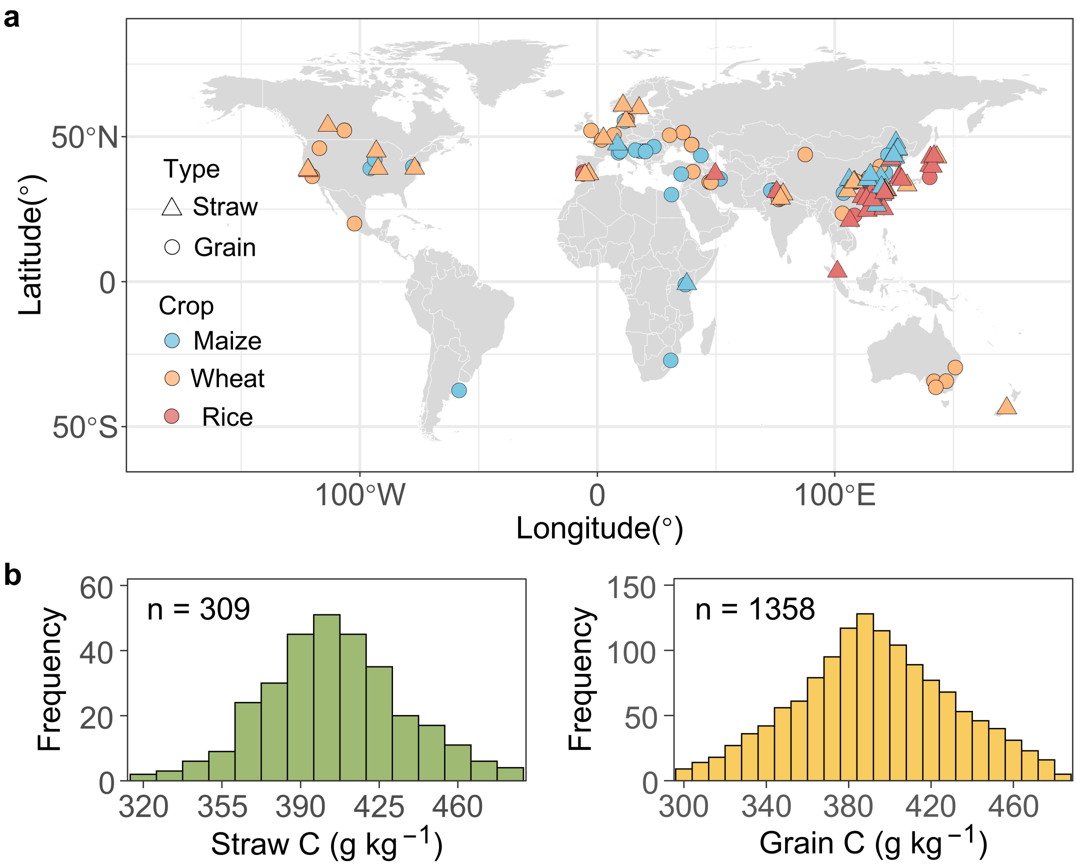
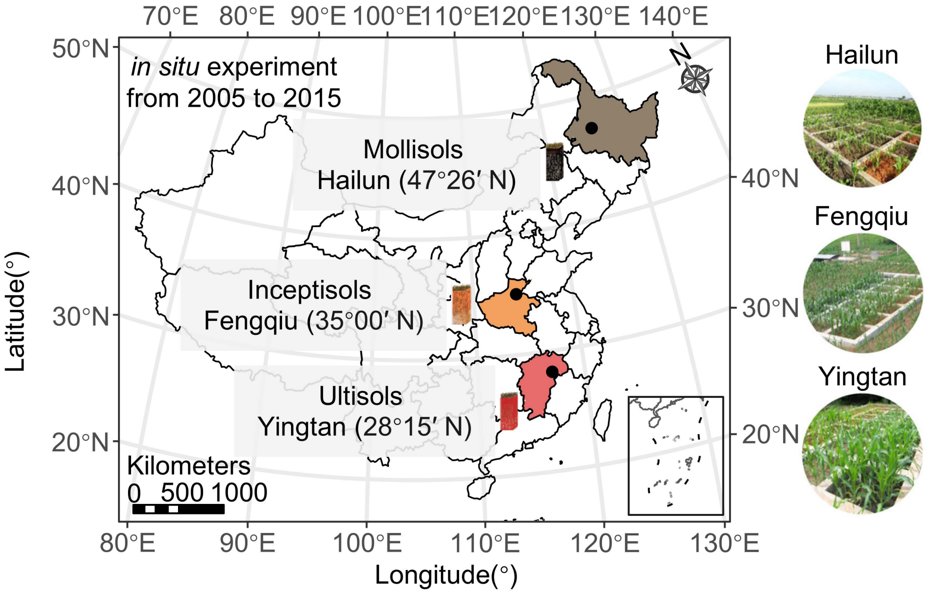
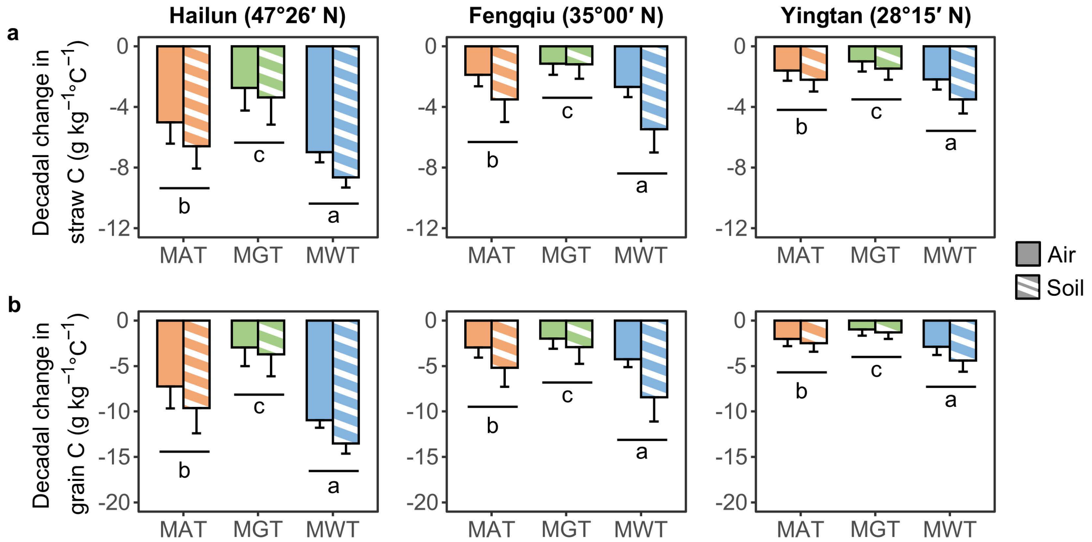
Supplementary Figures and Tables



