Supplementary Information

Substantial increase in yield predicted by wheat ideotypes for Europe under future climate

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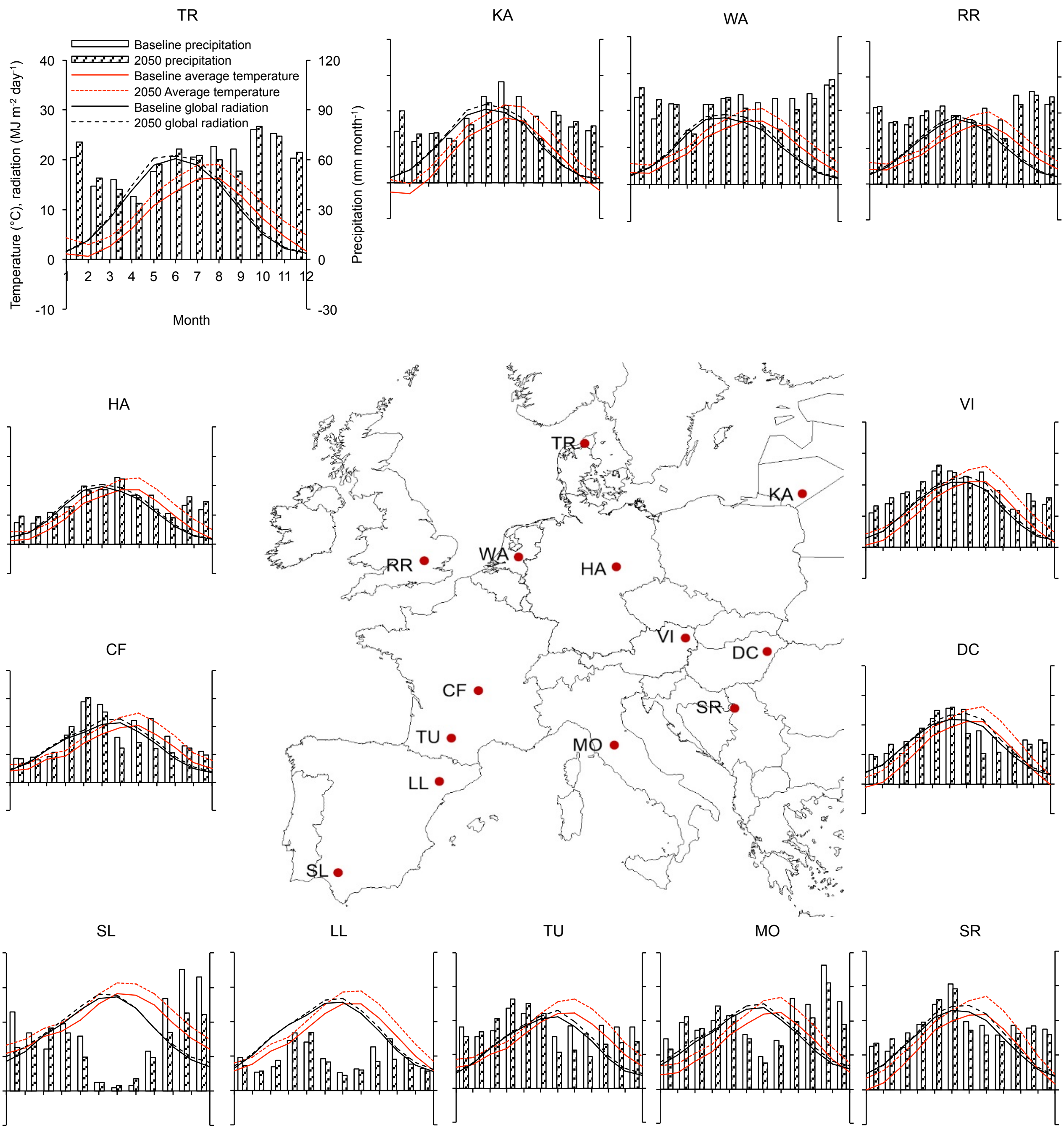

