Response to Reviewer #2 Comments

Thank you very much for your valuable comments on our manuscript. These comments are highly appreciated and have been very helpful in improving the quality of our manuscript and strengthening the overall research.

Comment 1: The North China Plain is one of the most heavily irrigated regions in the world. The authors acknowledge irrigation in the "Uncertainties" section (Lines 362–365), but it deserves more prominence in the Discussion. If the VPD was record-high in June, did irrigation effectively mitigate the heat stress, or did the atmospheric dryness (VPD) override soil moisture management? Please discuss whether the "positive NDVI/GPP" in April/May was partly sustained by intensive groundwater irrigation, and why irrigation seemed less effective in June (e.g., heat-induced stomatal closure regardless of water supply).

Reply: Thank you for this insightful comment. We agree that irrigation plays a critical role in the North China Plain (NCP), and we have expanded the discussion to better address its influence.

The added description in the Discussion is as follows: "*However, in the NCP winter wheat–summer maize rotation system, irrigation practices are primarily scheduled according to critical crop growth stages (e.g., green-up, jointing, heading, and grain filling) (Zhang 2018). In addition, existing research indicates that the total irrigation amount tends to remain relatively stable (typically around 120–150 mm with two irrigation events) across dry, normal, and wet years to achieve optimal winter wheat yield (Zhou et al., 2022). These findings suggest that irrigation in this region is largely governed by crop developmental requirements, with limited responsiveness to short-term climate fluctuations.*"

Moreover, our analysis is based on anomalies derived from 2001 to 2023, which helps to remove the influence of recurring management practices such as irrigation. Therefore, the observed positive NDVI and GPP anomalies in April and May are more likely driven by short-term climatic variations rather than irrigation effects.

For June, irrigation mainly occurs during the maize sowing period. As noted above, the anomaly-based approach can partially offset the influence of such management practices. In addition, Fig. 2(d), (h), and (p) shows that June is characterized by significantly increased temperature, elevated VPD, and decreased soil moisture. During the critical maize germination and emergence stage, even with irrigation, strong hot-dry stress may induce stomatal closure, reduce seedling vigor, and ultimately lower emergence rates.

Comment 2: The Multiple Linear Regression (MLR) model (Eq. 3) includes TAS (Temperature), VPD, SW (Soil Water), and PRE (Precipitation). These variables are often highly correlated during dry-hot events (e.g., high Temp often drives high VPD and low SW).Provide the Variance Inflation Factor (VIF) for the independent variables to ensure that multicollinearity does not bias the sensitivity coefficients.

Reply: We thank the reviewer for this constructive suggestion regarding multicollinearity. Following this recommendation, we calculated the Variance Inflation Factor (VIF) for all explanatory variables, and the results are presented in supplementary Table S3.

Table S3. VIF list of TAS, VPD, SW, PRE, SSRD, Pre_NDVI (Pre_GPP) in multiple linear regression model.

	Month	TAS	VPD	SW	PRE	SSRD	Pre_NDVI (Pre_GPP)
NDVI	April	2.70	4.21	1.26	1.79	1.79	1.32
	May	3.34	6.21	1.57	2.40	2.27	1.48
	June	7.00	8.57	2.45	2.64	1.76	1.27
GPP	April	2.49	4.31	1.22	1.87	1.84	1.26
	May	3.42	5.94	1.66	2.24	2.38	1.35
	June	6.87	8.34	2.29	2.38	1.82	1.37

As shown in Table S3, most explanatory variables exhibit VIF values below 5, indicating generally low multicollinearity. However, in June, the VIF values of TAS and VPD increase to approximately 6-9, suggesting a moderate level of collinearity. This is mainly attributable to their inherent physical coupling, as high temperature conditions are typically associated with increased atmospheric water demand, leading to elevated VPD, especially during dry-hot events.

We acknowledge that such collinearity may increase the uncertainty in separating the independent effects of individual climate variables and could affect the interpretability of regression coefficients under extreme conditions. Nevertheless, the observed VIF values remain within the range of moderate multicollinearity and do not indicate severe instability. Therefore, the regression results are still considered robust, and the model retains reasonable explanatory power for assessing climate sensitivities.