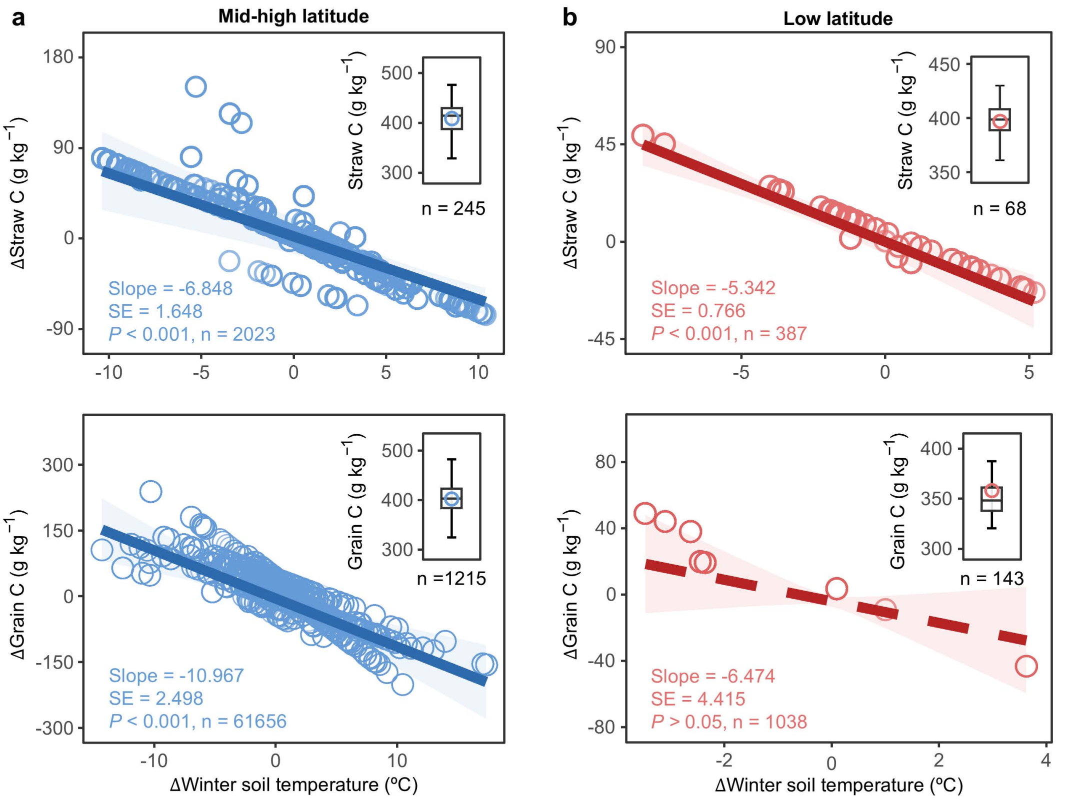
Supplementary Fig. 1 Global distribution of the study sites included in the collected datasets. a, Geographic distribution of the observations of crop biomass C, including straw C content (n = 309) and grain C content (n = 1358). The triangles represent straw C data, and the circles represent grain C data. **b**, Distribution of straw C content and grain C content. Straw C refers to the carbon content in straw. Grain C refers to the carbon content in grain.



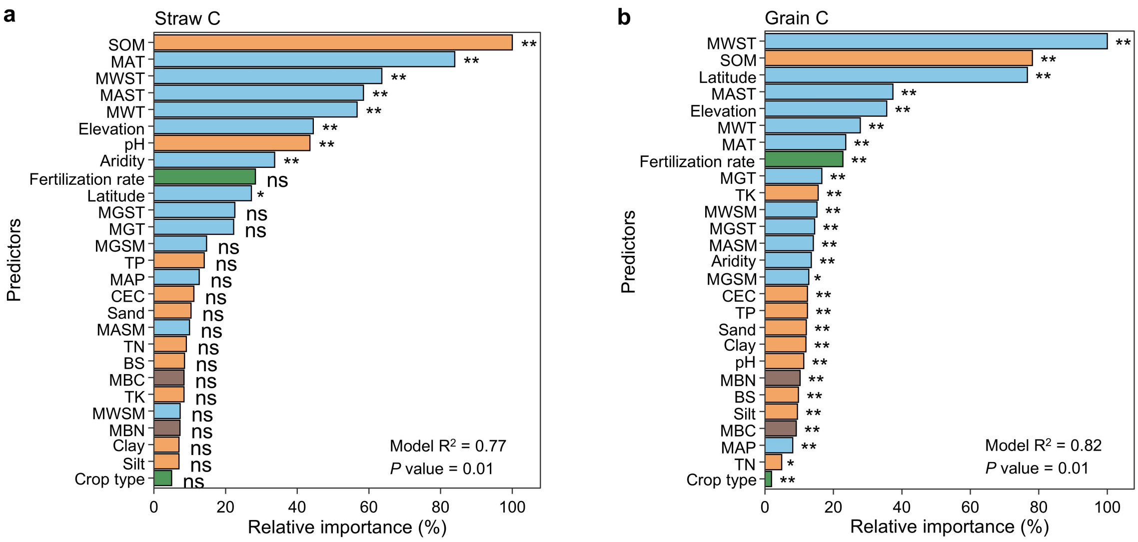
Supplementary Fig. 2 Geospatial distribution of ten-year *in situ* field experiments. The figure presents three typical agroecological experimental stations of the Chinese Academy of Sciences (CAS): Hailun (47º26′ N), Fengqiu (35º00′ N) and Yingtan (28º15′ N). The soil types at these stations are Mollisols at Hailun, Inceptisols at Fengqiu, and Ultisols at Yingtan. Hailun Station is located in the cold-temperate (high latitude) climatic zone of Heilongjiang Province in northern China; Fengqiu Station is located in the warm-temperate (mid-latitude) climatic zone of Henan Province in central China; and Yingtan Station is located in the subtropical (low latitude) climatic zone of Jiangxi Province in southern China. At each station, the sample plots are planted with maize.



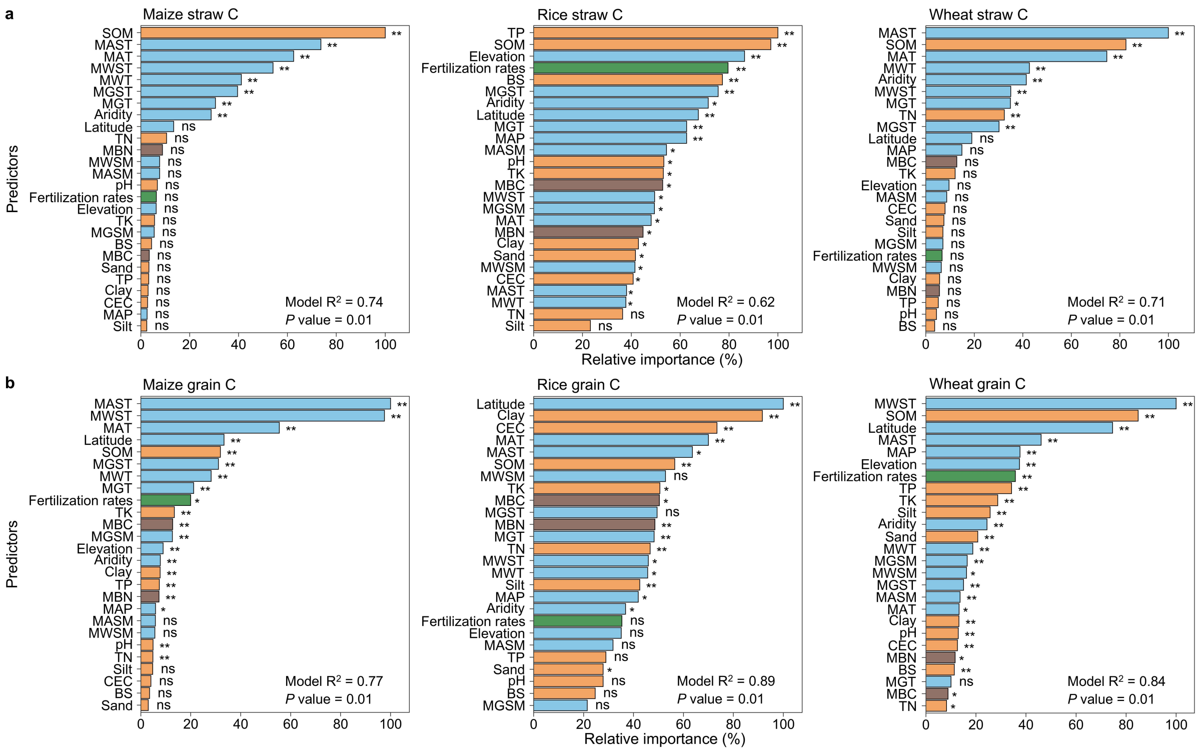
Supplementary Fig. 3 Temperature dependency of decadal changes in crop biomass C with different temperature types. a, Straw C content. **b**, Grain C content. Data are presented as beta coefficients from linear regression models, with error bars representing the standard deviation of bootstrap estimates (n = 999). This figure shows the results of decade-long *in situ* field experiments conducted 2006 to 2015 across three locations. The bar plots represent the beta coefficient that describe the relationships between different temperature types and straw and grain C content. One-way ANOVA evaluates the effects of different temperature types on straw and grain C content. Tukey's post-hoc test was applied for multiple comparisons of mean annual temperature (MAT), mean growing-season temperature (MGT) and mean winter temperature (MWT), with results indicated by lowercase letters. Different letters indicate statistically significant differences, while the same letter denotes nonsignificant differences. "Air" refers to air temperature (solid color bars), and "Soil" refers to soil temperature (stripe bars).



