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Modeling wheat development under extreme weather with WOFOST-EW v1

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Supplementary Text

S1. Detailed description of parameter sensitivity analysis for WOFOST model

In this study, the Sobol sensitivity analysis method is applied to evaluate parameter sensitivity in the WOFOST model. This approach quantifies the influence of input parameter variations on model outputs by calculating global sensitivity indices (Sobol, 2001). Following Wu et al. (2021), the analysis requires running the model $p \times s$ times, where p is the number of parameters and s is the number of samples. The analysis is conducted using the SALib library in Python. The Sobol algorithm generates parameter samples, which are then input into the PCSE framework to simulate crop growth and compute global sensitivity indices for each crop parameter in the WOFOST model.

S2. Model calibration

This study employed the Shuffled Complex Evolution Algorithm (SCE-UA), developed by the University of Arizona, to optimize parameter combinations for the WOFOST model. Model calibration was conducted using the Python package "spotpy", where the SCE-UA algorithm iteratively runs the WOFOST model to minimize a predefined cost function. Originally proposed by Duan et al. (1992; 1993), SCE-UA integrates the strengths of deterministic search, random sampling, and evolutionary strategies, and has demonstrated strong performance in global optimization and multi-parameter calibration. A key advantage of SCE-UA is its low sensitivity to initial parameter values, enhancing its robustness across various scenarios (Duan et al., 1994; Huang et al., 2018).

As shown in Table S4, ten parameters with the highest global sensitivity indices were selected for calibration. The SCE-UA algorithm was run for 200 iterations. In addition, the loss function in this study was designed as a weighted multi-objective function, with the specific form given as:

$$\mathrm{Loss} = \alpha \times \mathrm{Loss}_{\mathrm{phenology}} + \beta \times \mathrm{Loss}_{\mathrm{yield}} \tag{S1}$$

where $\mathrm{Loss}_{\mathrm{phenology}}$ represents the root mean square error (RMSE) between the simulated and observed phenological stages (heading and maturity), and $\mathrm{Loss}_{\mathrm{yield}}$ represents the RMSE between simulated and observed yields. After repeated testing and cross-validation, the weight coefficients were finally set as $\alpha = 0.8$ and $\beta = 0.2$.