Comment 3: The authors emphasize the "vegetation carryover effect" as a dominant driver in May. While the statistical meaning is clear, the physiological mechanism could be better explained. Is this "memory" primarily due to accumulated biomass, root system development, or sustained soil moisture from previous months? A few sentences in the Discussion (Section 4.1) would clarify this for readers.

Reply: Thank you for this insightful and valuable comment. We agree that the "vegetation carryover effect" should be better explained from an eco-physiological perspective to strengthen the interpretation of our results.

The added description in the Discussion is as follows: "*In this context, the dependence of vegetation conditions in May on preceding months can be attributed to multiple interacting processes. Specifically, favorable and warm conditions in earlier periods promote vegetation growth, leading to the accumulation of biomass and leaf area that can persist into subsequent stages (Lian et al., 2021). Under increasing atmospheric and soil drought in May, the previously accumulated photosynthetic products provide a buffer that helps vegetation cope with adverse conditions (Ogle et al., 2015).*"

Comment 4: The study notes a reduction in summer maize yield based on June observations. However, maize is harvested in September/October. Clarify if the "reduced yield" mentioned is a final harvested statistic for 2024 or an early-season projection. If June only affects the "establishment phase," could favorable rains in

July/August have compensated for the early loss?

Reply: We thank the reviewer for this important clarification regarding the timing of yield impacts. We clarify that the "reduced yield" mentioned in this study refers to the final harvested yield for 2024, rather than an early-season projection.

Our conclusion that the extreme event in June was the decisive driver of the final yield loss is supported by the following evidence:

(1) The extreme heat and drought in June 2024 coincided with the critical sowing-to-emergence phase for summer maize in the North China Plain. This event severely compromised the emergence rates and seedling vigor. As shown in Fig. R2, despite the favorable hydro-thermal conditions in July (ample rainfall and low VPD, see Fig. R1), both NDVI and GPP continued to exhibit significant negative anomalies. This persistent suppression is a clear manifestation of the lagged impact from the June event. Because the initial plant population (stand density) and early growth potential were damaged at the foundation, the vegetation productivity remained low even after meteorological stresses subsided.

(2) The reviewer noted the potential for compensation during July and August. However, our analysis suggests a decoupling between late-season weather and final productivity. As seen in Fig. R1(b), while August 2024 experienced a significant warm anomaly, Figs. R2(b) and (e) shows that NDVI and GPP anomalies did not exhibit a corresponding sharp decline in the northern part of the study region where this warming was most intense. This indicates that the spatial pattern of productivity loss was primarily determined by the initial June damage rather than subsequent temperature fluctuations in August.

(3) It is well-established in agronomic research within the NCP that summer maize yield is primarily determined by the initial plant population density and emergence quality (Albarenque et al., 2023; Yan et al., 2025). Studies have consistently shown that severe drought and thermal stress during the seedling stage create a physiological "bottleneck" and a reduction in the "yield ceiling" that cannot be fully compensated for by favorable mid-to-late season weather (Du et al., 2025; Teng et al., 2022).

In summary, the 2024 yield loss was the result of an emergence failure triggered in June, which set a trajectory for reduced harvest that subsequent rains in July and August could not overcome.