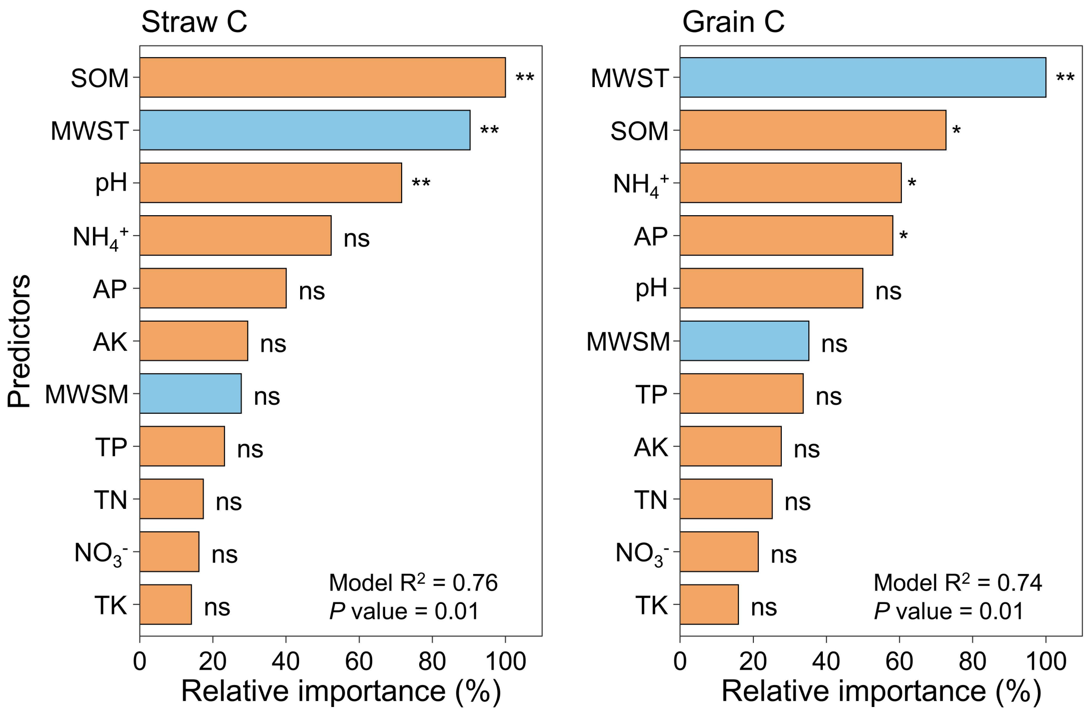
Supplementary Fig. 4 Latitudinal variation of crop biomass C response to winter soil temperature changes. a, Mid to high latitudes. **b,** Low latitudes. Crop biomass C includes both straw and grain C content. Boxplots show the distribution of straw and grain C content in the compiled global dataset, with the number of observations noted at the base of each box and mean values indicated by dots. The solid line in the box plot represents the median (50th percentile), the ends of the box represent the upper quartile (75th percentile, Q3) and lower quartile (25th percentile, Q1), and the whiskers indicate the range from the minimum to maximum values based on the quartiles. Scatterplots depict the relationship between changes in crop biomass C (ΔStraw C and ΔGrain C) and variations in winter soil temperature (ΔWinter soil temperature), derived from differences between two separate years with identical climate classification and crop types (see Methods for detailed calculation). Scatters points are adjusted using fixed and random effects from a linear mixed-effects model. The fitted lines represent predictions from the liner mixed-effects model, with confidence intervals via bootstrap resampling (n = 999). The slope represents the coefficient estimate for the fixed effects in the linear mixed-effects model, SE denotes the standard error. For **a**, *P* values for straw and grain at mid-to-high latitudes are 0.0007 and 0.0003, respectively. For **b**, *P* values are 2.05e-18 and 0.143, respectively. Winter soil temperature is characterized as the mean annual soil temperature during winter.



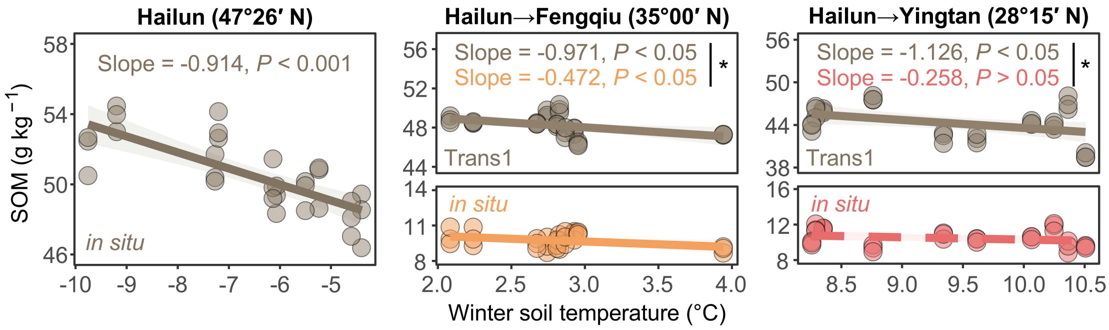
Supplementary Fig. 5 Relative importance of predictors to crop biomass C in the collected datasets. **a**, Straw C content. **b**, Grain C content. Abbreviations are as follows: SOM, Soil organic matter; MAP, mean annual precipitation; MAT, mean annual temperature; MAST, mean annual soil temperature; MGT, mean growing-season temperature; MGST, mean growing-season soil temperature; MWT, mean winter temperature; MWST, mean winter soil temperature; MASM, mean annual soil moisture content; MGSM, mean growing-season soil moisture content; MWSM, mean winter soil moisture content; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; BS, base saturation; CEC, cation exchange capacity. The R^2 and *P* values indicate the coefficient of determination and the probability of the model, respectively. Orange, blue and brown bars represent soil-related variables, climate-related variables, and microbial related variables, respectively. Green bars represent other variables including crop type and fertilization rate. ns: not significant, *: $P < 0.05$; **: $P < 0.01$.