Fig. S1. Locations of 13 selected study sites, representing major wheat growing regions across Europe. The current (baseline) and 2050-climate (*HadGEM2*, *RCP8.5*) viz. average air temperature, mean monthly precipitation and mean daily global solar radiation. TR: Tylstrup, Denmark; KA: Kaunas, Lithuania; WA: Wageningen, Netherlands; RR: Rothamsted, UK; HA: Halle, Germany; VI: Vienna, Austria; DC: Debrecen, Hungary; CF: Clermont-Ferrand, France; SR: Sremska, Serbia; TU: Toulouse, France; MO: Montagnano, Italy; LL: Lleida, Spain; SL: Seville, Spain.

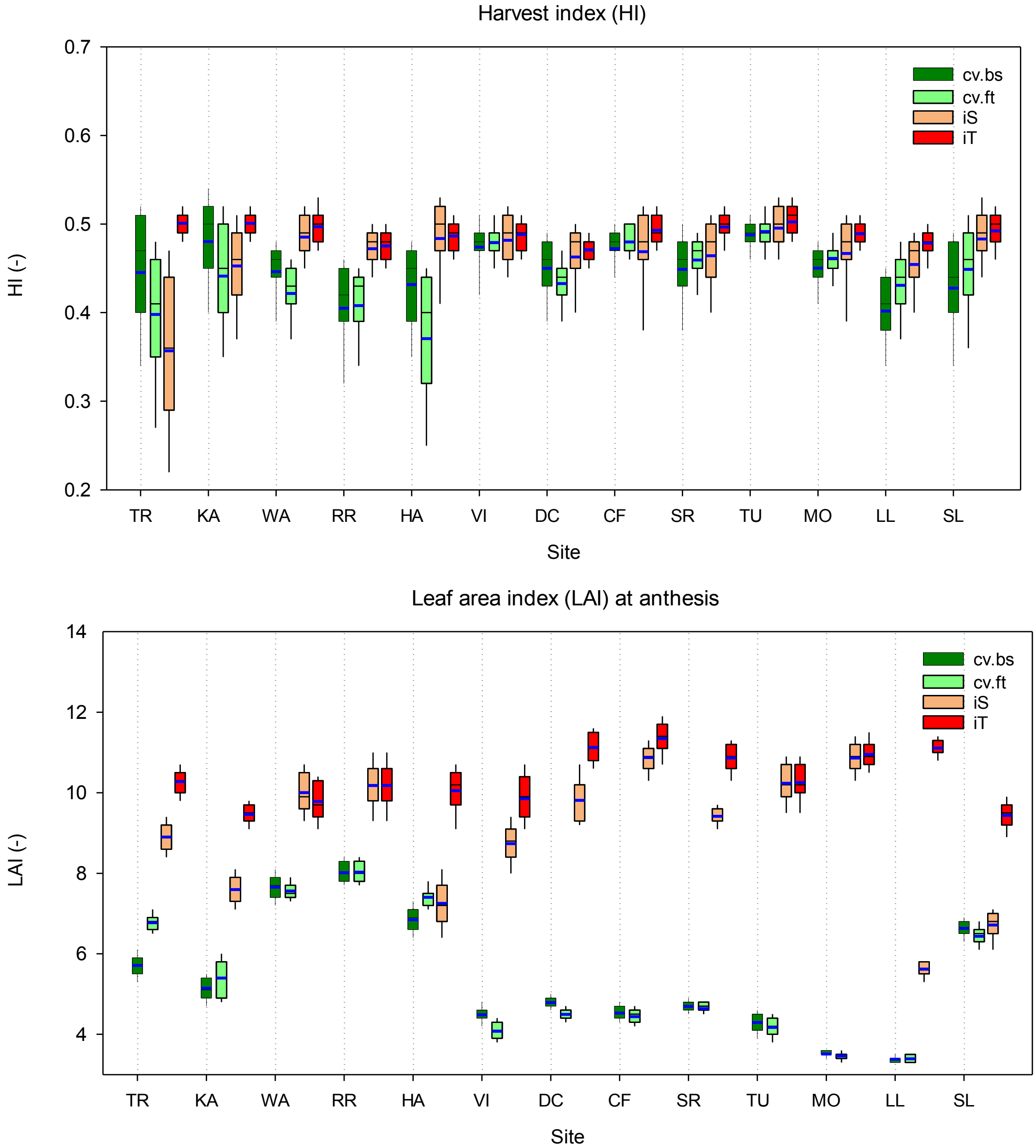

Fig. S2. Box plot showing 5th-, 25th-, 50th-, 75th- and 95th- percentiles and mean value (blue bar) of simulated HI, and leaf area index (LAI) at flowering of local wheat cultivar across Europe under baseline- (cv.bs) and 2050-climate (cv.ft), and wheat ideotypes designed as heat and drought sensitive (iS) or tolerant (iT) around flowering to achieve high yield potential under 2050-climate.

Table S1. Site characteristics of the selected wheat growing regions across Europe

No.	ID	Site	Country	Latitude (º)	Longitude (º)	Average air temperature (ºC)†	Precipitation (mm yr^{-1}) †	Radiation (MJ m^{-2} day^{-1}) †	Local wheat cultivar, or baseline cultivar (cv.bs)††	Sowing date of local wheat cultivar