Supplementary Figures

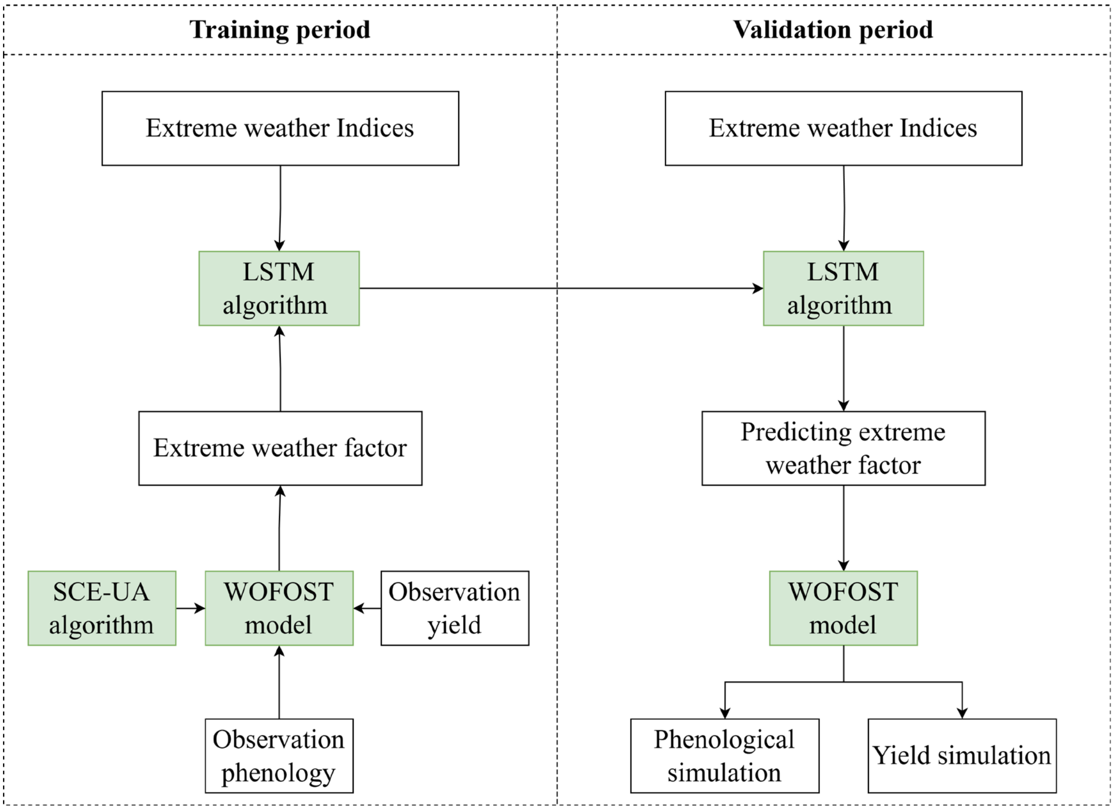

Figure S1. The training and validation workflow of the Long Short-Term Memory (LSTM) network in the WOFOST-EW model.

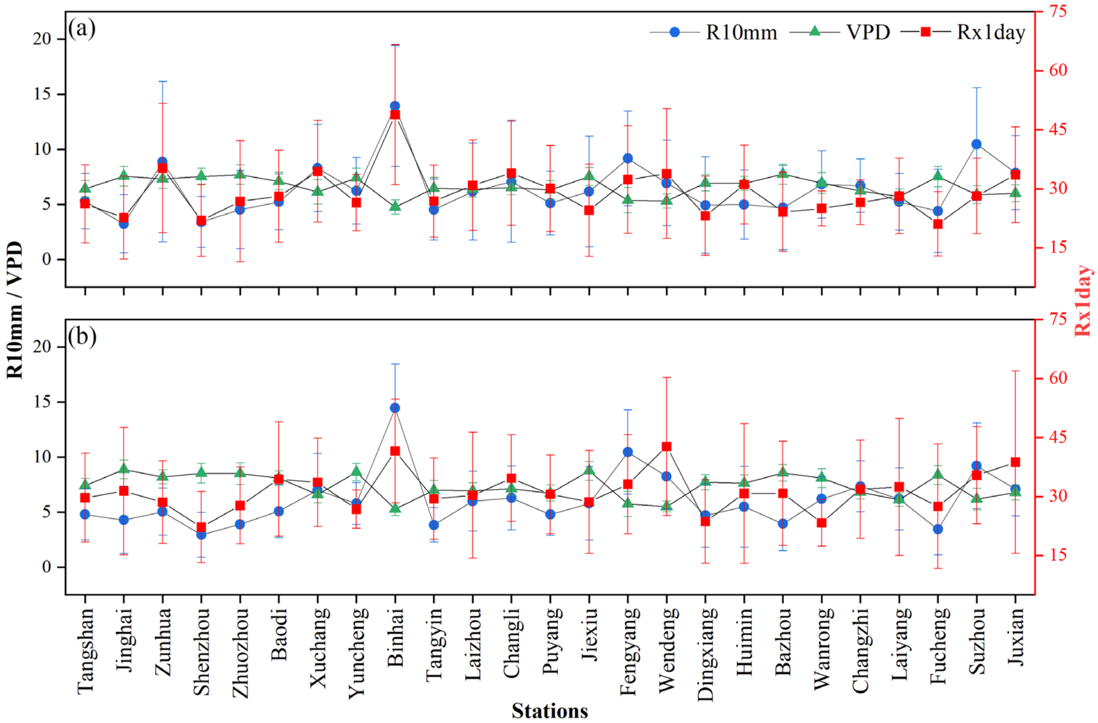

Figure S2. The extreme weather index results for the 25 sites in the study area for the calibration years (a) and validation years (b). R10mm and Rx1day represent extreme precipitation-related weather indices. VPD represents vapor pressure deficit.

Supplementary Tables

Table S1. Details of the agricultural meteorological experiment stations.