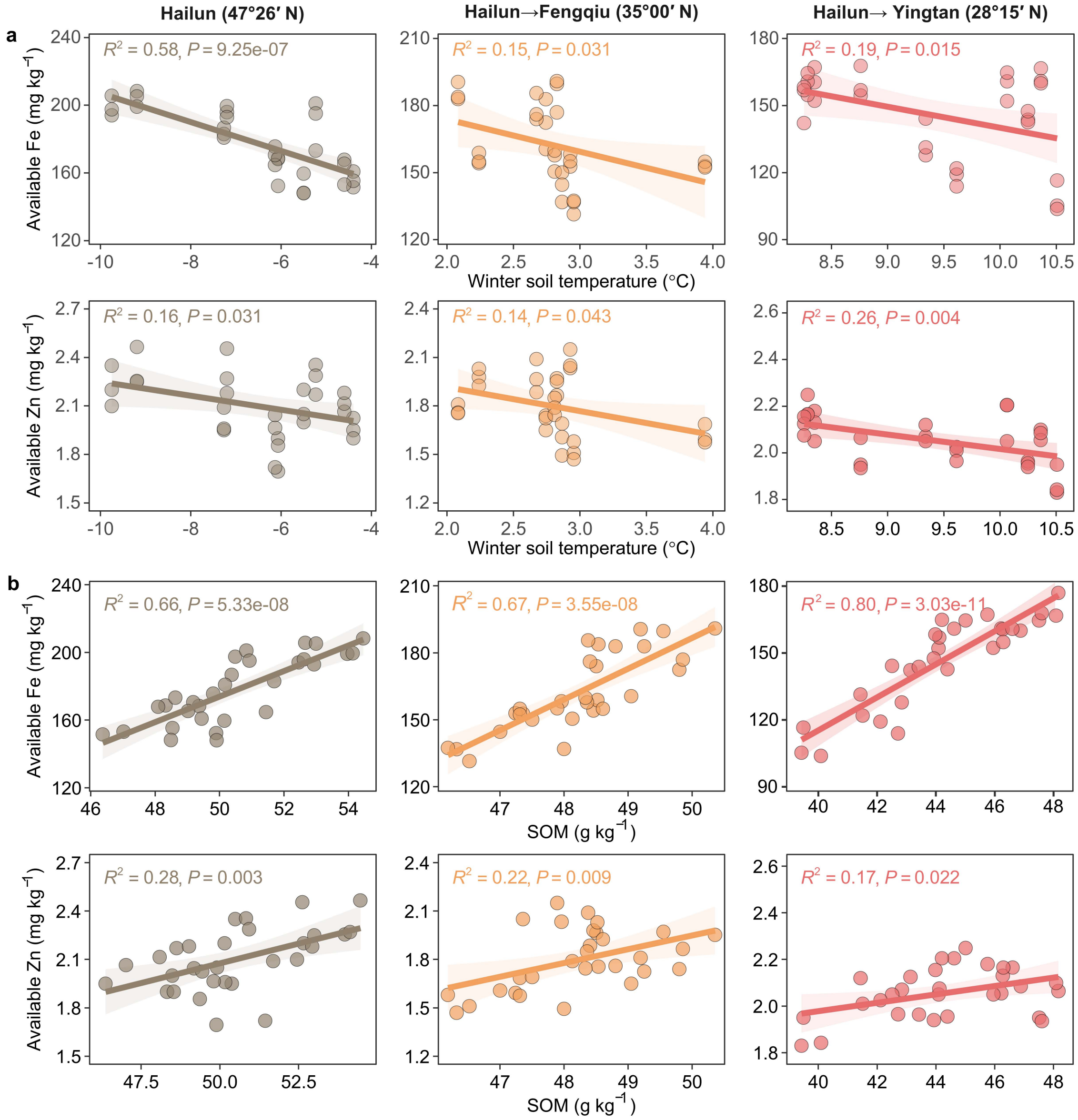
Supplementary Fig. 6 Relative importance of predictors to crop biomass C among three crop types in the collected datasets. a, Straw C content. **b**, Grain C content. Some abbreviations are the same as in **Supplementary Fig. 5**, including SOM, MAP, MAT, MAST, MGT, MGST, MWT, MWST, MASM, MGSM, MWSM, MBC, MBN, TN, TP, TK, BS and CEC. The R^2 and P values indicate the coefficient of determination and the probability of the model, respectively. Orange bars indicate soil-related variables; blue bars indicate climate-related variables; brown bars indicate biology-related variables; and green bars indicate other variables. ns: not significant, *: $P < 0.05$; **: $P < 0.01$.



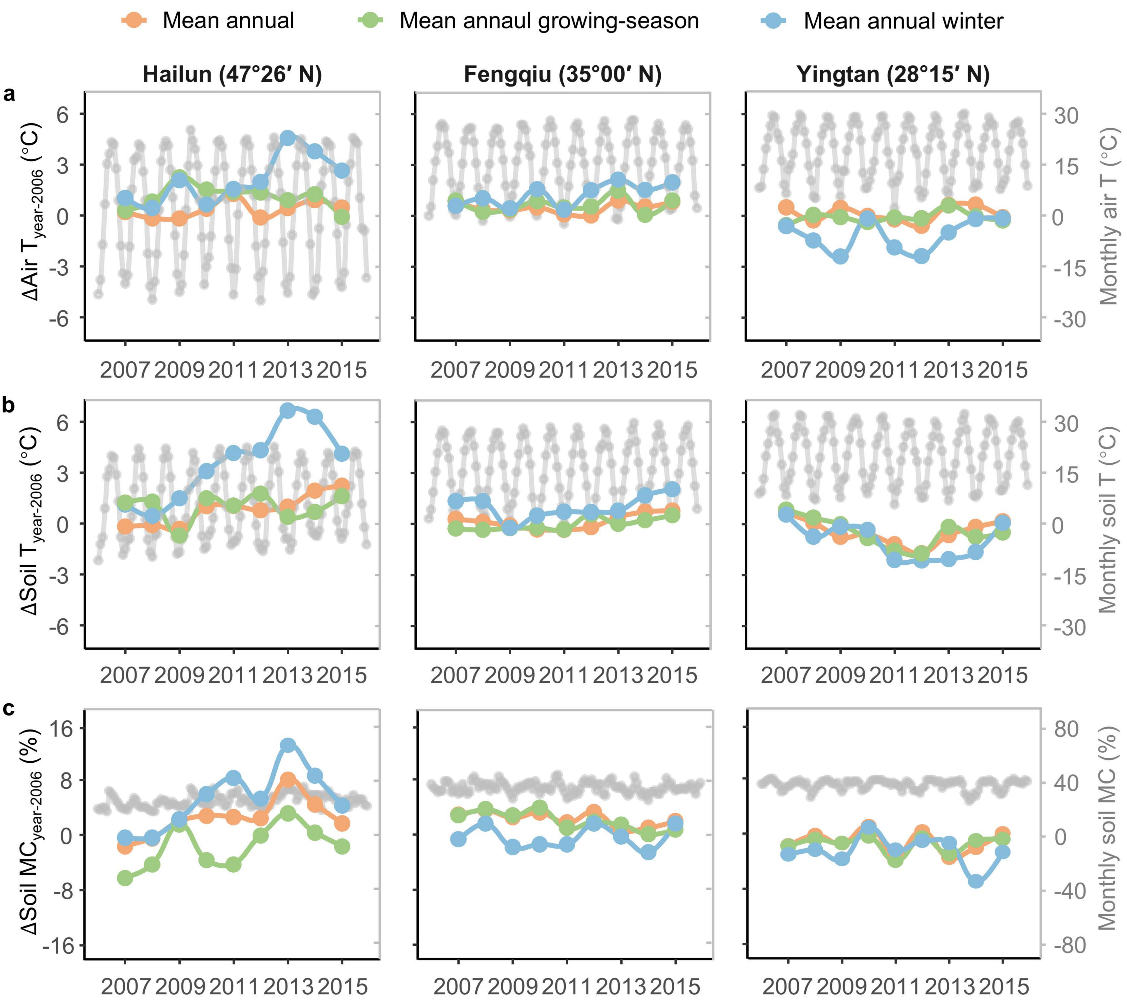
Supplementary Fig. 7 Relative importance of predictors to crop biomass C in the decade-long *in situ* field experiment. Crop biomass C refers to both straw and grain C contents. Some abbreviations are the same as in **Supplementary Fig. 5**, including MWST, MWSM, SOM, TN, TP, TK. Other abbreviations are as follows: NH_4^+ for ammonium nitrogen, NO_3^- for nitrate nitrogen, AP for available phosphorus, AK for available potassium. Orange bars indicate soil-related variables; blue bars indicate climate-related variables. The R^2 and P values indicate the coefficient of determination and the probability of the model, respectively. ns: not significant, *: $P < 0.05$; **: $P < 0.01$.



