Journal of Agriculture and Rural Development Studies
Volume 3 – Issue 2 – 2026
ISSN Online 3061-2756
www.imadr.jards.ugal.ro

DOI https://doi.org/10.35219/jards.2026.2.04

Agroclimatological Evidence of Thermal Gap Periods and Phenological Mismatch in Iraqi Potato Agroecosystems

Raghad Mouhamad*, Maysaa H. Ahmed**, Hamid Sh. Al-Delfi***, Maryam W. Huwaish****

A R T I C L E   I N F O

Article history:
Received: May 25, 2026
Accepted: June 28, 2026
Published: June 30, 2026

Keywords:
Agroclimatology; Potato production; Thermal gap periods; Phenological mismatch; Remote sensing; Climate stress

A B S T R A C T

Potato production in Iraq is increasingly exposed to accelerated warming, recurrent heat stress, and shifting seasonal conditions that may disrupt crop developmental timing and reduce yield stability. This study developed an integrated agroclimatological framework combining ERA5 climate data, MODIS land surface temperature, satellite-derived vegetation dynamics, and potato production statistics to evaluate three major thermal instability periods (2008–2011, 2015–2018, and 2022–2024). A weighted Thermal–Phenological Gap Index (TPGI) was constructed to integrate thermal accumulation, heat-stress frequency, NDVI temporal displacement, and growing season contraction. Random Forest regression was additionally applied to evaluate predictor importance and model performance. Overall results showed a gradual increase in the magnitude of thermal and phenological stress during subsequent instability periods, especially in the central and southern Iraqi agroecosystems. Weighted TPGI showed significant negative correlations with potato yield variation (($r=-0.74$), ($p<0.001$)), indicating that the downward trend of production was more related to a combination of thermal and phenological disruption rather than seasonal warming per se. The study highlights the importance of a combined remote sensing and agroclimatological approach for monitoring climate-related crop instability in dryland agricultural systems.

1. Introduction

Potato (Solanum tuberosum L.) is among the most climate-sensitive food crops cultivated under irrigated dryland systems, particularly in regions where increasing thermal accumulation and unstable water availability increasingly disrupt crop phenology and tuber development. Unlike many cereal crops, potato productivity depends strongly on narrow thermal thresholds that regulate canopy expansion, assimilate partitioning, tuber initiation, and dry matter accumulation. Temperatures above the optimal limits of physiological processes speed up the respiration rate, shorten the tuber filling time and hinder stolon differentiation, finally leading to yield destabilization (Singh et al., 2020; Rykaczewska, 2015). Such responses are becoming critically important in arid and semi-arid agroecosystems subjected to increasing temperatures at land surface, heat wave events and inadequate irrigation alongside soil

* Scientific Research Commission, Baghdad, Iraq, **Department of Applied Biology, College of Biotechnology, Al-Nahrain University, Baghdad, Iraq *** Ministry of Higher Education and Scientific Research, Baghdad, Iraq, **** Genetic Resources Department, Ministry of Agriculture, Baghdad, Iraq. Email addresses: raghad.s.mouhamad@src.edu.iq (Corresponding author - R. Mouhamad), maysaa.hamed@nahrainuniv.edu.iq (M. H. Ahmed), HamidAl-Delfi@mohesr.gov.iq (H. S. M. Al-Delfi), maryamw.huwaish@yahoo.com (M. W. Huwaish).

degradation and evapotranspiration stresses (Muthoni & Shimelis, 2020; Dahal et al., 2019). Recent global assessments have shown that potato production systems are becoming more challenged by agroclimatic instability. Comparable climate-driven shifts in potato productivity have also been projected under future warming scenarios in other production regions (Jégo et al., 2025). Similar climate-related yield responses under adaptation scenarios were also reported by Jennings et al. (2020), from gradual temperature change but also from changing patterns of thermoperiods and phenological synchronisations (Dushyant et al., 2024; Kávássy et al., 2025). For numerous regions, increasing numbers of growing degree days (GDD) result in the completion of developmental cycles earlier than before. Consequently, the shortened growing period leads to lower amounts of accumulated biomass of tubers. This problem becomes particularly serious for areas where planting schedules are set in accordance with historical climatic patterns but current temperatures are different from them. Iraq belongs to the category of environmentally vulnerable potato producing countries of West Asia because of an increasing frequency of high temperatures, chronic water deficiency, expanding salinization, and unreliable irrigation system. In recent years, Iraqi agriculture has experienced multiple disruptions related to abnormally hot weather and drought conditions. According to national data, there appear several intervals of sudden yield drop of potatoes in the country, namely in 2008–2011, 2015–2018, and 2022–2024. Thus, one can observe the existence of particular phases of thermal instabilities in the region, and not random failures in potato productivity. Despite various research attempts in the field of potato physiology, drought response, irrigation methods and climate adaptation technologies (Franke et al., 2020; Shams et al., 2023), the role of particular agroclimatological factors in repeated productivity declines still need to be further elucidated in arid Middle Eastern agroecosystems. The potato-climate relations are usually analysed in terms of the average seasonal temperature values and general drought effects. However, the question of changes in thermal accumulation, phenological shift and season shortening is much less studied. Most of remote sensing approaches are limited to vegetation state and yield forecast, neglecting thermal anomalies and its effects on phenology and vegetation state (Mukiibi et al., 2024; Hoelle et al., 2023). Therefore, the need for exploring new factors affecting agroclimatic stability of potatoes under climate stress conditions and their roles in recurrent productivity failure has become rather urgent. Fortunately, modern advances in the field of agroclimatological satellite-based observations create great opportunities to address this problem by studying complex phenomena of climate impact; Similar remote sensing approaches for climate-related crop monitoring have also been demonstrated in agricultural systems by Shiff et al. (2021). Products related to land surface temperature, vegetation index dynamics, and phenological shifts allow quantifying growing season shortening, thermal anomalies, shifts in canopy development, and vegetation stress reactions connected to production instability caused by climate change (Han et al., 2025; Tudor, 2023).When combined with national production records and thermal accumulation analysis, these datasets allow identification of "thermal gap periods," defined here as intervals during which cumulative heat stress and phenological disruption exceed the adaptive capacity of potato production systems. Therefore, this study investigates the agroclimatological relationships between thermal accumulation, phenological shifts, and potato yield instability across Iraq during three major thermal gap periods (2008–2011, 2015–2018, and 2022–2024). Specifically, the study integrates remote sensing indicators, thermal anomaly analysis, growing season dynamics, and national production trends to evaluate whether recurrent heat-induced phenological mismatch has become a dominant driver of potato production instability under accelerating climate stress.