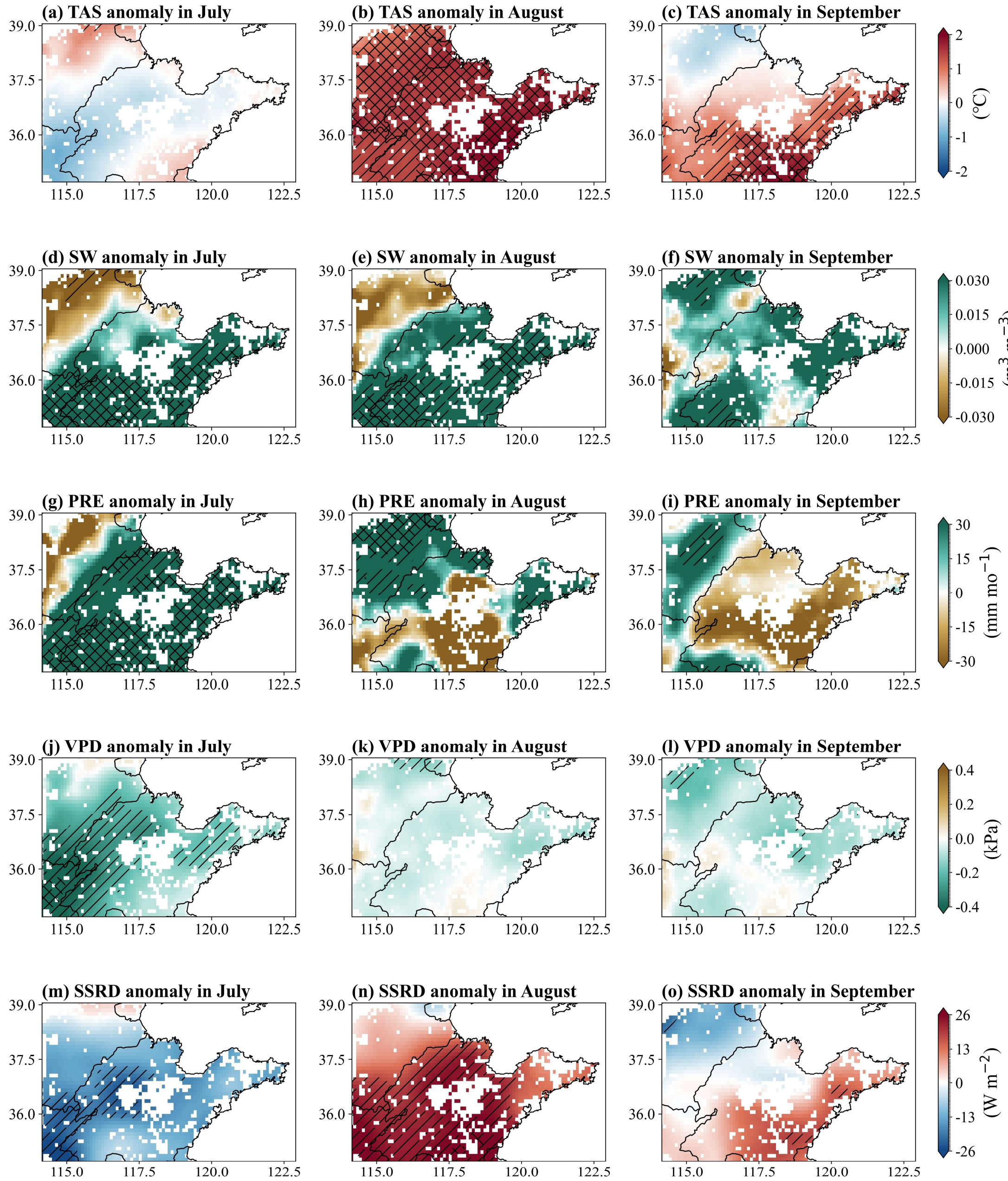


Figure R1. Climate anomalies from July to September 2024. (a–c) Surface air temperature (TAS), (d–f) shortwave radiation (SW), (g–i) precipitation (PRE), (j–l) vapor pressure deficit (VPD), and (m–o) surface solar radiation downwards (SSRD). Areas hatched with “//” and “XX” indicate anomalies exceeding and, respectively.