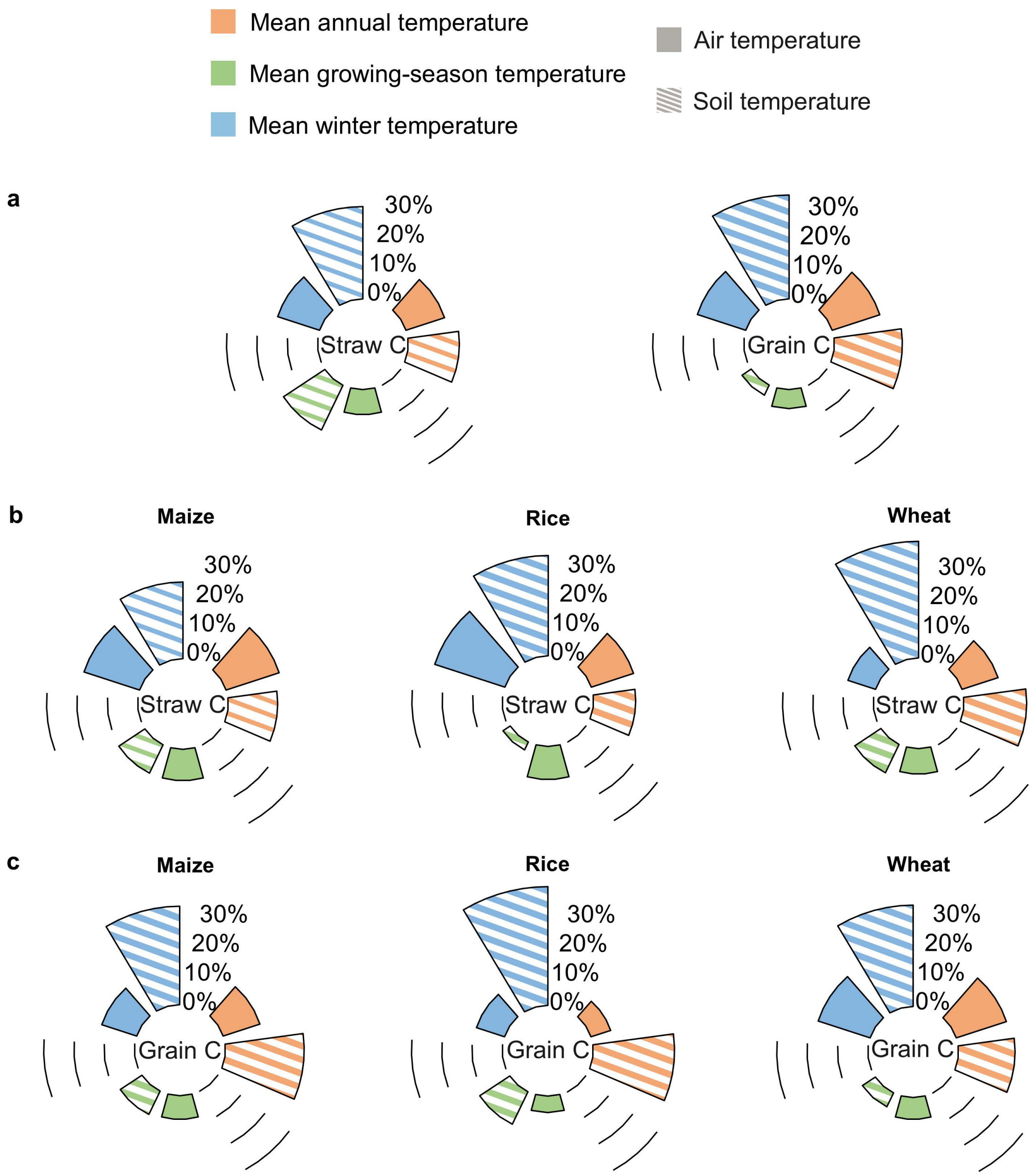
Supplementary Fig. 8 Relationship between winter soil temperature and SOM in ten-year *in situ* and soil translocation field experiments. Linear regression models depict the relationship between winter soil temperature and SOM under fertilized treatment across three locations (each site n = 30). The fitted lines represent the linear regression models, with shaded areas indicating 95% confidence intervals around the mean values. Solid lines indicate statistically significant effects ($P < 0.05$), while dashed lines indicate nonsignificant effects. Slope comparisons between the *in situ* and translocation models were performed using the bootstrap method (n = 999), followed by a two-sided t-test to assess statistical significance. Asterisk (*) denotes statistically significant differences between regression slopes at the 0.05 level. P values for the relationships at Hailun (*in situ*), Fengqiu (Trans1 and *in situ*), Yingtan (Trans2 and *in situ*) are 8.11e-07, 0.0138, 0.0449, 0.028 and 0.196, respectively. Winter soil temperature is defined as the mean annual soil temperature during winter.



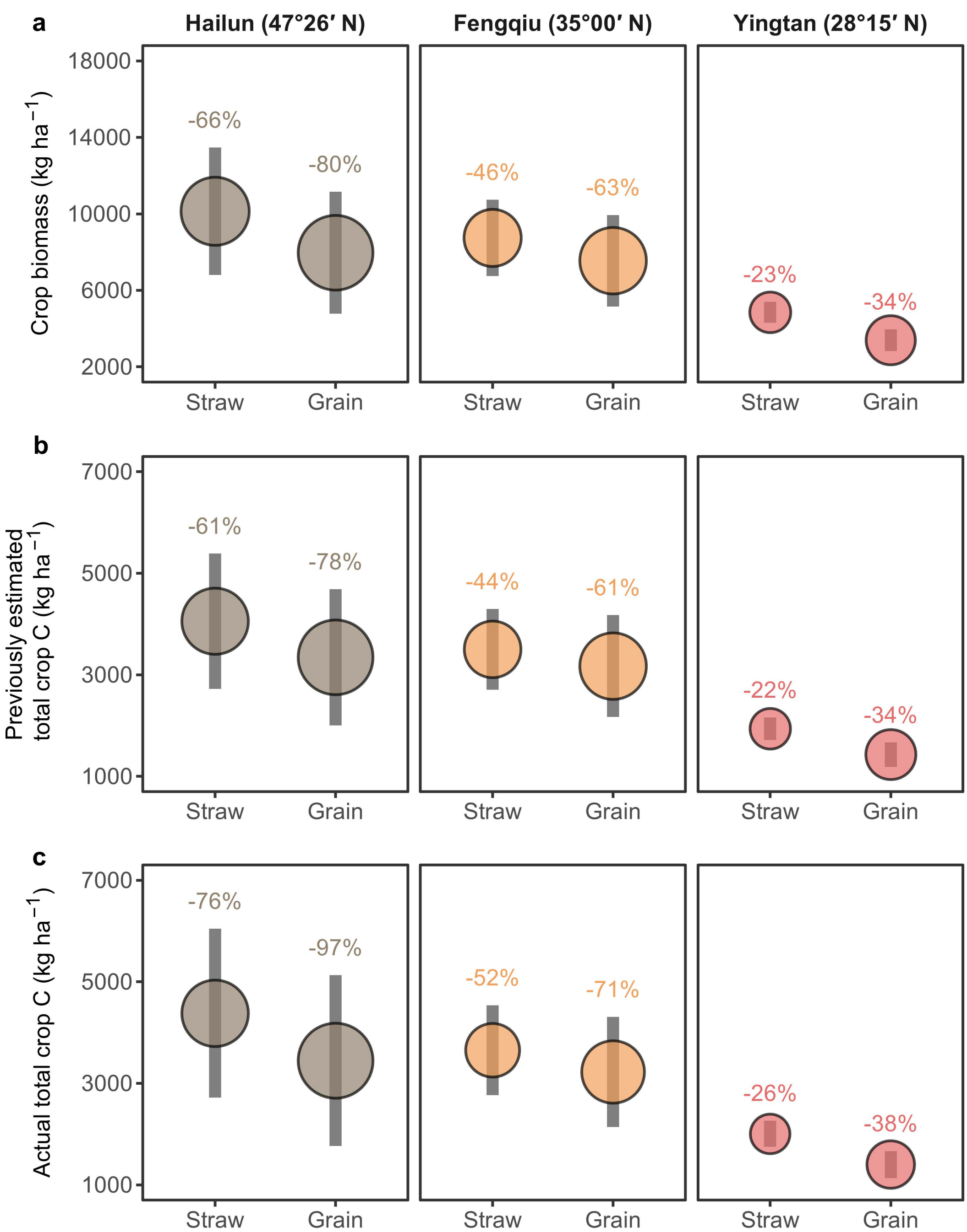
Supplementary Fig. 9 Relationship between winter soil temperature, SOM, and available Fe and Zn. a, The relationship between winter soil temperature and available Fe and Zn. **b**, The relationship between SOM and available Fe and Zn. Linear regression models illustrate the relationships between winter soil temperature, SOM and available Fe and Zn across three locations (each site n = 30), with shaded areas indicating 95% confidence intervals around the mean values. R^2 values represent the proportion of variance explained by the models, and *P* values indicate the statistical significance of the relationships. Winter soil temperature is defined as the mean annual soil temperature during winter.