2. Materials and Methods

Study Area and Agroclimatological Zonation

The study was conducted across the principal potato-producing agroecosystems of Iraq, which span strong climatic and environmental gradients ranging from relatively cooler semi-arid northern regions to highly arid irrigated systems in central and southern Iraq. These production environments differ substantially in thermal regime, irrigation dependence, atmospheric aridity, and seasonal crop suitability. To reduce oversimplification associated with national-scale aggregation, Iraq was stratified into three agroclimatological zones: (i) northern semi-arid systems, characterized by comparatively moderate thermal accumulation and longer seasonal suitability; (ii) the central irrigated production corridor, representing the dominant intensive potato-growing region under increasing heat exposure; and (iii) southern arid systems, where elevated land surface temperature (LST), salinity stress, and evaporative demand increasingly constrain seasonal crop development. Rather than assuming a uniform national production calendar, the analysis considered regional differences in planting windows and seasonal crop timing. Spring and autumn potato cycles were evaluated where phenological signals could be differentiated from satellite-derived vegetation trajectories. Because long-term governorate-scale phenological observations were limited, agroclimatological interpretation focused on regional thermal and phenological patterns rather than field-scale crop chronology. Three major periods of potato production instability were identified from long-term national production trajectories and subsequently designated as thermal gap periods: 2008–2011, 2015–2018, and 2022–2024. These intervals were characterized by sustained yield decline coinciding with intensified thermal anomalies, increased heat stress exposure, and apparent phenological displacement.

Potato Production Data

Annual potato production statistics covering the period 1961–2024 were obtained from the Food and Agriculture Organization FAOSTAT database and supplemented using publicly available production datasets from the Our World in Data platform where available (Our World in Data, 2024), with national agricultural reports (FAO, 2024). The analyzed variables included total production (kt), harvested area (ha), and yield (t ha^{-1}). Temporal segmentation analysis was used to identify sustained instability intervals relative to preceding production phases. Because production statistics may reflect combined climatic, agronomic, economic, and infrastructural influences, national yield records were interpreted as broad indicators of production instability rather than direct measurements of climate-induced crop response alone.

Climate and Thermal Data

Daily climatic variables were derived from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). Extracted variables included daily maximum temperature (Tmax), minimum temperature (Tmin), and mean temperature (Tmean). Thermal accumulation was quantified using Growing Degree Days (GDD) according to Equation (1):

$$GDD = \sum\left[\frac{Tmax + Tmin}{2} - Tbase\right] \qquad \textit{(Equation 1)}$$

where: (T base) was fixed at 7 °C according to established potato agroclimatology literature.

Thermal anomaly was estimated according to Equation (2):

$$\Delta T = T\ period - T\ baseline \qquad (Equation\ 2)$$

Heat stress intensity was quantified as the cumulative number of days exceeding critical potato thermal thresholds (>30 °C and >35 °C) during sensitive developmental stages. Because elevated nighttime temperatures may intensify respiratory carbon loss and reduce assimilate allocation toward tuber biomass, nighttime warming intensity was additionally evaluated using Tmin anomalies. Although ERA5 provides consistent long-term climatic coverage, reanalysis-derived temperatures in arid regions may contain regional uncertainty associated with sparse meteorological station density and strong land–atmosphere coupling. Consequently, thermal analyses were interpreted at regional agroclimatological scale rather than as exact field-level measurements.

Remote Sensing Data Processing

Satellite-derived vegetation and thermal indicators were processed within the Google Earth Engine cloud-computing environment (Gorelick et al., 2017). Multi-temporal datasets included Landsat 5 TM, Landsat 8 OLI, Sentinel-2 MSI, and MODIS Terra products. These datasets were selected to capture both long-term thermal variability and seasonal vegetation dynamics across Iraqi potato production systems.