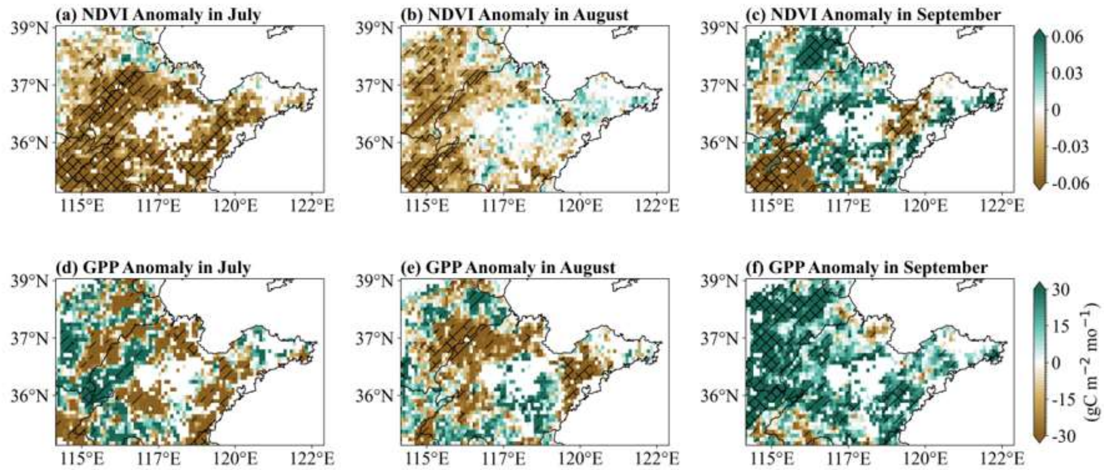
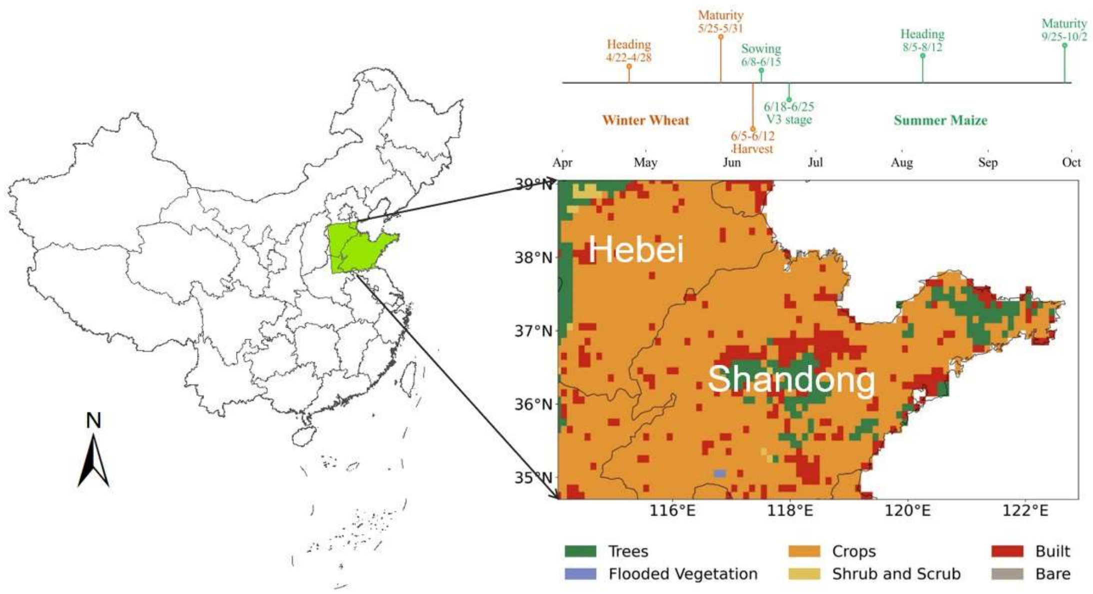


Figure R2. NDVI and GPP anomalies from July to September 2024. (a-c) NDVI and (d-f) GPP anomalies. Areas hatched with "//" and "XX" indicate anomalies exceeding and, respectively.

The results indicate that, despite the occurrence of rainfall after the dry-hot event, vegetation recovery was limited. Specifically, NDVI remained negative across most regions in both July and August. While GPP showed partial recovery in some areas in July, it declined again across most regions in August. These patterns suggest that the dry-hot stress in June likely constrained maize growth during the critical seedling stage. Therefore, although favorable rainfall occurred later in the season, the early-stage damage was not fully reversible. This indicates that stress during the seedling stage can have lasting impacts, ultimately contributing to the observed reduction in final yield.

Comment 5: Figure 2 & 3: The spatial maps are excellent. However, adding a small inset map showing the "Winter Wheat-Summer Maize" cropping intensity would help international readers understand the land-use context better.

Reply: We thank the reviewer for this helpful suggestion. We have added a detailed phenological timeline for 2024 directly into Figure 1 of the manuscript. Unlike a multi-year average calendar, this timeline is derived from the 2024 Weekly Agricultural Meteorological Intelligence (National Meteorological Center 2024) and official progress reports from the Shandong Provincial Department of Agriculture and Rural Affairs.