1	TR	Tylstrup	Denmark	57.20	9.90	7.9	717	9.9	Avalon	18-Oct
2	KA	Kaunas	Lithuania	54.88	23.83	7.1	644	10.0	Avalon	25-Oct
3	WA	Wageningen	Netherlands	51.97	5.67	9.7	801	9.7	Claire	20-Oct
4	RR	Rothamsted	UK	51.80	-0.35	9.7	735	9.7	Mercia	10-Oct
5	HA	Halle	Germany	51.51	11.95	9.6	507	10.0	Claire	20-Oct
6	VI	Vienna	Austria	48.23	16.35	10.8	651	11.4	Thesee	20-Oct
7	DC	Debrecen	Hungary	47.60	21.60	10.4	591	12.7	Thesee	18-Oct
8	CF	Clermont-Ferrand	France	45.80	3.10	11.6	606	12.2	Thesee	15-Nov
9	SR	Sremska	Serbia	45.00	19.51	11.5	654	13.4	Thesee	15-Nov
10	TU	Toulouse	France	43.62	1.38	13.8	666	12.4	Thesee	20-Nov
11	MO	Montagnano	Italy	43.30	11.80	12.8	738	14.7	Creso	25-Nov
12	LL	Lleida	Spain	41.63	0.60	15.1	344	15.6	Creso	25-Nov
13	SL	Seville	Spain	37.42	-5.88	19.2	595	17.0	Cartaya	30-Dec

†Current or baseline climate. Mean monthly variation can be found in Figure S1.
††Detailed cultivar descriptions can be found in Table S2.

Table S2. Description of the Sirius cultivar parameters of the local wheat cultivars at study sites across major wheat growing regions in Europe.