Counties	Longitude	Latitude	Climate type	Mean temperature during winter wheat growing period (°C)	Precipitation during winter wheat growing period (mm)
Tangshan	118.2 °E	39.7 °N	Temperate continental	6.8	181.2
Jinghai	116.9 °E	38.9 °N	Warm temperate continental	7.6	157.3
Zunhua	118.0 °E	40.2 °N	Temperate continental	6.6	247.4
Shenzhou	115.6 °E	38.0 °N	Warm temperate semi-arid	8.2	136.6
Zhuozhou	116.0 °E	39.5 °N	Warm temperate continental	8.0	170.9
Baodi	117.3 °E	39.7 °N	Warm temperate semi-humid	7.2	192.7
Xuchang	113.9°E	34.0°N	Warm temperate monsoon	9.9	266.5
Yuncheng	111.0 °E	35.0 °N	Temperate monsoon	7.6	227.2
Binhai	119.8 °E	34.0 °N	Warm temperate semi-humid	9.6	459.7
Tangyin	114.4 °E	35.9 °N	North temperate continental	9.5	165.3
Laizhou	119.9 °E	37.2 °N	Warm temperate continental	7.8	225.5
Changli	119.2 °E	39.7 °N	Warm temperate semi-humid	7.6	253.4
Puyang	115.0 °E	35.7 °N	Subtropical monsoon	9.6	186.2
Jiexiu	111.9 °E	37.1 °N	Temperate monsoon	6.5	233.5
Fengyang	117.6 °E	32.9 °N	Subtropical monsoon	9.5	332.0
Wendeng	122.0 °E	37.2 °N	Temperate maritime	8.5	285.5
Dingxiang	113.0 °E	38.5 °N	Warm temperate semi-humid	5.4	197.7
Huimin	117.5 °E	37.5 °N	Temperate monsoon	8.5	190.5
Bazhou	116.4 °E	39.1 °N	Temperate continental	7.7	169.4
Wanrong	110.8 °E	35.4 °N	Temperate continental	8.7	245.3
Changzhi	113.1 °E	36.1 °N	Warm temperate semi-humid	5.9	263.8
Laiyang	120.7 °E	36.9 °N	Temperate monsoon	7.2	213.2
Fucheng	116.2 °E	37.9 °N	Temperate monsoon	8.4	155.6
Suzhou	117.0 °E	33.6 °N	North temperate monsoon	9.7	312.8
Juxian	118.8 °E	35.6 °N	Warm temperate monsoon	8.1	252.2

Table S2. Detailed information on the study stations affected by extreme weather.

Station	Longitude	Latitude	Station	Longitude	Latitude
Changping	116.2 °E	40.2 °N	Qinxian	112.6 °E	36.7 °N
Shunyi	116.7 °E	40.2 °N	Qinshui	112.4 °E	35.7 °N
Tongzhou	116.7 °E	39.8 °N	Yangcheng	112.4 °E	35.4 °N
Daxing	116.4 °E	39.6 °N	Lingchuan	113.3 °E	35.7 °N
Huairou	116.6 °E	40.6 °N	Shouguang	118.8 °E	37.0 °N
Miyun	117.0 °E	40.5 °N	Linqu	118.6 °E	36.4 °N
Pingshan	113.9 °E	38.4 °N	Gaomi	119.7 °E	36.4 °N
Xiangyuan	113.0 °E	36.6 °N	Yanzhou	116.7 °E	35.6 °N
Licheng	113.4 °E	36.6 °N	Jiaxiang	116.3 °E	35.4 °N
Wuxiang	113.0 °E	36.9 °N			

Table S3. List of parameters for WOFOST model calibration and their first-order and global sensitivity coefficients.

Parameter	First order sensitivity coefficient	Parameter	Global sensitivity coefficient
EFFTB400	0.255	EFFTB400	0.355
TMPFTB30	0.122	TMPFTB30	0.311
TSUM1	0.088	SPAN	0.185
AMAXTB200	0.065	TSUM1	0.128
SPAN	0.060	AMAXTB200	0.104
SLATB200	0.052	TMPFTB20	0.066
CVO	0.048	CVO	0.058
TMPFTB40	0.033	SLATB000	0.055
TSUM2	0.030	TBASE	0.053
SLATB000	0.020	SLATB200	0.042

Table S4. Detailed descriptions and ranges of calibrated crop parameters in the WOFOST model.