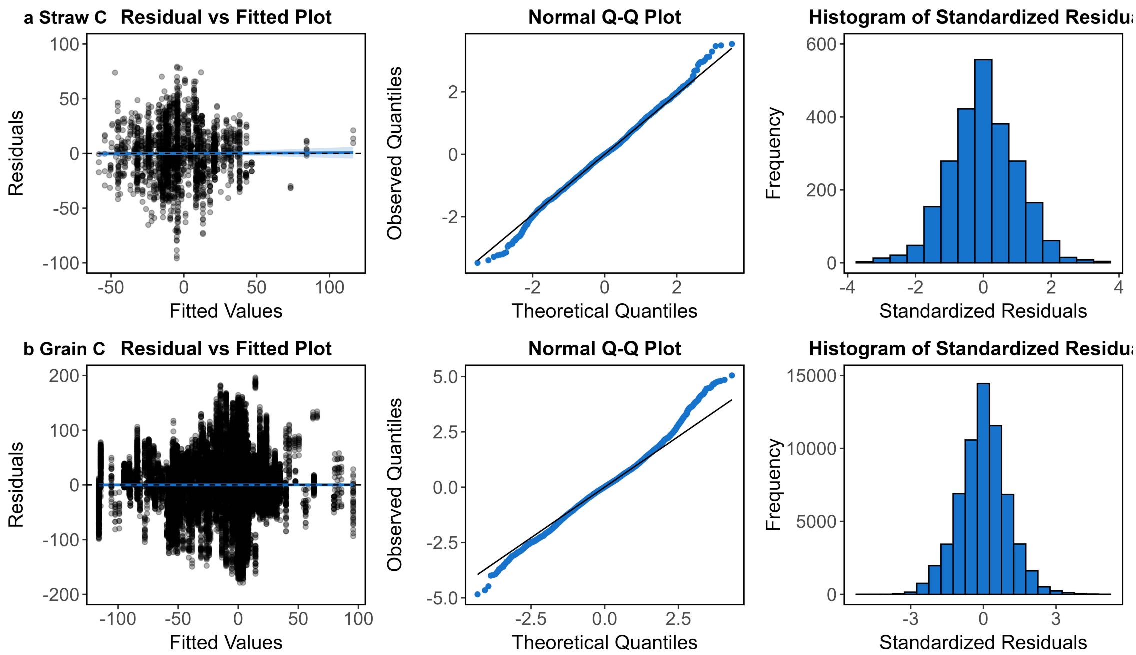
Supplementary Fig. 10 Temperature and moisture dynamics over ten years from 2006 to 2015 across three typical climate zones. a, Air temperature. **b**, Soil temperature. **c**, Soil moisture content. The left y-axis shows the differences between the annual mean air temperature, annual mean soil temperature, and annual mean soil moisture content in topsoil for each year from 2007 to 2015 and the values in 2006. The year 2006 is when the crops were planted at each site. The right side shows the monthly mean air temperature, soil temperature and soil moisture changes from 2006 to 2015. The mean growing season air temperature, soil temperature and soil moisture are the average values for the corresponding crop-growing seasons at the three experimental sites: Hailun, Fengqiu and Yingtan. The mean winter air temperature, soil temperatures and soil moisture are the average values for the corresponding lowest three-month temperatures in Hailun, Fengqiu and Yingtan, respectively.



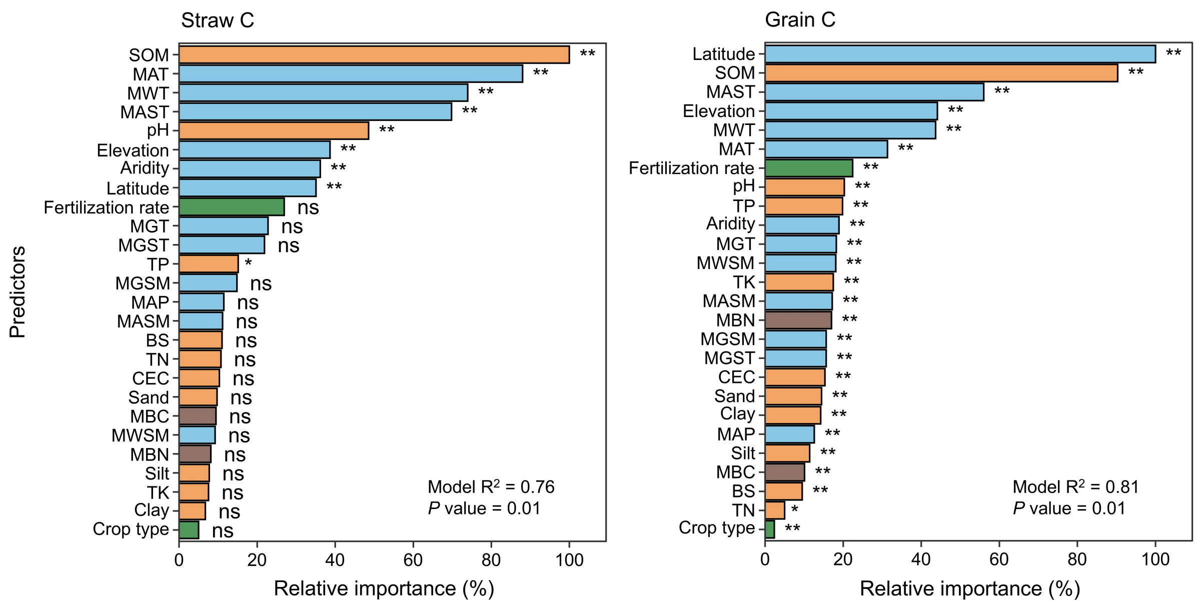
Supplementary Fig. 11 Relative importance of different temperatures on crop biomass C in the collected datasets. a, Effects on straw and grain C content across all crops. **b**, Effects on straw C content for maize, rice and wheat. **c**, Effects on grain C content for maize, rice and wheat. Crop biomass C refers to straw C content and grain C content. This analysis calculates the relative contributions of different temperature types to crop biomass C using hierarchical partitioning.