No.	Parameters	Symbol	Unit	Value†					
				Avalon	Cartaya	Claire	Creso	Mercia	Thesee
1	Phyllochron	P_h	ºC day	90.0	105.0	110.0	90.0	107.0	94.0
2	Day length response	P_p	Leaf h^{-1}day length	0.65	0.20	0.50	0.60	0.53	0.4
3	Thermal time from sowing to emergence	TT_{SOWEM}	ºC day	150.0	150.0	150.0	160.0	150.0	175.0
4	Thermal time from anthesis to beginning of grain fill	TT_{ANBGF}	ºC day	50.0	100.0	100.0	100.0	160.0	100.0
5	Thermal time from beginning of grain fill to end of grain fill	TT_{BGFEGF}	ºC day	650.0	550.0	650.0	650.0	650.0	650.0
6	Thermal time from end of grain fill to harvest maturity	TT_{EGFMAT}	ºC day	200.0	200.0	200.0	200.0	200.0	200.0
7	Maximum area of flag leaf	A_{Max}	m^2 leaf m^{-2} soil	0.0065	0.0065	0.007	0.003	0.0075	0.004
8	Minimum possible leaf number	L_{Min}	-	8.55	8.50	8.0	8.50	8.0	8.0
9	Absolute maximum leaf number	L_{Max}	-	24.0	24.0	18.0	24.0	24.0	18.0
10	Response of vernalisation rate to temperature	*VAI*	Day^{-1}°C	0.0012	0	0.0012	0.0015	0.0012	0.0012
11	Vernalisation rate at 0°C	*VBEE*	Day^{-1}	0.015	0	0.012	0.012	0.011	0.012
12	Heat stress grain number reduction threshold temperature	*HSGNT*	ºC	30.0	30.0	30.0	30.0	30.0	30.0
13	Heat stress grain number reduction rate	*HSGNR*	ºC^{-1}	0.04	0.04	0.04	0.04	0.04	0.04
14	Drought stress grain number reduction stress threshold	*DSGNT*	-	0.90	0.90	0.90	0.90	0.90	0.90
15	Drought stress grain number reduction stress saturation	*DSGNS*	-	0.30	0.30	0.30	0.30	0.30	0.30
16	Maximum drought stress grain number reduction	*DSGNRMax*	-	0.20	0.20	0.20	0.20	0.20	0.20
17	Maximum potential grain weight	*MaxGW*	g	0.045	0.045	0.045	0.045	0.045	0.045
18	Grain number per g DM ear	*GNEar*	g^{-1}	100	100	100	100	100	100
19	Stay green	S_G	-	0.50	0.50	0.50	0.50	0.50	0.50
20	Rate coefficient of root water uptake from the root bottom	R_u	-	0.03	0.03	0.03	0.03	0.03	0.03
21	Maximum leaf senescence acceleration factor due to water stress	W_{ss}	-	1.27	1.27	1.27	1.27	1.27	1.27

†References

Semenov MA, Shewry PR (2011) Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. Sci Rep 1, 66

He J, Le Gouis J, Stratonovitch P, Allard V, Gaju O, Heumez E, Orford S, Griffiths S, Snape JW, Foulkes MJ, Semenov M A, Martre P (2012). Simulation of environmental and genotypic variations of final leaf number and anthesis date for wheat. Eur J Agron 42: 22-33

Table S3. Sirius parameters of sensitive to heat and drought stress around flowering ideotype (iS) and tolerant to heat and drought stress around flowering ideotype (iT).

Parameters	Symbol	Unit	Value†	
			iS ideotype	iT ideotype
Heat stress grain number reduction threshold temperature	*HSGNT*	ºC	30.0	60.0
Heat stress grain number reduction rate	*HSGNR*	$ºC^{-1}$	0.04	0.00
Drought stress grain number reduction stress threshold	*DSGNT*	-	0.90	1.00
Drought stress grain number reduction stress saturation	*DSGNS*	-	0.30	1.00
Maximum drought stress grain number reduction	*DSGNRMax*	-	0.20	1.00

†**References**

Barber HM, Lukac M, Simmonds J, Semenov MA, Gooding MJ (2017) Temporally and genetically discrete periods of wheat sensitivity to high temperature. Front Plant Sci 8:51

Senapati, N, Stratonovitch P, Paul MJ, Semenov MA 2019 Drought tolerance during reproductive development is important for increasing wheat yield potential under climate change in Europe. J Exp Bot 70: 2549–2560

Stratonovitch P, Semenov MA (2015) Heat tolerance around flowering in wheat identified as a key trait for increased yield potential in Europe under climate change. J Exp Bot 66: 3599-3609

Table S4. Seven Sirius cultivar parameters used for optimising wheat ideotypes under the 2050-climate with cultivar parameter ranges based on wheat cultivars calibrated in diverse climates and observed genetic variation in those parameters reported in the literature for wheat.