Parameter	Description	Unit	Range
TSUM1	Accumulated temperature from emergence to heading	$℃\ d$	1300–1600
SLATB000	Specific leaf area at corresponding development stage (DVS=0.0)	$ha{\cdot}kg^{-1}$	0.001–0.004
SLATB200	Specific leaf area at corresponding development stage (DVS=2.0)	$ha{\cdot}kg^{-1}$	0.001–0.004
SPAN	Leaf senescence coefficient	d	20.0–50.0
TBASE	Lower temperature limit for leaf age	$℃$	−10.0–10.0
EFFTB400	Initial light uses efficiency of CO_2 assimilation of single leaves as a function of daily mean temperature (T=40℃)	$kg{\cdot}hm^{-2}{\cdot}hr^{-1}{\cdot}j^{-1}{\cdot}m^{2}{\cdot}s$	0.1–0.4
AMAXTB200	Maximum CO_2 assimilation rate at corresponding development stage (DVS=2.0)	$kg{\cdot}hm^{-2}{\cdot}hr^{-1}$	20–70
TMPFTB20	Daytime average temperature effect on maximum CO_2 assimilation rate (T=20℃)	-	0–1.0
TMPFTB30	Daytime average temperature effect on maximum CO_2 assimilation rate (T=30℃)	-	0–1.0
CVO	Efficiency conversion of assimilates into storage organ dry matter	$kg{\cdot}kg^{-1}$	0.5–0.8

Table S5. Root mean square error (RMSE) between the phenological period and yield simulation results for the WOFOST and WOFOST-EW model on the calibration dataset at each station. Values in parentheses represent 95% bootstrap confidence intervals.

Station	Phenology (day)				Yield (kg/ha)	
	WOFOST		WOFOST-EW		WOFOST	WOFOST-EW
	Heading	Maturity	Heading	Maturity		
Tangshan	3.7 (±2.0)	5.4 (±3.0)	2.5 (±1.0)	5.4 (±2.5)	773.37 (±203.85)	589.14 (±292.06)
Jinghai	3.8 (±1.3)	3.8 (±1.5)	2.6 (±1.3)	1.0 (±0.5)	739.41 (±284.05)	474.61 (±243.34)
Zunhua	3.7 (±1.2)	3.1 (±0.7)	4.0 (±1.4)	1.5 (±0.6)	784.63 (±207.55)	485.39 (±166.24)
Shenzhou	5.5 (±2.3)	7.2 (±4.1)	5.0 (±0.7)	4.2 (±1.8)	529.98 (±206.00)	571.58 (±168.80)