Normalized Difference Vegetation Index (NDVI) was calculated as Equation 3:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad (Equation\ 3)$$

MODIS-derived LST products were used to characterize spatial thermal variability and identify persistent heat-stress hotspots across potato-growing regions (Wan, 2014). Image preprocessing included atmospheric correction, cloud masking, radiometric normalization, and seasonal compositing. Because cloud contamination and sensor differences may influence vegetation trajectories, only cloud-filtered seasonal composites were retained for phenological analysis. Spatial analyses were conducted using resolutions ranging from 250 m to 1 km depending on sensor characteristics and temporal availability.

Given the fragmented structure of Iraqi agricultural landscapes, mixed-pixel effects may occur in some irrigated zones where potato fields coexist with other seasonal crops. Therefore, remote sensing indicators were interpreted as regional vegetation responses associated with dominant production systems rather than crop-pure spectral signatures.

Phenological Analysis

Potato phenological dynamics were evaluated using multi-temporal NDVI trajectories derived from Landsat and Sentinel imagery. Four phenological metrics were extracted: Start of Season (SOS), Peak Greenness Timing (PGT), End of Season (EOS), and Growing Season Length (GSL). Growing season duration was calculated as Equation 4:

$$GSL=EOS-SOS \qquad (Equation\ 4)$$

Temporal displacement in NDVI peak timing and growing season duration was evaluated among the identified thermal gap periods to assess climate-associated phenological instability. Because long-term field-observed potato phenology records were not consistently available across Iraqi governorates, phenological metrics were indirectly evaluated using agricultural calendars, seasonal NDVI trajectories over irrigated potato production zones, and consistency with reported planting and harvesting windows. Consequently, SOS, EOS, PGT, and GSL should be interpreted as satellite-derived phenological proxies rather than direct field-measured developmental stages.

Phenological mismatch was defined as the increasing temporal decoupling between historically favourable potato developmental windows and observed thermal conditions during tuber initiation and filling stages.

Development of the Thermal–Phenological Gap Index (TPGI)

To quantify integrated agroclimatological instability, a weighted Thermal–Phenological Gap Index (TPGI) was developed by combining standardized anomalies associated with cumulative thermal accumulation, surface warming, heat stress exposure, night-time warming, NDVI temporal displacement, and growing season contraction.

The weighted TPGI was calculated as Equation 5:

$$TPGI\omega = \omega 1z(GDD) + \omega 2z(LST) + \omega 3z(HSD35) + \omega 4z(Tmin) + \omega 5z(NDVIshift) - \omega 6z(GSL) \quad \textit{(Equation 5)}$$

where:

(HSD_{35}) represents the number of days exceeding 35 °C,
($NDVI_{shift}$) represents displacement in peak NDVI timing,
(GSL) represents growing season length anomaly.

To avoid imposing arbitrary equal weighting, variable weights were derived using a combination of principal component loadings and Random Forest variable importance. Prior to index construction, multicollinearity among variables was evaluated using Pearson correlation analysis and variance inflation factor (VIF) diagnostics. Variables exhibiting moderate correlation were retained when they represented distinct agroclimatological mechanisms. Sensitivity analysis was further conducted by recalculating TPGI under multiple weighting schemes, including equal weighting, PCA-derived weighting, and Random Forest-derived weighting. This procedure was used to evaluate the robustness of the observed relationships between TPGI and potato yield instability. Higher TPGI values indicated stronger combined thermal and phenological disruption associated with elevated agroclimatological instability risk.

Spatial and Statistical Analysis

Spatial analyses were conducted using ArcGIS Pro and Google Earth Engine (Gorelick et al., 2017). Raster datasets were standardized to a common coordinate reference system and spatial resolution prior to analysis. Relationships among potato yield, thermal accumulation, LST anomalies, heat stress frequency, phenological displacement, and TPGI were evaluated using Pearson correlation analysis, linear regression, Mann–Kendall trend analysis, and Sen's slope estimation. The Random Forest model was implemented using the machine learning environment available in Google Earth Engine with 500 decision trees; Machine learning approaches have increasingly been applied for potato yield prediction and climatic response assessment (Kurek et al., 2023). Recent reviews further emphasize the growing importance of predictive modeling frameworks in potato agroclimatology (Piekutowska & Niedbała, 2025). Predictor variables included GDD anomaly, LST anomaly, heat-stress frequency, Tmin anomaly, NDVI peak displacement, growing season length reduction, and weighted TPGI. Data were randomly partitioned into training (70%) and testing (30%) subsets. Model robustness was evaluated using repeated cross-validation procedures. Variable importance analysis was subsequently used to identify the dominant agroclimatological predictors contributing to potato yield variability. Model performance was evaluated using coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE).