Parameters	Symbol	Unit	Range used in model optimization*	Genetic variation	References of observed genetic variation
Canopy structure					
Maximum area of flag leaf	A_{Max}	m^2 leaf m^{-2} soil	0.005–0.01	≤40%	Fischer et al. (1998), Shearman et al. (2005)
Stay green	S_G	-	0.00–1.50		
Canopy Phenology					
Phyllochron	P_h	ºC day	80.0–140.0	≤20%	Ishag et al. (1998), Mosaad et al. (1995)
Day length response	P_p	Leaf h^{-1}day length	0.05–0.90	9.74–107.40†	Kosner & Zurkova (1996)
Duration of grain filling	G_f	ºC day	500–900	≤40%	Akkaya et al. (2006), Charmet et al. (2005), Robert et al. (2001)
Root water uptake					
Rate coefficient of root water uptake from the root bottom	R_u	-	0.01–0.07	Large variation	Asseng et al. (1998), Manschadi et al. (2006)
Drought tolerance					
Maximum leaf senescence acceleration factor due to water stress	W_{ss}	-	1.0–1.7		

*Cultivar parameter ranges used in optimization are based on previously calibrated modern wheat cultivars for Sirius in diverse climates: Jamieson et al. (1998), Ewert et al. (2002), Lawless et al. (2008), Semenov et al. (2009), Asseng et al. (2015), Martre et al. (2015) (see also references in Table S2 and Table S3).

†Varietal difference in number of days till heading under long- and short-day conditions found between 9.74 and 107.40 in a photoperiodic response experiment (Kosner & Zurkova 1996)

References

Akkaya A, Dokuyucu T, Kara R, Akçura M (2006) Harmonization ratio of post- to pre-anthesis durations by thermal times for durum wheat cultivars in a Mediterranean environment. Eur J Agron 24: 404-408

Asseng S, Ewert F, Martre P, Roetter RP, Lobell DB, Cammarano D, Kimball BA, Ottman MJ, Wall GW, White JW, Reynolds MP, Alderman PD, Prasad PVV, Aggarwal PK, Anothai J, Basso B, Biernath C, Challinor AJ, De Sanctis G, Doltra J, Fereres E, Garcia-Vile M, Gayler S, Hoogenboom G, Hunt LA, Izaurralde RC, Jabloun M, Jones CD, Kersebaum KC, Koehler AK, Mueller C, Kumar SN, Nendel C, O'Leary G, Olesen JE, Palosuo T, Priesack E, Rezaei EE, Ruane AC, Semenov MA, Shcherbak I, Stoeckle C, Stratonovitch P, Streck T, Supit I, Tao F, Thorburn PJ, Waha K, Wang E, Wallach D, Wolf I, Zhao Z, Zhu Y (2015) Rising temperatures reduce global wheat production. Nat Clim Change 5:143-147

Asseng S, Ritchie J T, Smucker AJM, Robertson MJ (1998) Root growth and water uptake during water deficit and recovering in wheat. Plant Soil 201: 265-273

Charmet G, Robert N, Branlard G, Linossier L, Martre P, Triboï E (2005) Genetic analysis of dry matter and nitrogen accumulation and protein composition in wheat kernels. Theor Appl Genet 111: 540-550

Ewert F, Rodriguez D, Jamieson P, Semenov MA, Mitchell RAC, Goudriaan J, Porter JR, Kimball BA, Pinter PJ, Manderscheid R, Weigel HJ, Fangmeier A, Fereres E, Villalobos F (2002) Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. Agric Ecosyst Environ 93:249-266

Fischer RA, Rees D, Sayre KD, Lu ZM, Condon AG, Saavedra AL (1998) Wheat yield progress associated with higher stomatal conductance and photosynthetic rate, and cooler canopies. Crop Sci 38: 1467-1475

