipitation (October–March), shown as the deviation from the mean seasonal precipitation. Background colors represent the ENSO phase. (b) Average annual yield gap, defined as the difference between potential yield and water-limited yield.

Most La Niña seasons had below-average precipitation, while El Niño seasons tended toward above-average rainfall, consistent with the known influence of ENSO on regional water availability. Even so, precipitation anomalies varied substantially among years within the same phase, showing that ENSO sets a general tendency rather than determining seasonal rainfall outright. These differences in water availability provide the climatic context for interpreting the interannual variability in the simulated yield gap.

Fig. 1.(b) shows the temporal evolution of the average yield gap, where the line represents the annual average value across the selected grid cells, while the

shaded band indicates spatial variability among cells, expressed as the standard deviation.

In years when the band is narrow, there is little variation in yield gaps across cells. In contrast, a wider band indicates greater differences in observed values across regions, meaning that not all areas responded in the same way to water conditions. This latter point can be observed, for example, around 2010–2011 and in 2021–2022.

Additionally, there are years in which the average yield gap reaches high values, such as 2011, 2017, and 2022, while in other years the gap is close to zero. This suggests that water limitation is not constant, but rather strongly depends on the meteorological conditions of each crop season.

Overall, the precipitation patterns shown in panel (a) are consistent with the temporal evolution of the simulated yield gap in panel (b). Seasons with below-average growing-season precipitation generally coincide with larger yield gaps, whereas wetter seasons tend to exhibit smaller gaps.

4 Future Work

This study is part of ongoing research, therefore several improvements still need to be incorporated. Currently, the analysis is being conducted on a limited set of five grid cells located in the central region of Argentina, with the aim of validating the proposed approach and verifying the consistency of the results. This analysis is expected to be extended to the full grid covering Argentina, which will allow for more representative conclusions at the national level.

In addition, further calibration of crop parameters is proposed in order to improve the representation of local production conditions. Furthermore, progress is expected in analyzing the relationship between the obtained results and climatic phenomena once the model has been validated.

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