Zhuozhou	6.4 (±2.5)	8.9 (±1.9)	5.1 (±2.5)	7.0 (±1.9)	594.66 (±253.08)	396.24 (±214.06)
Baodi	5.3 (±1.8)	7.0 (±3.5)	4.9 (±2.5)	4.4 (±1.0)	680.63 (±172.56)	654.73 (±210.65)
Xuchang	4.7 (±1.6)	8.2 (±1.8)	4.6 (±2.1)	6.9 (±3.7)	802.56 (±268.22)	386.05 (±119.07)
Yuncheng	3.8 (±1.5)	10.1 (±3.4)	3.8 (±1.5)	6.8 (±4.0)	804.86 (±194.41)	714.46 (±165.33)
Binhai	10.3 (±5.5)	9.7 (±3.0)	5.5 (±3.5)	2.1 (±1.5)	614.97 (±175.59)	688.87 (±179.84)
Tangyin	9.6 (±4.0)	13.1 (±5.9)	5.6 (±3.0)	8.4 (±3.4)	640.65 (±253.36)	394.63 (±105.77)
Laizhou	7.6 (±4.4)	6.7 (±2.7)	4.6 (±1.7)	5.5 (±3.6)	740.81 (±252.61)	620.27 (±186.12)
Changli	2.2 (±1.0)	6.9 (±2.8)	3.9 (±2.5)	5.9 (±1.8)	844.58 (±187.71)	563.38 (±263.94)
Puyang	5.8 (±1.6)	5.4 (±2.7)	6.0 (±2.5)	2.2 (±1.3)	619.23 (±275.19)	472.76 (±148.53)
Jiexiu	1.4 (±1.0)	6.5 (±3.2)	0.7 (±0.5)	6.1 (±2.6)	717.55 (±198.60)	526.53 (±197.06)
Fengyang	12.8 (±5.4)	9.4 (±4.3)	4.5 (±1.6)	6.4 (±2.8)	657.47 (±137.39)	627.60 (±181.68)
Wendeng	10.2 (±3.8)	10.2 (±5.0)	5.0 (±1.5)	7.4 (±4.5)	700.84 (±319.50)	295.63 (±66.30)
Dingxiang	8.5 (±3.0)	10.9 (±1.4)	5.7 (±3.5)	6.2 (±2.4)	355.83 (±131.60)	488.31 (±206.96)
Huimin	3.8 (±1.9)	4.6 (±1.9)	3.1 (±1.4)	2.9 (±2.0)	481.25 (±289.12)	519.26 (±266.62)
Bazhou	4.5 (±2.0)	7.1 (±4.5)	4.8 (±1.8)	7.5 (±5.5)	665.49 (±209.07)	468.48 (±218.09)
Wanrong	2.5 (±0.5)	12.4 (±5.0)	2.8 (±2.0)	8.7 (±5.5)	521.87 (±173.67)	598.07 (±156.53)
Changzhi	5.0 (±3.1)	10.3 (±2.0)	4.2 (±1.7)	8.7 (±2.1)	779.40 (±182.15)	557.60 (±142.77)
Laiyang	3.6 (±2.0)	11.6 (±5.1)	4.2 (±3.0)	4.7 (±1.4)	792.39 (±204.05)	596.14 (±145.54)
Fucheng	4.3 (±1.3)	8.8 (±2.9)	2.5 (±1.1)	5.9 (±2.7)	699.14 (±176.24)	611.51 (±217.97)
Suzhou	6.8 (±1.8)	4.6 (±1.0)	5.4 (±1.4)	3.5 (±1.1)	519.59 (±173.15)	488.10 (±184.63)
Juxian	7.5 (±2.9)	7.0 (±1.3)	4.7 (±1.6)	5.1 (±1.4)	764.12 (±269.29)	758.14 (±146.20)