Ishag HM, Mohamed BA, Ishag KHM (1998) Leaf development of spring wheat cultivars in an irrigated heat-stressed environment. Field Crop Res 58: 167-175

Jamieson PD, Brooking IR, Semenov MA, Porter JR (1998) Making sense of wheat development: a critique of methodology. Field Crops Res 55:117-127

Kosner J, Zurkova D (1996) Photoperiodic response and its relation to earliness in wheat. Euphytica 89: 59-64

Lawless C, Semenov MA, Jamieson PD (2008) Quantifying the effect of uncertainty in soil moisture characteristics on plant growth using a crop simulation model. Field Crop Res 106:138-147

Manschadi AM, Christopher J, deVoil P, Hammer GL (2006) The role of root architectural traits in adaptation of wheat to water-limited environments. Funct Plant Biol 33: 823-837

Martre P, He J, Le Gouis J, Semenov MA (2015) *In silico* system analysis of physiological traits determining grain yield and protein concentration for wheat as influenced by climate and crop management. J Exp Bot 66:3581-3598

Mosaad MG, Ortizferrara G, Mahalakshmi V, Fischer RA (1995) Phyllochron response to vernalization and photoperiod in spring wheat. Crop Sci 35: 168-171

Robert N, Berard P, Hennequet C (2001) Dry matter and nitrogen accumulation in wheat kernel. Genetic variation in rate and duration of grain filling [Triticum aestivum L.]. J Genet Breed 55: 297-305

Semenov MA, Martre P, Jamieson PD (2009) Quantifying effects of simple wheat traits on yield in water-limited environments using a modelling approach. Agric Forest Meteorol 149:1095–1104

Shearman VJ, Sylvester-Bradley R, Scott RK, Foulkes MJ (2005) Physiological processes associated with wheat yield progress in the UK. Crop Sci 45: 175-185

Table S5. Local wheat cultivar parameters (cv.bs), and optimised cultivar parameter values of wheat ideotypes viz. sensitive to heat and drought stress around flowering (iS) and tolerant to heat and drought stress around flowering (iT) under 2050-climate (based on *HadGEM2* and *RCP8.5*) at study sites across major wheat growing regions in Europe