Revised Figure 1. Geographic location and land use distribution of the study area, derived from the Dynamic World V1 land cover product. A detailed phenological timeline for 2024 was shown according to the 2024 Weekly Agricultural Meteorological Intelligence (National Meteorological Center 2024) and official progress reports from the Shandong Provincial Department of Agriculture and Rural Affairs.

In addition, we incorporated a 1km resolution phenological dataset for China to generate a spatial map of winter wheat and summer maize phenology (Luo et al., 2020), which is shown in the supplementary Fig. S1. This supplementary figure provides further insight into the cropping system and helps contextualize the spatial patterns presented in Fig. 2 and Fig. 3.

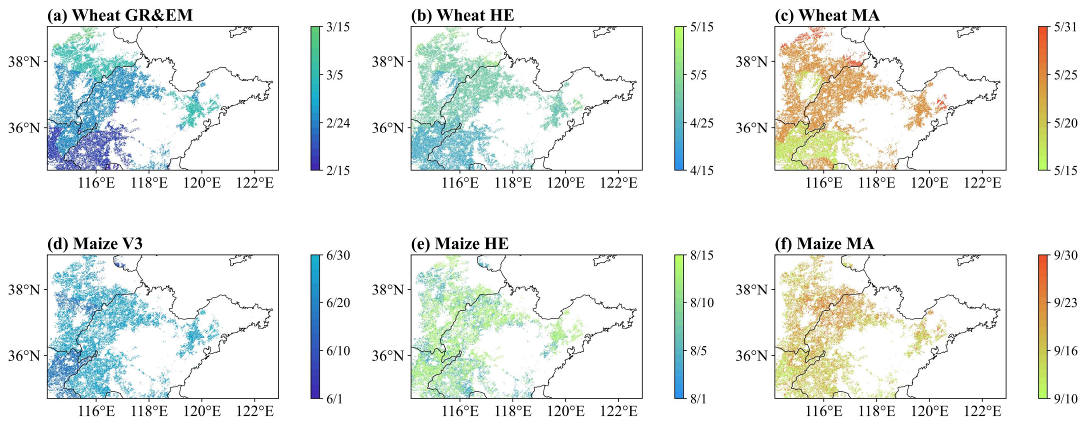


Figure S1. Phenological Map of Winter Wheat Summer Maize in NCP. GR&EM represents Green up & Emergence date for wheat; V3 represents V3 stage for maize; HE represents Heading date for all the crops; MA represents Maturity date for all the crops.

Comment 6: Line 123: Equation 1 for VPD calculation is standard, but please confirm if the "monthly TAS and TD values" were averaged from daily VPDs or calculated from monthly mean temperatures. (The authors address this briefly in L125, but a bit more detail on the temporal aggregation would be helpful).

Reply: We appreciate the reviewer's attention to this detail. In this study, VPD was calculated using the monthly mean TAS and TD from the ERA5-Land dataset.

This approach is consistent with the methodological validation provided by He et al. (2022). In their study, the authors specifically compared VPD values calculated from daily and monthly data. Their results (as detailed in the their Supplementary Information) demonstrated that the differences between the two calculation frequencies are negligible and do not affect the analysis of VPD variations. Therefore, we proceeded with the monthly data for our VPD calculations.

Comment 7: In Line 38, the term "early establishment" for maize is used. Perhaps "emergence and seedling stage" is more specific to the phenological terminology used in agronomy.

Reply: We thank the reviewer for this helpful suggestion regarding terminology. We agree that “emergence and seedling stage” is more precise in an agronomic context. Accordingly, we have replaced “early establishment” with “emergence and seedling stage” throughout the manuscript.

Comment 8: Line 115: "in integrates" should be "it integrates."Check for consistency in the unit "gC m-2 mo-1" throughout the text and figures.

Reply: We thank the reviewer for the careful attention to detail. We have corrected “in integrates” to “it integrates” in the revised manuscript. In addition, we have thoroughly checked the consistency of the GPP units across the text and figures, and ensured that they are uniformly presented as gC m^{-2} mo^{-1}.

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