Supplementary Fig. 12 Decadal changes in total crop C in the *in situ* field experiment. a, Crop biomass. **b**, Previously estimated total crop C. **c**, Actual total crop C. The previously estimated total crop C is determined by multiplying crop biomass with a constant crop biomass C content (approximately 40% for straw and 42% for grain[61-63]). The actual total crop C is determined by multiplying crop biomass with the observed change in crop biomass C, encompassing both straw and grain. Gray lines depict the actual change from the beginning to the end of the decade. The size of the data points and the numerical values indicate the magnitude of change over the decade, computed as the ratio of the difference between initial and final values to the ten-year average.



Supplementary Fig. 13 Residual diagnostic plots for mixed-effects model of MWST on crop biomass C. a, Straw C content**. b**, Grain C content. The Residual vs Fitted plots show residuals around the zero line, indicating model fit. Normal Q-Q plots check residuals' normality, with points along the diagonal indicating normal distribution. Histograms of Standardized Residuals display a bell-shaped curve, confirming normality. These plots evaluate model assumptions, including normality and homoscedasticity of residuals.



Supplementary Fig. 14 Relative importance of predictors to crop biomass C in MWST variable excluded. Some abbreviations are the same as in **Supplementary Fig. 5**, including SOM, MAP, MAT, MAST, MGT, MGST, MWT, MWST, MASM, MGSM, MWSM, MBC, MBN, TN, TP, TK, BS and CEC. The R^2 and P values indicate the coefficient of determination and the probability of the model, respectively. Orange bars indicate soil-related variables; blue bars indicate climate-related variables; brown bars indicate biology-related variables; and green bars indicate other variables. ns: not significant, *: $P < 0.05$; **: $P < 0.01$.

Supplementary Table 1 Comparison among linear mixed effect models with different random effects

Model Formula	AIC		BIC	
	Straw C	Grain C	Straw C	Grain C
R ~ (1 | climate)	23610.57	673014.93	23628.00	673042.11
R ~ (1 | crop)	23731.64	681713.96	23749.06	681741.15
R ~ (0 + T | climate)	23063.62	663129.04	23081.04	663156.23
R ~ (0 + T | crop)	23047.88	665276.57	23065.30	665303.75
R ~ (1 | climate) + (1 | crop)	23594.98	671457.59	23618.21	671493.84
R ~ (0 + T | climate) + (0 + T | crop)	23046.39	662875.47	23069.62	662911.72
R ~ (0 + T | climate) + (1 | crop)	22909.03	660193.50	22932.26	660229.75
R ~ (1 | Climate) + (0 + T | crop)	22755.96	659174.01	22779.19	659210.26
R ~ (T | climate)	22707.79	656926.41	22736.83	656971.72
R ~ (T | crop)	22928.42	663635.09	22957.46	663680.41
R ~ (0 + T | climate) + (T | crop)	22899.21	660124.97	22934.06	660179.35
R ~ (T | climate) + (0 + T | crop)	22687.77	656921.81	22734.23	656976.19
R ~ (T | climate) + (1 | crop)	22708.53	656160.68	22743.38	656215.05
R ~ (1 | climate) + (T | crop)	22745.28	658909.64	22780.13	658964.02
R ~ (T | climate) + (T | crop)	**22686.00**	**656130.32**	**22720.84**	**656202.82**

AIC stands for Akaike Information Criterion, and BIC stands for Bayesian Information Criterion. R represents the crop biomass C (including straw C and grain C contents). T is the fixed effect, while climate and crop are the random effects. The terms (1|site), (0+T|site), and (1+T|site) represent the random effects of the site on the intercept only, on the slope only, and on both the intercept and the slope, respectively. The model with the minimal AIC and BIC is indicated in bold text.

Supplementary Table 2 Effects of MWST on crop biomass C using the mixed-effects model

Component	Slope	SE	95% CI	t value	*P*-value
Straw C	-6.621	1.651	[-9.630, -3.591]	-4.294	1.82e-05***
Grain C	-10.212	2.307	[-14.733, -5.691]	-4.427	9.58e-06***

The results are obtained from the linear mixed-effects model (two-sided). The slope represents the coefficient estimate of the fixed effects of the linear mixed-effects model, while the SE denotes the standard error. The 95% Confidence interval (CI) represents the range within which the true slope is expected to lie. The P value suggests that statistical significance at the 0.05 level. *** $P < 0.001$.

Supplementary Table 3 Effects of winter soil temperature on crop biomass C across different latitudes, fertilization rates, and crop types

Latitudes	Crop type	Fertilization rates	Straw C		Grain C	
			Slope	*P* value	Slope	*P* value
Mid-high	Total	<=50 kg N ha^{-1}	-6.28 [-10.02, -2.55]	0.001 ***	-6.39 [-9.22, -3.55]	1.02e-05 ***
Mid-high	Total	50-150 kg N ha^{-1}	-4.75 [-5.99, -3.52]	9.43e-10 ***	-3.92 [-7.15, -0.68]	0.0018 *
Mid-high	Total	>150 kg N ha^{-1}	-8.76 [-17.39, -0.12]	0.0475 *	-8.17 [-13.50, -2.84]	0.0027 **
Mid-high	Maize	Total	-5.47 [-7.99, -2.95]	2.18e-05 ***	-9.62 [-14.28, -4.96]	5.22e-05 ***
Mid-high	Maize	<=50 kg N ha^{-1}	-5.02 [-5.88, -4.16]	2.2e-16 ***	-8.19 [-12.11, -4.27]	4.23e-05 ***
Mid-high	Maize	50-150 kg N ha^{-1}	-5.84 [-8.10, -3.57]	5.43 ***	-4.96 [-6.09, -3.83]	2.2e-16 ***
Mid-high	Maize	>150 kg N ha^{-1}	-3.39 [-4.02, -2.76]	1.08e-21 ***	-8.62 [-23.16, -5.93]	0.245 ns
Mid-high	Wheat	Total	-4.68 [-6.54, -2.82]	1.16e-60 ***	-10.35 [-23.59, -2.89]	0.1255 ns
Mid-high	Wheat	<=50 kg N ha^{-1}	-4.84 [-8.83, -0.84]	0.0184 *	-4.57 [-35.20, 26.07]	0.770 ns
Mid-high	Wheat	50-150 kg N ha^{-1}	-4.93 [-6.35, -3.52]	1.17e-09 ***	-0.71 [-4.46, 3.05]	0.712 ns
Mid-high	Wheat	>150 kg N ha^{-1}	-5.35 [-7.51, -3.19]	5.22e-06 ***	-7.13 [-9.90, -4.35]	4.89e-07 ***
Mid-high	Rice	Total	-7.44 [-12.69, -2.19]	0.0058 **	-15.77 [-18.26, -13.29]	2.2e-16 ***
Mid-high	Rice	<=50 kg N ha^{-1}	-9.49 [-21.58, 2.61]	0.1281 ns	-19.43 [-27.33, -11.53]	2.68e-06 ***
Mid-high	Rice	50-150 kg N ha^{-1}	-3.65 [-7.29, 0.0003]	0.0518 ns	-15.74 [-17.38, -14.09]	2.2e-16 ***
Mid-high	Rice	>150 kg N ha^{-1}	-31.96 [-61.50, -2.42]	0.0361 *	NA	NA
Low	Total	<=50 kg N ha^{-1}	-4.54 [-5.97, -3.12]	6.68e-09 ***	-6.48 [-13.84, 0.89]	0.0849 ns
Low	Total	50-150 kg N ha^{-1}	-3.74 [-5.20, -2.29]	1.37e-06 ***	NA	NA
Low	Total	>150 kg N ha^{-1}	-11.16 [-15.94, -6.38]	1.13e-05 ***	NA	NA
Low	Maize	Total	-7.53 [-8.68, -6.38]	2.2e-16 **	-10.94 [-12.94, -8.94]	2.2e-16 ***
Low	Maize	<=50 kg N ha^{-1}	-7.97 [-9.63, -6.32]	2.23e-11 ***	-10.94 [12.90, -8.98]	2.2e-16 ***
Low	Maize	50-150 kg N ha^{-1}	-7.41 [-9.57, -5.25]	4.79e-09 ***	NA	NA
Low	Maize	>150 kg N ha^{-1}	-6.66 [-9.68, -3.65]	0.0004 ***	NA	NA
Low	Wheat	Total	NA	NA	-2.05 [-3.59, -0.52]	0.0088 **
Low	Wheat	<=50 kg N ha^{-1}	NA	NA	-2.05 [-3.55, -0.55]	0.0076 **
Low	Wheat	50-150 kg N ha^{-1}	NA	NA	NA	NA
Low	Wheat	>150 kg N ha^{-1}	NA	NA	NA	NA
Low	Rice	Total	-4.47 [-5.88, -3.06]	1.97e-09 ***	NA	NA
Low	Rice	<=50 kg N ha^{-1}	-4.18 [-5.96, -2.41]	1.44e-05 ***	NA	NA
Low	Rice	50-150 kg N ha^{-1}	-3.13 [-5.33, -0.94]	0.0063 **	NA	NA
Low	Rice	>150 kg N ha^{-1}	-13.07 [-16.71, -9.43]	2.06e-10 ***	NA	NA