Site	Cultivar/ ideotype	Cultivar parameter/trait						
		A (m^2 leaf m^{-2} soil)	S_G (-)	P_h (ºC day)	P_p (Leaf h^{-1}day length)	G_f (ºC day)	R_u (%)	W_{ss} (-)
		Local wheat cultivar/baseline cultivar (cv.bs)						
Tylstrup, Denmark (TR)	Avalon	0.0065	0.500	90.0	0.650	650.0	0.030	1.270
Kaunas, Lithuania (KA)	Avalon	0.0065	0.500	90.0	0.650	650.0	0.030	1.270
Wageningen, Netherlands (WA)	Claire	0.0070	0.500	110.0	0.500	650.0	0.030	1.270
Rothamsted, UK (RR)	Mercia	0.0075	0.500	107.0	0.530	650.0	0.030	1.270
Halle Germany (HA)	Claire	0.0070	0.500	110.0	0.500	650.0	0.030	1.270
Vienna, Austria (VI)	Thesee	0.0040	0.500	94.0	0.400	650.0	0.030	1.270
Debrecen, Hungary (DC)	Thesee	0.0040	0.500	94.0	0.400	650.0	0.030	1.270
Clermont-Ferrand, France (CF)	Thesee	0.0040	0.500	94.0	0.400	650.0	0.030	1.270
Sremska, Serbia (SR)	Thesee	0.0040	0.500	94.0	0.400	650.0	0.030	1.270
Toulouse, France (TU)	Thesee	0.0040	0.500	94.0	0.400	650.0	0.030	1.270
Montagnano, Italy (MO)	Creso	0.0030	0.500	90.0	0.600	650.0	0.030	1.270
Lleida, Spain (LL)	Creso	0.0030	0.500	90.0	0.600	650.0	0.030	1.270
Seville, Spain (SL)	Cartaya	0.0065	0.500	105.0	0.200	550.0	0.030	1.270
Wheat ideotype optimised under 2050-climate as sensitive to heat and drought stresses around flowering (iS)								
Tylstrup, Denmark (TR)	Ideotype	0.0050	0.350	110.9	0.050	877.4	0.070	1.329
Kaunas, Lithuania (KA)	Ideotype	0.0074	0.830	126.2	0.373	847.4	0.070	1.045
Wageningen, Netherlands (WA)	Ideotype	0.0093	0.970	138.9	0.050	898.8	0.070	1.000
Rothamsted, UK (RR)	Ideotype	0.0100	0.740	139.8	0.074	900.0	0.063	1.012
Halle Germany (HA)	Ideotype	0.0077	1.330	112.9	0.050	899.6	0.070	1.001
Vienna, Austria (VI)	Ideotype	0.0084	1.350	140.0	0.055	900.0	0.070	1.270
Debrecen, Hungary (DC)	Ideotype	0.0100	0.880	109.8	0.050	870.6	0.070	1.045
Clermont-Ferrand, France (CF)	Ideotype	0.0094	0.430	139.8	0.050	900.0	0.070	1.087
Sremska, Serbia (SR)	Ideotype	0.0079	1.040	133.1	0.050	898.8	0.070	1.000
Toulouse, France (TU)	Ideotype	0.0100	1.400	139.5	0.050	900.0	0.070	1.301
Montagnano, Italy (MO)	Ideotype	0.0100	1.010	119.0	0.058	899.5	0.065	1.006
Lleida, Spain (LL)	Ideotype	0.0050	0.520	80.4	0.518	723.7	0.070	1.000
Seville, Spain (SL)	Ideotype	0.0064	1.260	104.4	0.117	900.0	0.070	1.023
Wheat ideotype optimised under 2050-climate as tolerant to heat and drought stresses around flowering (iT)								
Tylstrup, Denmark (TR)	Ideotype	0.0100	0.990	140.0	0.050	900.0	0.039	1.000
Kaunas, Lithuania (KA)	Ideotype	0.0099	1.310	140.0	0.055	900.0	0.029	1.000
Wageningen, Netherlands (WA)	Ideotype	0.0090	0.710	138.8	0.050	900.0	0.049	1.000
Rothamsted, UK (RR)	Ideotype	0.0100	0.870	139.8	0.074	899.3	0.061	1.004
Halle Germany (HA)	Ideotype	0.0096	1.270	139.5	0.050	900.0	0.027	1.129
Vienna, Austria (VI)	Ideotype	0.0100	0.800	140.0	0.112	900.0	0.056	1.000
Debrecen, Hungary (DC)	Ideotype	0.0100	1.030	140.0	0.050	900.0	0.035	1.000
Clermont-Ferrand, France (CF)	Ideotype	0.0100	0.760	140.0	0.056	900.0	0.062	1.000
Sremska, Serbia (SR)	Ideotype	0.0100	1.290	136.6	0.050	900.0	0.047	1.245
Toulouse, France (TU)	Ideotype	0.0100	0.970	139.5	0.050	900.0	0.051	1.000
Montagnano, Italy (MO)	Ideotype	0.0098	1.130	122.3	0.050	898.8	0.015	1.006
Lleida, Spain (LL)	Ideotype	0.0100	1.190	129.3	0.050	900.0	0.021	1.000
Seville, Spain (SL)	Ideotype	0.0100	1.500	128.3	0.050	900.0	0.039	1.000

A : Maximum area of flag leaf
S_G : Stay green
P_h : Phyllochron
P_p : Day length response
G_f : Duration of grain filling
R_u : Rate coefficient of root water uptake from the root bottom
W_{ss} : Maximum leaf senescence acceleration factor due to water stress