Disease management shapes genotype-by-environment interactions in European winter wheat

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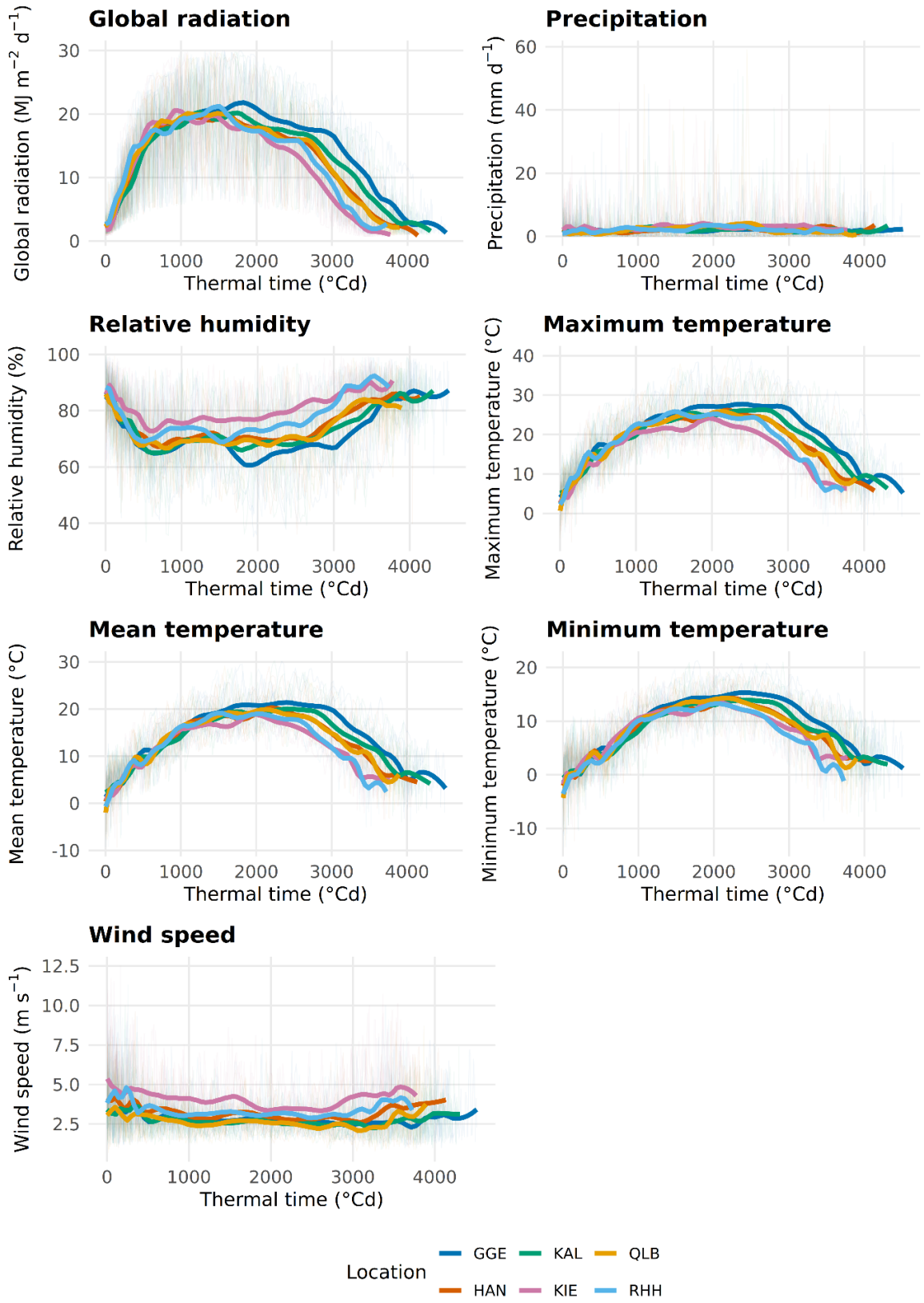
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Supplementary

Supplementary Table S1 | Summary of the 25 trial environments included in the study. For each environment, the location, year, number of genotypes evaluated, and descriptive statistics for grain yield (dt ha^{-1}) are reported. Mean yield, standard deviation (SD), minimum yield, and maximum yield were calculated from plot-level observations.