The results are analyzed using the linear mixed-effects model (two-sided). Latitudes are classified into mid-high latitudes and low latitudes. Crop types are divided into maize, rice and wheat. Fertilization rates are categorized into three levels: low (<=50 kg N ha^{-1}), medium (50-150 kg N ha^{-1}), and high (>150 kg N ha^{-1}). Total represents the combined data for all crops or for all fertilization rates. The values in brackets represent 95% confidence intervals (CI). NA indicates that no data is available for the category. ns: not significant; *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$.

Supplementary Table 4 Comparison of the impacts of winter warming on crop biomass C at mid-high and low latitudes

Component	Model formula	df	AIC	BIC	LogLik	Test	L.Ratio	*P* value
Straw C	Model 1: R ~ MWST + Latitude + (MWST | Climate) + (MWST | Crop)	15	22017.18	22103.99	-10993.59			
	Model 2: R ~ MWST + Latitude + MWST : Latitude + (MWST | Climate) + (MWST | Crop)	16	22202.90	22295.50	-11085.45	1 vs 2	183.72	< 0.001
Grain C	Model 1: R ~ MWST + Latitude + (MWST | Climate) + (MWST | Crop)	16	620008.00	620153.00	-309988.00			
	Model 2: R ~ MWST + Latitude + MWST : Latitude + (MWST | Climate) + (MWST | Crop)	17	620005.00	620159.00	-309986.00	1 vs 2	4.79	0.029

The results are obtained from the mixed-effects model (two-sided). The table presents two linear mixed effect model formulas for each crop component. Model 1 includes mean winter soil temperature (MWST) and latitude (including mid-high and low latitudes) as predictors for crop biomass C, while Model 2 adds the interaction between MWST and latitude to the predictors. Degrees of freedom (df), Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), log-likelihood (LogLik), and the results from likelihood ratio tests (L.Ratio) with corresponding *P* values are reported to evaluate model fit and compare Model 1 against Model 2. The two nested models were compared using a L.Ratio via ANOVA.

Supplementary Table 5 Comparison of decreasing rates of crop biomass C across three *in situ* regions in response to rising winter soil temperature

Component	Climatic zone	Slope	Significance
Straw C	Hailun (47°26′ N)	-8.679	c
	Fengqiu (35°00′ N)	-5.532	b
	Yingtan (28°15′ N)	-3.454	a
Grain C	Hailun (47°26′ N)	-13.607	c
	Fengqiu (35°00′ N)	-8.463	b
	Yingtan (28°15′ N)	-4.459	a

The slope values are obtained from the beta coefficients of a linear regression model through 999 bootstrapping iterations, with each iteration's slope value contributing to the overall mean. The analysis results are subjected to one-way ANOVA, followed by subsequent multiple comparisons using Duncan's New Multiple Range Test across three regions (Hailun, Fegnqiu and Yingtan). Statistical significance is denoted by lowercase letters, differing letters signify significant differences, whereas identical letters indicate no statistically significant difference.

Supplementary Table 6 Comparison of goodness of fit between potential models

Common models	Formula	AIC	BIC
Linear regression model	$y = \beta x + \varepsilon$	673479.10	673506.40
Nonlinear regression model	$y = ax^2 + bx + c + \varepsilon$	670804.00	670840.30
	$y = ae^{bx} + \varepsilon$	683285.20	683312.40
	$y = a \log x + c + \varepsilon$	--	--
	$y = ax^b + \varepsilon$	--	--
Mixed linear effects model	$y = \beta x + \gamma z + \varepsilon$	**668130.90**	**668176.30**
Mixed nonlinear effects model	$y = (a + \gamma_1 z)x^2 + (b + \gamma_2 z)x + c + \varepsilon$	668674.40	668728.90
	$y = ae^{(b+\gamma z)x} + \varepsilon$	673517.50	673562.90
	$y = (a + \gamma z) \log x + c + \varepsilon$	--	--
	$y = (a + \gamma z)x^b + \varepsilon$	--	--

In statistical modeling, the linear regression model is expressed as $y = \beta x + \varepsilon$, where y is the dependent or response variable, x is the predictor or independent variable, β represents the slope coefficient of the influence of x on y, and ε denotes the error term capturing random fluctuations not explained by the model. Nonlinear regression models introduce nonlinearities into the relationship between predictor and response variables. For instance, the equation $y = ae^{bx} + \varepsilon$ captures exponential growth, while $y = a \log x + c + \varepsilon$ reflects a logarithmic relationship, with a, b and c as the respective model parameters. Additionally, the quadratic model $y = ax^2 + bx + c + \varepsilon$ denotes another type of nonlinear regression that shows parabolic relationships. The mixed linear effects model $y = \beta x + \gamma z + \varepsilon$ introduces random effects to the linear framework, where z corresponds to a design matrix for random effects capturing the data's grouping structure and γ represents a vector of parameters for these random effects. Mixed nonlinear effects models take the concept further by allowing the parameters of the nonlinear functions to change within groups or clusters within the data, as dictated by the random effects captured in z. These models include $y = (a + \gamma z)x^b + \varepsilon$, $y = (a + \gamma z) \log x + c + \varepsilon$ and $y = (a + \gamma z)x^b + \varepsilon$. The fit of these models is assessed using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), which also guide the selection of the optimal model.

Supplementary Table 7 Effects of SOM on model residuals of MWST on crop biomass C using the mixed-effects model

Component	Slope	SE	95% CI	t value	*P*-value
Straw C	0.324	0.094	[0.139, 0.509]	3.434	0.0006***
Grain C	1.375	0.047	[1.283, 1.467]	29.283	2.2e-16***

The results are obtained from the linear mixed-effects model (two-sided). The slope represents the coefficient estimate of the fixed effects of the linear mixed-effects model, while the SE denotes the standard error. The 95% Confidence interval (CI) represents the range within which the true slope is expected to lie. The *P* value suggests that statistical significance at the 0.05 level. *** $P < 0.001$.

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