3. Results and Discussion

3.1 Emergence of Thermal Gap Periods Across Iraqi Potato Agroecosystems

Long-term analysis of Iraqi potato production revealed three major intervals of agroclimatological instability during 2008–2011, 2015–2018, and 2022–2024 (Figure 2A). These instability phases coincided with increasing thermal accumulation, elevated land surface temperature (LST), intensified heat-stress frequency, and progressive shortening of the effective growing season across major potato-producing regions. The spatial analysis also indicated that the intensity of the thermal response was characterized by pronounced regional heterogeneity among agroclimatological zones (Figure 1B–G; Table 1). The northern semi-arid zone, in general, was characterized by relatively moderate thermal anomalies during the study period. During 2008–2011, mean Growing Degree Day (GDD) anomalies remained below +170 °C Day, while LST anomalies rarely exceeded +1 °C above baseline conditions (Figure 1B–C; Table 1). In contrast, the central irrigated corridor and southern arid systems exhibited substantially stronger thermal accumulation and higher frequencies of days exceeding 35 °C (Figure 1D). These regional contrasts became increasingly pronounced during subsequent instability periods. During 2015–2018, cumulative thermal forcing intensified across central and southern Iraq, where GDD anomalies exceeded +300 °C Day in several irrigated systems (Table 1).

Table 1. Integrated agroclimatological characteristics and variable contribution across thermal gap periods in Iraqi potato agroecosystems

Thermal gap period	Agroclimatological zone	GDD anomaly (°C Day)	LST anomaly (°C)	Heat stress days >35°C	NDVI peak shift (days)	GSL reduction (days)	Weighted TPGI	Relative contribution to yield instability (%)
2008–2011	Northern semi-arid zone	+162 ± 28	+0.9 ± 0.3	9–14	−4 to −7	−8 to −12	0.74	11.3
2008–2011	Central irrigated corridor	+241 ± 41	+1.6 ± 0.4	18–24	−8 to −10	−15 to −17	1.12	17.6
2008–2011	Southern arid systems	+278 ± 52	+1.9 ± 0.5	21–28	−10 to −12	−16 to −19	1.31	19.4
2015–2018	Northern semi-arid zone	+214 ± 36	+1.2 ± 0.3	14–19	−6 to −9	−11 to −15	1.02	13.5
2015–2018	Central irrigated corridor	+306 ± 48	+2.0 ± 0.4	25–34	−12 to −15	−18 to −22	1.74	22.8
2015–2018	Southern arid systems	+337 ± 56	+2.2 ± 0.5	29–37	−14 to −17	−20 to −24	1.96	24.1
2022–2024	Northern semi-arid zone	+268 ± 43	+1.5 ± 0.4	18–24	−8 to −11	−13 to −17	1.28	16.4

Thermal gap period	Agroclimatological zone	GDD anomaly (°C Day)	LST anomaly (°C)	Heat stress days >35°C	NDVI peak shift (days)	GSL reduction (days)	Weighted TPGI	Relative contribution to yield instability (%)
2022–2024	Central irrigated corridor	+384 ± 61	+2.2 ± 0.5	35–46	−16 to −19	−22 to −26	2.31	31.7
2022–2024	Southern arid systems	+417 ± 67	+2.5 ± 0.6	39–51	−18 to −22	−24 to −29	2.48	33.5

Source: Author

At the same time, the timing of the NDVI peak shifted earlier compared to historical seasonal trajectories, while the length of the growing season (GSL) showed a significant decrease (Figure 1E–F). The observed shortening of the duration of seasonal vegetation suggests that crop development increasingly took place under accelerated thermal conditions, rather than within historically stable climatic windows.

The most pronounced thermal anomalies were observed during 2022–2024. In the central irrigated corridor, mean GDD anomalies approached +384 °C Day, accompanied by LST anomalies exceeding +2.2 °C and frequent exposure to extreme daytime heat (>35 °C) (Figure 1B–D). Southern arid systems exhibited even stronger thermal loading, with growing season reduction exceeding 24 days in some agricultural zones (Figure 1F; Table 1).

However, northern agroecosystems had lower weighted TPGI and weaker phenological shift than southern regions, suggesting partial buffering of extreme warming by climate (Figure 1G). The spatial distribution of these thermal responses indicates that potato production instability in Iraq is not spatially uniform. Instead, thermal saturation appears increasingly concentrated within central and southern irrigated systems where elevated evaporative demand, persistent surface warming, and seasonal heat accumulation interact to shorten effective crop duration (Figure 1C–G). The progressive increase in weighted TPGI values across the identified instability intervals further suggests that potato production decline cannot be attributed solely to seasonal warming. Rather, instability appears associated with the combined influence of thermal acceleration, phenological displacement, and contraction of the effective developmental period.

