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Unraveling varietal resilience: integrating APSIM and RF to assess wheat yield responses to extreme temperatures

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Abstract: Quantitative evaluation of genotype-specific winter wheat yield responses to extreme climate events is vital for developing climate-resilient agronomic strategies. While integrating crop models with machine learning offers promise for quantifying nonlinear climate-wheat yield relationships, their ability to accurately capture extreme climate impacts across diverse wheat varieties remains uncertain.

By integrating the APSIM-Wheat model with a random forest (RF) algorithm, this study quantitatively assessed the nonlinear impacts of extreme temperature events (ETEs) on the yield of six winter wheat varieties cultivated across the North China Plain (NCP). The APSIM-Wheat model was rigorously calibrated, achieving high accuracy in simulating both phenological development (RMSE=2.2–2.7 days) and yield simulation (RMSE=225–303 kg ha^{-1}).

We further developed a hybrid model that integrates the APSIM-Wheat model with the RF algorithm. This hybrid model significantly improved the explanatory power for winter wheat yield, accounting for 84% of the observed variance in yield—an increase of 37.7% over the APSIM alone. The key ETE indicators exhibited variety-specific effects on yield variability. Specifically, low-temperature stress during the sowing–jointing stage contributed 20.37% to 53.67%, and during the jointing–flowering stage accounted for 10.52% to 34.02%. Additionally, high-temperature stress occurring between flowering and ripening explained 2.74% to 14.76% of the yield variability.

Thresholds of low temperature (tmin_sj) and its days (tmin_sj_days) during sowing–jointing were -2.8 to -1.7 degree and 73.7 to 78.0 days, compared to -1.4 to -0.6 degree and 5.4 to 14.0 days during jointing-flowering (tmin_jf and tmin_jf_days). Additionally, the threshold for the cumulative number of days with at least three consecutive low-temperature events during sowing–jointing (min_sj_days) varied from 70.7 to 81.1 days, while the number of high-temperature event days during flowering–ripening (max_fr_events) ranged from 0.8 to 2.8 days.

Future climate projections (2050s and 2080s) indicate phenological shifts with higher tmin_sj (0.1–1.3℃) and tmin_jf_days (2.1–4.8 days), but lower tmin_jf (0.6–2.2 degree), tmin_sj_days (11%–33%), and min_sj_days (28%–56%). These changes are projected to result in a decline in potential wheat yield ranging from 769 to 2463 kg ha^{-1}.

These findings reveal genotype-specific thermal sensitivities and provide a basis for phase-targeted adaptation strategies under intensifying climate extremes.

Keywords: *Extreme temperature events; Random forest; High-yielding variety; APSIM-Wheat model*