Location	Year	Environment	Genotypes	Mean yield	SD yield	Minimum yield	Maximum yield
GGE	2015	GGE_2015	219	62.2	12.3	26.7	91.3
GGE	2016	GGE_2016	219	52.1	13.0	8.7	82.3
GGE	2017	GGE_2017	219	67.1	9.5	35.8	92.7
GGE	2019	GGE_2019	51	56.1	11.0	0.0	135.5
HAN	2015	HAN_2015	219	73.7	20.1	4.0	114.5
HAN	2016	HAN_2016	219	63.7	14.1	11.9	98.1
HAN	2017	HAN_2017	219	62.0	12.8	11.5	103.4
HAN	2018	HAN_2018	52	66.0	14.1	14.5	97.5
HAN	2019	HAN_2019	52	59.2	10.0	37.7	89.0
KAL	2015	KAL_2015	219	89.5	24.3	17.7	141.6
KAL	2016	KAL_2016	219	75.8	19.7	11.5	123.9
KAL	2017	KAL_2017	219	92.0	16.6	45.3	125.8
KAL	2018	KAL_2018	221	83.3	9.9	46.2	109.9
KAL	2019	KAL_2019	221	79.1	7.8	33.0	99.3
KIE	2015	KIE_2015	219	74.0	14.3	26.5	113.0
KIE	2016	KIE_2016	219	58.4	12.2	5.0	94.5
KIE	2018	KIE_2018	52	62.7	9.1	40.3	91.1
KIE	2019	KIE_2019	52	69.8	12.6	35.6	108.6
QLB	2015	QLB_2015	219	45.3	9.5	9.1	83.3
QLB	2016	QLB_2016	219	66.3	21.6	6.4	110.3
QLB	2017	QLB_2017	219	54.9	16.2	11.7	98.2
RHH	2015	RHH_2015	219	72.5	18.7	4.0	115.1
RHH	2016	RHH_2016	219	63.1	16.0	8.0	98.1
RHH	2017	RHH_2017	50	70.4	8.3	50.0	90.7
RHH	2019	RHH_2019	52	73.9	10.3	50.0	98.1



Supplementary Figure S1 | Weather conditions across the six experimental locations expressed as a function of thermal time. Daily values of global radiation, precipitation, relative humidity, maximum temperature, mean temperature, minimum temperature, and wind speed are shown for Gross-Gerau (GGE), Hannover (HAN), Klein-Altendorf (KAL), Kiel (KIE), Quedlinburg (QLB), and Rauischholzhausen (RHH). Thin lines represent individual location-year combinations, whereas thick lines indicate location-specific trends estimated using LOESS smoothing. Thermal time (°Cd) was calculated as the cumulative sum of daily mean temperatures above a base temperature of 0 °C.

Supplementary Table S2 | Summary of the IFA4 model fitted to the multi-environment trial dataset. For each environment, the estimated genetic variance (Var_i), specific variance (v_{si}), proportion of variance explained by the factor analytic structure (v_i), and environment loadings (λ_1–λ_4) for the four latent factors are shown.