3.2 Integrated Thermal–Phenological Stress and Variable Interactions

Correlation analysis demonstrated generally negative relationships between potato yield and indicators of thermal stress, including GDD anomalies, LST anomalies, heat-stress frequency, and NDVI peak displacement (Table 2). In contrast, growing season length showed a positive relationship with yield stability, indicating the importance of maintaining sufficient physiological duration for tuber development. Among the evaluated predictors, weighted TPGI exhibited the strongest inverse relationship with potato yield (($r = -0.74$), ($p < 0.001$)), as further illustrated in the regression relationship shown in Figure 2B. However, several individual thermal indicators also displayed substantial associations with production decline, suggesting that potato instability emerged from interacting agroclimatological processes rather than from a single dominant climatic driver. Heat-stress days exceeding 35 °C showed particularly strong negative relationships with yield stability (($r = -0.69$), ($p < 0.01$)), especially within the central irrigated corridor and southern agroecosystems where supra-optimal daytime temperatures occurred more frequently during sensitive developmental stages (Figure 1D; Table 2). Elevated LST anomalies also contributed substantially to regional production instability, likely through increased evaporative demand and accelerated canopy senescence. The relationship between NDVI peak displacement and yield decline further suggests that earlier canopy maturity increasingly reduced the effective duration available for tuber filling (Figure 1E; Figure 2B). Earlier peak greenness combined with shorter growing seasons indicates progressive disruption of crop–climate synchronization under accelerated warming conditions. Night-time warming had relatively weaker relationships with yield variability and was statistically non-significant in several analyses (Table 2). This indicates that T min anomalies were likely secondary stress amplifiers rather than collapse drivers per se. However, elevated night-time temperatures may still act indirectly via enhanced respiratory carbon losses during prolonged heat exposure. Variance inflation factor (VIF) analysis indicated moderate but acceptable multicollinearity among climatic predictors, with all variables below conservative exclusion thresholds (Table 2). Consequently, the variables were retained because they represented distinct agroclimatological mechanisms associated with thermal and phenological disruption.

Table 2. Correlation structure and multicollinearity diagnostics of agroclimatological variables associated with potato yield instability

Variable	GDD anomaly	LST anomaly	Heat stress days >35°C	Tmin anomaly	NDVI peak shift	GSL reduction	Weighted TPGI
Correlation with potato yield	−0.58	−0.64	−0.69	−0.32	−0.51	0.61	−0.74
p-value	<0.05	<0.01	<0.01	ns	<0.05	<0.01	<0.001
Variance inflation factor (VIF)	3.1	3.6	3.8	2.4	2.7	3.3	4.1

Source: Author

3.3 Comparative Model Performance and Sensitivity of TPGI Formulations

Comparative model analysis revealed that integrated thermal–phenological frameworks generally outperformed isolated climatic variables in explaining potato yield variability (Table 3). Models relying exclusively on cumulative thermal accumulation or LST anomalies produced only moderate explanatory performance ((R^2 = 0.37–0.43)), indicating that seasonal warming alone could not fully explain observed production instability.

Table 3. Comparative performance of thermal–phenological models under different weighting schemes

Model ID	M1	M2	M3	M4	M5	M6	M7
Predictor variables	GDD anomaly	LST anomaly	GDD + heat stress days	GDD + NDVI shift + GSL	Weighted TPGI	Weighted TPGI	Random Forest model
Weighting scheme	None	None	None	None	PCA-derived weighting	RF-derived weighting	All variables
R^2	0.37	0.43	0.54	0.59	0.63	0.65	0.69
RMSE	0.96	0.88	0.77	0.71	0.66	0.64	0.59
MAE	0.77	0.7	0.63	0.57	0.52	0.49	0.45

Source: Author

Model performance improved when phenological variables were incorporated alongside thermal indicators. In addition, the inclusion of NDVI peak displacement and growing season contraction improved the explanatory power of the models to approximately (R 2 = 0.59), indicating that developmental timing was an important factor in production variability under climatic pressure. As expected, weighted versions of the TPGI were always more correlated with yield than single variable indices despite the use of any weighting scheme. Both PCA weighting scheme and Random Forest weighting yielded similar results ((R^2 = 0.63–0.65)), suggesting that the aforementioned relationship between TPGI and potato yield was consistent across other schemes (Table 3). Moreover, using the latter as the source of weights helped us identify heat-stress frequency and GDD anomaly as major contributors to yield variability (Figure 2C). A sensitivity test further confirmed the persistence of the negative relationship between TPGI and potato production irrespective of the model formulation. In other words, this correlation could hardly be attributed to equal weighting or index construction per se. In comparison with other models, the Random Forest framework provided the highest explanatory performance ((R^2 = 0.69)), albeit with relatively low prediction error (RMSE = 0.59; MAE = 0.45) (Figure 2D). Nevertheless, substantial residual variability remained unexplained, indicating that additional factors beyond the present agroclimatological framework—including irrigation management, salinity conditions, cultivar differences, and socioeconomic instability—also influenced potato productivity. The comparatively moderate predictive performance observed across all models is consistent with the complexity of dryland agricultural systems where climate interacts continuously with agronomic and infrastructural processes.

3.4 Agroclimatological Interpretation of Climate–Phenology Decoupling

The combined thermal and phenological responses observed during the identified instability intervals support the emergence of progressive climate–phenology decoupling within Iraqi potato systems. Historically, potato developmental stages were synchronized with relatively stable seasonal thermal windows. However, accelerated warming appears to be compressing these windows and shifting canopy development toward earlier seasonal timing (Figure 1E–F). Earlier NDVI peak occurrence combined with growing season shortening suggests that potato canopies increasingly reach physiological maturity before completion of optimal tuber-filling processes. Under elevated thermal accumulation, respiration rates may increase while assimilate partitioning toward tuber biomass becomes progressively constrained by shortened developmental duration and intensified heat exposure. The negative TPGI–yield relationship shown in Figure 2B further supports the interpretation that integrated thermal–phenological disruption increasingly contributes to production instability under warming conditions. Importantly, these patterns were not spatially uniform. Northern agroecosystems retained comparatively lower thermal saturation and weaker phenological contraction relative to central and southern Iraq (Figure 1G).

