Article:

Wang, E, Martre, P, Zhao, Z et al. (53 more authors) (2017) The uncertainty of crop yield projections is reduced by improved temperature response functions. Nature Plants, 3. 17102. ISSN 2055-026X

https://doi.org/10.1038/nplants.2017.102

Supplementary Information

Supplementary Table 1 | The 29 wheat crop models used in the AgMIP Wheat project and analyzed in this study.

Model (version)	Reference	Documentation
APSIM-Wheat-E	[1-4]	http://www.apsim.info/Wiki/
APSIM-Nwheat (V.1.55)	[2,5,6]	http://www.apsim.info
APSIM-Wheat (V.7.3)	[2]	http://www.apsim.info/Wiki/
AQUACROP (V.4.0)	[7]	http://www.fao.org/nr/water/aquacrop.html
CropSyst (V.3.04.08)	[8]	http://www.bsyse.wsu.edu/CS_Suite/CropSyst/index.html
DAISY (V.5.24)	[9,10]	http://daisy.ku.dk/
DSSAT-CERES (V.4.0.1.0)	[11-13]	http://www.icasa.net/dssat/
DSSAT-CROPSIM (V4.5.1.013)	[12,14]	http://www.icasa.net/dssat/
EPIC (V1102)	[15-17]	http://epicapex.brc.tamus.edu/
Expert-N (V3.0.10) - CERES (V2.0)	[18-21]	http://www.helmholtz-muenchen.de/en/iboe/expertn/
Expert-N (V3.0.10) – GECROS (V1.0)	[20,21]	http://www.helmholtz-muenchen.de/en/iboe/expertn/
Expert-N (V3.0.10) – SPASS (2.0)	[18,20-23]	http://www.helmholtz-muenchen.de/en/iboe/expertn/
Expert-N (V3.0.10) - SUCROS (V2)	[18,20,21,24]	http://www.helmholtz-muenchen.de/en/iboe/expertn/
FASSET (V.2.0)	[25,26]	http://www.fasset.dk
GLAM (V.2)	[27,28]	http://www.see.leeds.ac.uk/research/icas/climate-impacts-group/research/glam/
HERMES (V.4.26)	[29,30]	http://www.zalf.de/en/forschung/institute/lsa/forschung/oekomod/hermes
INFOCROP (V.1)	[31]	http://www.iari.res.in
LINTUL (V.1)	[32,33]	http://models.pps.wur.nl/models
LPJmL (V3.2)	[34-39]	http://www.pik-potsdam.de/research/projects/lpjweb
MCWLA-Wheat (V.2.0)	[40-43]	Request from taofl@igsnrr.ac.cn
MONICA (V.1.0)	[44]	http://monica.agrosystem-models.com
OLEARY (V.7)	[45-48]	Request from gjoleary@yahoo.com
SALUS (V.1.0)	[49,50]	http://www.salusmodel.net
SIMPLACE<LINTUL2-CC-HEAT> (V.1)	[51]	Request from frank.ewert@uni-bonn.de
SIRIUS (V2010)	[52-55]	http://www.rothamsted.ac.uk/mas-models/sirius.php
SiriusQuality (V.2.0)	[56-58]	http://www1.clermont.inra.fr/siriusquality/
STICS (V.1.1)	[59,60]	http://www6.paca.inra.fr/stics_eng/
WHEATGROW	[61-67]	Request from yanzhu@njau.edu.cn
WOFOST (V.7.1)	[68]	http://www.wofost.wur.nl

Supplementary Table 2 | Summary of the temperature responses of physiological processes simulated in the 29 wheat models analysed in this study.

Temperature response functions for each process and model are shown in Supplementary_Data_Set_D1.xlsx.

Temperature responses of physiological processes simulated in the 29 wheat models used in this study.