Env	Var	v_{sj}	v_j	$\hat{\lambda}_1$	$\hat{\lambda}_2$	$\hat{\lambda}_3$	$\hat{\lambda}_4$
GGE_2015	19.50	8.80	91.30	0.20	0.08	0.23	0.08
GGE_2016	21.55	7.20	88.00	0.21	-0.07	-0.03	-0.19
GGE_2017	18.21	6.30	70.40	0.16	0.20	0.01	-0.09
GGE_2019	8.49	52.40	100.00	0.09	0.25	-0.25	0.06
HAN_2015	68.92	0.30	97.70	0.39	-0.23	-0.08	0.00
HAN_2016	22.83	9.20	99.70	0.22	-0.02	-0.08	-0.41
HAN_2017	22.81	8.50	93.40	0.21	0.01	-0.17	-0.42
HAN_2018	12.31	2.10	87.90	0.13	0.24	0.01	-0.18
HAN_2019	8.08	4.10	93.90	0.10	0.23	-0.13	0.08
KAL_2015	50.10	3.10	100.00	0.33	-0.15	0.26	0.30
KAL_2016	43.16	15.80	88.50	0.30	-0.08	-0.08	-0.25
KAL_2017	15.82	16.60	100.00	0.18	0.21	0.13	-0.03
KAL_2018	10.81	19.60	82.30	0.10	0.24	0.22	0.02
KAL_2019	8.50	20.80	64.80	0.08	0.18	0.13	0.11
KIE_2015	23.43	11.90	89.00	0.19	0.27	0.26	0.08
KIE_2016	13.73	9.80	90.20	0.16	0.15	0.03	-0.11
KIE_2018	10.27	39.70	100.00	0.11	0.23	0.30	0.02
KIE_2019	12.64	19.60	100.00	0.13	0.30	0.12	-0.05
QLB_2015	15.61	10.00	86.10	0.16	-0.07	-0.22	0.33
QLB_2016	26.02	13.90	88.60	0.22	0.04	-0.32	0.24
QLB_2017	17.50	15.60	85.70	0.15	0.13	-0.49	-0.06
RHH_2015	75.23	1.40	100.00	0.39	-0.42	0.14	0.19
RHH_2016	18.92	26.50	63.90	0.16	-0.17	-0.05	0.02
RHH_2017	8.38	24.60	68.20	0.02	0.18	-0.26	0.36
RHH_2019	9.71	24.80	78.10	0.07	0.26	-0.16	0.22
Overall	**22.50**	**10.30**	**91.50**	**73.40**	**11.40**	**3.90**	**2.80**

Supplementary Table S3 | Environmental covariates included in IFA4 and their contributions to the four factors. REML estimates are given for additive genetic covariance (Covar) and known factor loadings ($\hat{\lambda}_{s_l}$). The percentage of variance explained by the known covariates ($\bar{v}_s$) and by individual factors (v_{s_l}) is presented in the final row.

Covariate	Covar	v_{s_i}	$\hat{\lambda}_{s_1}$	$\hat{\lambda}_{s_2}$	$\hat{\lambda}_{s_3}$	$\hat{\lambda}_{s_4}$
Tmean	-39.03	0.08	2.45	-2.52	4.71	-0.06
Prec	0.22	0.00	-0.11	0.31	-0.41	0.59
Hum	25.15	0.39	0.59	-0.80	2.18	-0.29
Rad	21.22	2.14	-0.15	0.40	0.30	1.01
Wind	11.02	0.74	-0.18	0.35	0.44	-0.50
Tmin	13.83	0.07	-0.91	1.26	-1.26	-0.65
Tmax	25.35	0.12	-1.39	1.15	-1.83	-0.64
Overall	**8.25**	**10.27**	**3.13**	**3.36**	**2.26**	**1.52**

Supplementary Table S4 | Prediction accuracies obtained from leave-one-environment-out cross-validation of the IFA4 model. Each of the 25 environments represents a specific location-year combination. For each environment, prediction accuracy was quantified by the Pearson correlation (r_j) of observed genotype mean yields with the corresponding predicted additive GE effects.

Location	Correlation
GGE_2015	0.90
GGE_2016	0.88
GGE_2017	0.88
GGE_2018	0.49
GGE_2019	0.71
HAN_2015	0.84
HAN_2016	0.92
HAN_2017	0.88
HAN_2018	0.77
HAN_2019	0.82
KAL_2015	0.09
KAL_2016	0.93
KAL_2017	0.91
KAL_2018	0.62
KAL_2019	0.73
KAL_2020	0.63
KIE_2015	0.87
KIE_2016	0.79
KIE_2017	0.84
KIE_2018	0.41
KIE_2019	0.87
QLB_2015	0.69
QLB_2016	0.64
QLB_2017	0.74
RHH_2015	0.60
RHH_2016	0.73
RHH_2017	0.60
RHH_2019	0.67
Overall	**0.74**