Table S6. Root mean square error (RMSE) between the phenological period and yield simulation results for the WOFOST and WOFOST-EW model on the validation dataset at each station. Values in parentheses represent 95% bootstrap confidence intervals.

Station	Phenology (day)				Yield (kg/ha)	
	WOFOST		WOFOST-EW		WOFOST	WOFOST-EW
	Heading	Maturity	Heading	Maturity		
Tangshan	4.2 (±2.5)	6.9 (±2.3)	5.0 (±3.5)	6.8 (±2.4)	938.19 (±275.80)	960.75 (±157.0)
Jinghai	3.8 (±3.0)	6.0 (±2.6)	5.5 (±2.6)	7.0 (±2.2)	790.60 (±219.27)	605.14 (±189.0)
Zunhua	4.4 (±1.7)	6.2 (±2.7)	5.6 (±1.9)	7.3 (±2.7)	547.16 (±171.16)	657.43 (±161.5)
Shenzhou	3.5 (±1.8)	7.4 (±2.3)	6.0 (±1.6)	8.8 (±2.5)	714.13 (±293.43)	418.84 (±187.4)
Zhuozhou	3.0 (±1.2)	4.5 (±3.1)	5.1 (±2.8)	7.3 (±3.4)	699.40 (±198.35)	641.68 (±202.4)
Baodi	4.3 (±2.9)	4.8 (±1.8)	4.8 (±1.2)	6.8 (±2.2)	918.80 (±269.57)	651.05 (±190.1)
Xuchang	4.1 (±3.5)	3.2 (±1.0)	4.7 (±2.0)	3.6 (±2.5)	824.02 (±236.13)	639.53 (±203.8)
Yuncheng	4.3 (±2.8)	7.3 (±3.4)	2.4 (±1.2)	4.3 (±1.5)	511.74 (±265.95)	500.31 (±259.8)
Binhai	6.5 (±0.5)	7.4 (±3.8)	3.3 (±2.1)	4.2 (±2.3)	761.25 (±172.79)	663.29 (±175.6)
Tangyin	7.9 (±5.1)	10.0 (±4.1)	4.6 (±1.7)	5.8 (±2.9)	616.91 (±208.45)	378.98 (±75.3)
Laizhou	4.8 (±2.4)	9.3 (±5.3)	3.9 (±1.7)	6.4 (±2.7)	552.23 (±378.68)	683.83 (±246.4)
Changli	9.5 (±3.2)	6.0 (±2.4)	4.7 (±1.4)	3.9 (±1.2)	301.43 (±149.21)	565.89 (±339.7)
Puyang	5.5 (±1.3)	5.3 (±3.0)	4.5 (±1.3)	4.5 (±3.0)	632.95 (±230.36)	529.37 (±194.0)
Jiexiu	5.7 (±3.5)	10.8 (±5.5)	4.7 (±1.5)	8.2 (±4.0)	616.06 (±134.72)	515.65 (±242.1)
Fengyang	3.1 (±1.5)	5.5 (±1.7)	4.4 (±2.8)	5.9 (±1.9)	906.73 (±120.31)	586.79 (±243.1)
Wendeng	2.0 (±0.5)	5.3 (±3.5)	4.0 (±1.0)	6.8 (±2.5)	648.87 (±176.23)	386.52 (±124.9)
Dingxiang	6.7 (±2.5)	11.8 (±3.6)	3.7 (±3.0)	5.7 (±1.7)	794.52 (±173.28)	893.47 (±188.23)
Huimin	1.7 (±0.5)	7.7 (±3.8)	4.3 (±2.0)	6.9 (±2.1)	559.67 (±255.12)	536.54 (±273.7)
Bazhou	4.0 (±0.5)	5.5 (±2.4)	1.0 (±0.3)	6.8 (±3.8)	862.60 (±424.32)	383.14 (±121.3)
Wanrong	1.0 (±0.5)	10.6 (±5.0)	1.1 (±0.5)	8.1 (±3.6)	619.98 (±172.42)	703.24 (±152.2)
Changzhi	4.6 (±1.8)	5.4 (±3.0)	4.7 (±1.5)	5.2 (±1.5)	573.08 (±305.99)	297.47 (±182.7)
Laiyang	8.5 (±4.6)	6.2 (±2.3)	4.3 (±2.4)	3.2 (±1.8)	256.61 (±96.10)	279.64 (±94.0)
Fucheng	5.4 (±3.4)	5.9 (±2.6)	4.2 (±2.5)	6.9 (±2.9)	769.21 (±348.52)	453.30 (±191.9)
Suzhou	4.4 (±1.2)	4.8 (±1.4)	4.4 (±1.6)	4.6 (±2.1)	342.92 (±129.45)	390.50 (±193.8)
Juxian	4.4 (±2.7)	11.1 (±5.5)	3.0 (±1.9)	7.3 (±2.8)	436.12 (±83.58)	531.86 (±191.2)

Table S7. Comparison of yield simulation performance between WOFOST and WOFOST-EW under the influence of extreme weather using Pearson's r, coefficient of determination (R^2), root mean square error (RMSE), relative RMSE (RRMSE), mean absolute error (MAE), and mean relative error (MRE). All correlation coefficients and R^2 values are statistically significant at $p < 0.01$.

Model	Year	Pearson's r	R^2	RMSE (kg/ha)	RRMSE (%)	MAE (kg/ha)	MRE (%)
WOFOST	2009	0.87	0.71	922.40	19.81	862.16	20.94
	2010	0.81	0.65	1043.28	23.83	871.20	26.65
	2012	0.87	0.63	993.22	20.87	762.89	17.96
	2018	0.85	0.61	781.56	16.22	654.78	14.07
WOFOST-EW	2009	0.94	0.86	642.00	13.79	482.02	11.99
	2010	0.92	0.84	711.38	16.25	553.04	19.15
	2012	0.92	0.82	693.11	14.56	587.84	13.28
	2018	0.91	0.80	555.72	11.53	372.25	8.21

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