This spatial heterogeneity suggests that future potato suitability may progressively shift toward cooler agroclimatological zones unless adaptive management strategies are implemented. The results further indicate that irrigation alone may not fully compensate for accelerated developmental timing under persistent warming conditions. Even in irrigated systems, excessive thermal accumulation may shorten effective crop duration beyond physiologically favourable thresholds for tuber biomass accumulation. Collectively, the findings support the interpretation that potato production instability in Iraq increasingly reflects integrated thermal–phenological disruption rather than isolated climatic anomalies alone. Consequently, future adaptation strategies may require coordinated modification of planting calendars, heat-tolerant cultivars, irrigation scheduling, and remote sensing-based thermal monitoring systems capable of detecting emerging agroclimatological instability before severe production decline occurs.

Figure 1. Spatiotemporal thermal and phenological variability across Iraqi potato agroecosystems
(Anomalies relative to 2003–2007 baseline)

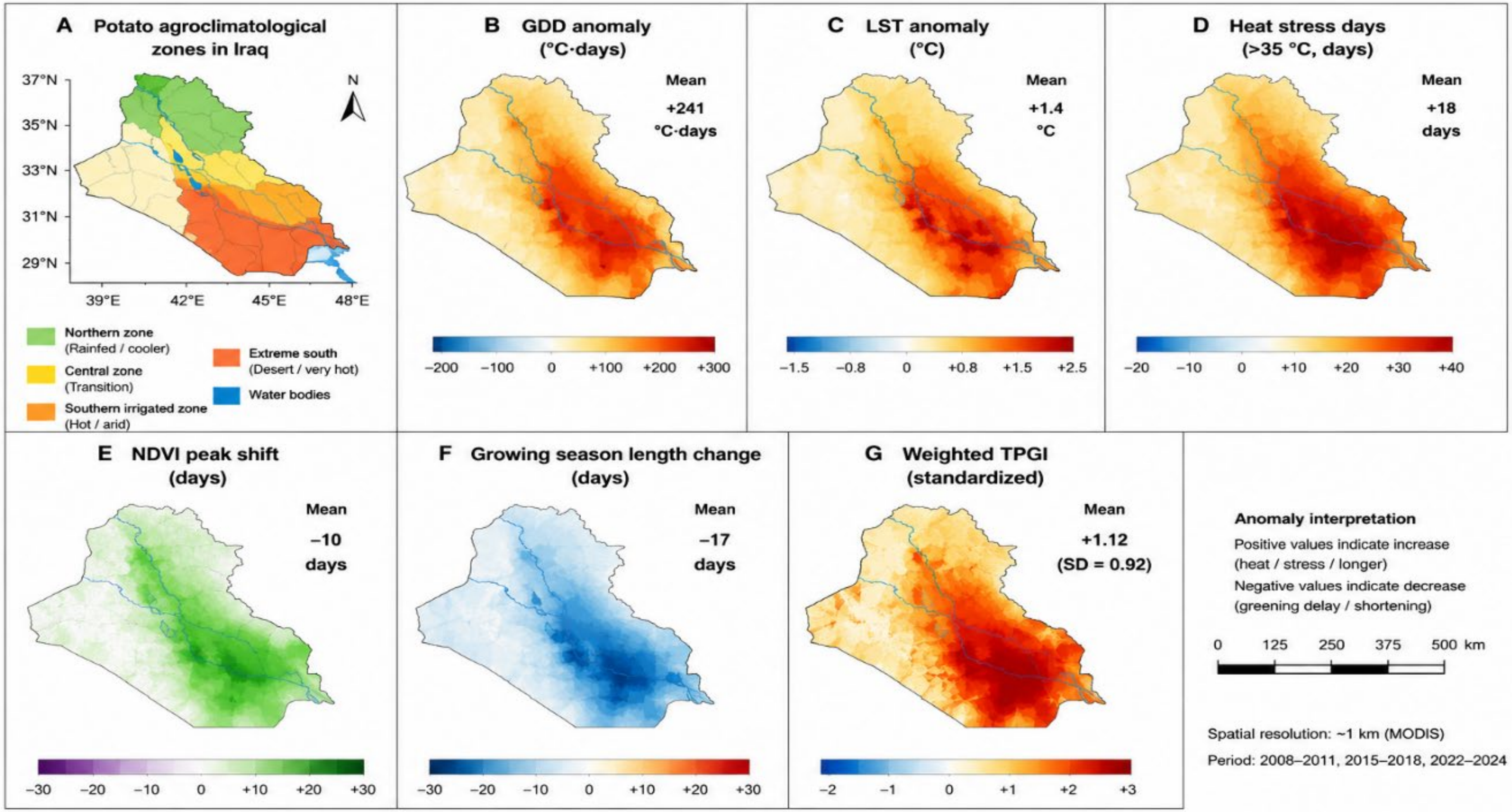
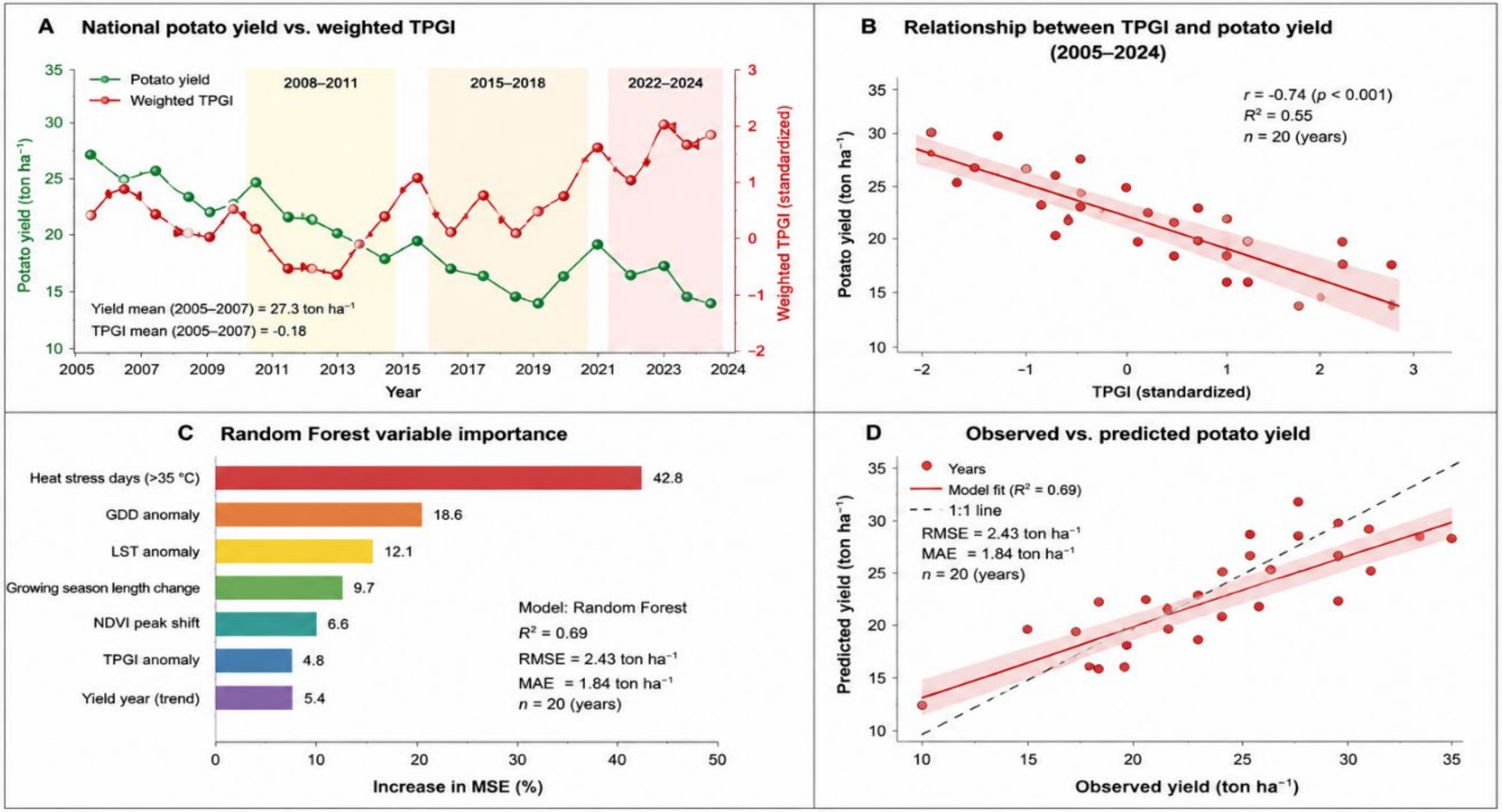


Figure 2. Integrated thermal–phenological relationships and predictive model performance for potato yield in Iraq



Note: TPGI = weighted Thermal–Phenological Gap Index. Positive TPGI indicates higher thermal and phenological stress and greater decoupling.

5. Conclusions

The findings suggest that recurrent potato production instability in Iraq is increasingly associated with combined thermal and phenological disruption under accelerating warming conditions. The identified thermal gap periods were generally characterized by elevated thermal accumulation, increased heat-stress frequency, earlier NDVI peak occurrence, and progressive shortening of the effective growing season, particularly within central irrigated and southern arid agroecosystems. The results further indicate that production decline may not be fully explained by seasonal warming alone. Instead, accelerated thermal accumulation appears to alter synchronization between crop developmental stages and favourable environmental windows, contributing to climate–phenology decoupling and reduced tuber-filling duration. The weighted Thermal–Phenological Gap Index (TPGI) provided an integrated representation of thermal and phenological instability and exhibited relatively strong relationships with potato yield variability across the evaluated agroclimatological zones. Overall, the study highlights the value of integrating remote sensing, thermal accumulation dynamics, and phenological indicators for regional monitoring of climate-associated crop instability in dryland agricultural systems.

References

Dahal, K., Li, X.-Q., Tai, H., Creelman, A., & Bizimungu, B. (2019). Improving potato stress tolerance and tuber yield under a climate change scenario: A current overview. Frontiers in Plant Science, 10, Article 563. https://doi.org/10.3389/fpls.2019.00563

Dushyant, Roy, S., Mahan, N., Rani, D. V., Kumar, R., Gupta, D. K., Sharma, K. K., & Kumar, M. (2024). Impact of climate change on global potato production: A review. Journal of Global Agriculture and Ecology, 16(2), 14–28. https://doi.org/10.56557/jogae/2024/v16i28590

Food and Agriculture Organization of the United Nations. (2024). FAOSTAT statistical database. https://www.fao.org/faostat/

Franke, A. C., Muelelwa, L. N., & Steyn, J. M. (2020). Impact of climate change on yield and water use efficiencies of potato in different production regions of South Africa. South African Journal of Plant and Soil, 37(3), 244–253. https://doi.org/10.1080/02571862.2020.1736345

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment, 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Han, D., Wang, P., Li, Y., Zhang, Y., & Guo, J. (2025). Mapping the main phenological spatiotemporal changes of summer maize in the Huang–Huai–Hai region based on multiple remote sensing indices. Agronomy, 15(5), Article 1182. https://doi.org/10.3390/agronomy15051182

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J.-N. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hoelle, J., Asch, F., Khan, A., & Bonierbale, M. (2024). Suitability of the stress severity index combined with remote-sensing data as a tool to evaluate drought resistance traits in potato. Journal of Agronomy and Crop Science, 210, e12671. https://doi.org/10.1111/jac.12671

Jennings, S., Koehler, A.-K., Nicklin, K. J., Deva, C., Sait, S. M., & Challinor, A. J. (2020). Global potato yields increase under climate change with adaptation and CO_2 fertilisation. Frontiers in Sustainable Food Systems, 4, Article 519324. https://doi.org/10.3389/fsufs.2020.519324

Jégo, G., Crépeau, M., Jing, Q., Grant, B., Smith, W., Mesbah, M., & Qian, B. (2025). Potato yield projections under climate change in Canada. Agronomy Journal, 117(1), e70017. https://doi.org/10.1002/agj2.70017

Kávássy, G., Szabó, A., & Szabó, É. (2025). The effects of the climate change and the drought stress on potato production: A review. Acta Agraria Debreceniensis, 1, 61–67. https://doi.org/10.34101/actaagrar/1/15256

Kurek, J., Niedbała, G., Wojciechowski, T., Świderski, B., Antoniuk, I., Piekutowska, M., Kruk, M., & Bobran, K. (2023). Prediction of potato (Solanum tuberosum L.) yield based on machine learning methods. Agriculture, 13(12), Article 2259. https://doi.org/10.3390/agriculture13122259

Mukiibi, A., Machakaire, A. T. B., Franke, A. C., & Steyn, J. M. (2025). A systematic review of vegetation indices for potato growth monitoring and tuber yield prediction from remote sensing. Potato Research, 68, 409–448. https://doi.org/10.1007/s11540-024-09748-7

Muthoni, J., & Shimelis, H. (2020). Heat and drought stress and their implications on potato production under dry African tropics. Australian Journal of Crop Science, 14(9), 1405–1414. https://doi.org/10.21475/ajcs.20.14.09.p2214

Our World in Data. (2024). Potato production [Dataset]. https://ourworldindata.org/grapher/potato-production

Piekutowska, M., & Niedbała, G. (2025). Review of methods and models for potato yield prediction. Agriculture, 15(4), Article 367. https://doi.org/10.3390/agriculture15040367

Rykaczewska, K. (2015). The effect of high temperature occurring in subsequent stages of plant development on potato yield and tuber physiological defects. American Journal of Potato Research, 92, 339–349. https://doi.org/10.1007/s12230-015-9436-x

Shams, S., Jamily, A. S., Yousofzai, W., Dadrasi, A., & Sarhadi, W. A. (2023). Evaluation of the past climate changes effects on potato growth and yield by modeling. Journal of Natural Science Review, 1(1), 27–38. https://doi.org/10.62810/jnsr.v1i1.4

Shiff, S., Lensky, I. M., & Bonfil, D. J. (2021). Using satellite data to optimize wheat yield and quality under climate change. Remote Sensing, 13(11), Article 2049. https://doi.org/10.3390/rs13112049

Singh, B., Kukreja, S., & Goutam, U. (2020). Impact of heat stress on potato (Solanum tuberosum L.): Present scenario and future opportunities. The Journal of Horticultural Science and Biotechnology, 95(4), 407–424. https://doi.org/10.1080/14620316.2019.1700173

Tudor, A. (2023). Remote sensing in biometeorology. Review of the Air Force Academy, 21(1), 95–102. https://doi.org/10.19062/1842-9238.2023.21.1.12

Wan, Z. (2014). New refinements and validation of the collection-6 MODIS land-surface temperature/emissivity product. Remote Sensing of Environment, 140, 36–45. https://doi.org/10.1016/j.rse.2013.08.027