	Development				Biomass accumulation			Canopy expansion/senescence			Heat stress response	
Model	**Emergence (Germination)[a]**	**Pre-anthesis phenology[a]**	**Post-anthesis phenology[a]**	**Vernalization[b]**	**Photosynthesis / RUE[c]**	**Respiration[d]**	**Grain growth / harvest index[e]**	**Leaf growth[f]**	**Leaf senescence[g]**	**Root growth[h]**	**Grain number / harvest index[i]**	**Heat accelerated leaf senescence[j]**
APSIM-E	TT~Ta(0,26,-,35)	TT~Ta(0,26,-,35)	TT~Ta(0,26,-,35)	V~ Tc,Tx,Tm(0,2,-,15)	RUE~Ta(0,20,-,35)	-	GR-Ta(0,26,-,∞)	TT~Ta(0,26,-,35)	TT~Ta(0,26,-,∞)	Rr~Ta(0,20,-,35)	-	-
APSIM-Nwheat	TT-Ta(0,28,32,45)	TT-Ta(0,28,32,45)	TT-Ta(0,28,32,45)	V~ Tc,Tx,Tm(0,2,-,15)	RUE-Ta(0,10,22,35)	-	GR-Ta(0,26,-,∞)	TT~Ta(0,11,24,35)	TT-Ta(0,28,32,45)	Rr-Ta(0,28,32,45)	-	Tx>34
APSIM-wheat	TT-Ta(0,26,-,34)	TT-Ta(0,26,-,34)	TT-Ta(0,26,-,34)	V~ Tc,Tx,Tm(0,2,-,15)	RUE-Ta(0,10,20,35)	-	GR-Ta(0,26,-,∞)	TT-Ta(0,26,-,34)	TT-Ta(0,28,32,45)	Rr-Ta(0,26,-,34)	-	Tx>34
AquaCrop	TT-Ta(0,26,-,∞)	TT-Ta(0,26,-,∞)	TT-Ta(0,26,-,∞)	-	TE~TT(0,14,-,∞)	-	-	TT-Ta(0,26,-,∞)	TT-Ta(0,26,-,∞)	Rr~TT-Ta(0,26,-,∞)	HI-Ta(0,5,35,40)	-
CropSyst	TT-Ta(0,∞-,-,-)	TT-Ta(0,-,-,33)	TT-Ta(0,-,-,33)	-	RUE-Ta(0,12,17,40)	-	-	-	-	-	HI<31	Th<0
DAISY	TT-Ta(0,25,-45)	TT-Ta(0,25,-45)	TT-Ta(3,25,35,45)	-	Ps~Ta(5,20,25,45)	Mr~Ta	-	-	-	-	-	-
DSSAT-CERES	TT-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	TT-Ta(0,30,50,60)	V-Ta(-5,0,7,15)	RUE-Ta(0,5,25,35)	-	GR-Ta(0,16,35,45)	TT-Ta(0,10,20,35)	TT-Ta(0,10,20,35)	TT-Ta(0,26,50,60)	-	-
DSSAT-CROPSIM	TT-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	V-Ta(-5,0,7,15)	RUE-Ta(0,5,25,35)	-	GR-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	TT-Ta(0,26,50,60)	-	-
EPIC-wheat	TT-Ta(5,20,-,∞)	TT-Ta(5,20,-,∞)	TT-Ta(5,20,-,∞)	-	RUE-Ta(0,20,-,50)	-	-	-	-	-	-	-
Expert-N-CERES	TT-Tc(2,26,34)	TT-Tc(2,26,34)	TT-Tc(2,26,34)	V-Tc(0,2,6,13)	RUE~Ta(-2,18,-,38)	-	GR~Ta(0,16,-,∞)	La~Ta(0,17,-,34)	TT-Ta(5,29,-,40)	-	-	-
Expert-N-GECROS	TT-Thc(0,25,-,37)	TT-Thc(0,25,-,37)	TT-Thc(0,25,-,37)	V~Ta(-1,2,-,15)	Ps~Ta(0,10,25,35)	Mr~Q_{10}^{Ta}	-	-	-	-	-	-
Expert-N-SPASS	TT~Ta(0,24,-,35)	TT~Ta(0,24,-,35)	TT~Ta(0,24,-,35)	V~Ta(-1,2,-,15)	Ps~Ta(0,22,-,35)	Pr~Td, Mr~Ta	GR~Ta(0,24,-,35)	La~Ta(0,22,-,35)	-	Rr~Ta(0,25,-,40)	-	Ta>30
Expert-N-SUCROS	TT-Ta(0,∞,–,–)	TT-Ta(0,∞,–,–)	TT-Ta(0,∞,–,–)	-	Ps-Ta(0,10,25,35)	Mr~Q_{10}^{Ta}	GR~Ta(0,16,-,∞)	La-Ta(0,∞,–,–)	-	Rr-Ta(0,31,-,∞)	-	-
FASSET	TT-Ta(0,∞,–,–)	TT-Ta(4,∞,–,–)	TT-Ta(6,∞,–,–)	-	RUE-Ta(4,10,-,∞)	-	GR-Ta(4,10,-,∞)	TT-Ta(0,10,-,∞)	TT-Ta(6,∞,–,–)	Rr-Ts(4,∞,–,–)	-	-
GLAM-Wheat	TT-Ta(0,23,-,35)	TT-Ta(1,23,-,35)	TT-Ta(1,22,-,35)	-	TE-Ta(-∞,28,-,36)	-	HI-Tx(-∞,28,-,36)	-	?	-	-	Tx>34
HERMES	TT-Ta(0,∞,–,–)	TT-Ta(1,∞,–,–)	TT-Ta(9,∞,-,-)	V~Ta(-4,0,3,18)	Ps~Ta(4,15,25,35)	Mr~Q_{10}^{Ta}	-	-	-	Rr~TT-Ta(-1,∞,–,–)	-	-
InfoCrop	TT~Th(3.6,25,-,40)	TT~Th(4.5,25,-, 40)	TT~Th(7.5,25, -,40)	-	RUE~Ta(0,10,25,50)	-	GR~Ta (0,16,-,∞)	TT-Ta(4.5, 25, -,40)	?	Rr-Th(4.5,25,-, 40)	PLN~(-∞,2,32,∞)	Ta>20
LINTUL-4	TT-Ta(0,30,–,∞)	TT-Ta(0,45,–,∞)	TT-Ta(0,45,–,∞)	-	RUE~Td(0,15,30,35)	-	-	-	TT-Ta(-10,∞,–,–)	-	-	-
LPJmL	-	TT-Ta(0,∞,–,–)	TT-Ta(0,∞,–,–)	V-Ta(-4,3,10,17)	Ps~Ta(0,12,17,40)	Mr~Q_{10}^{Ta}	-	-	-	-	-	-
MCWLA-Wheat	TT~Ta(0,24,-,35)	TT~Ta(0,24,-,35)	TT~Ta(0,29,-,40)	V~Ta(-1.5,5,-,15.5)	Ps~Ta(0,10,30,40)	Mr~Q_{10}^{Ta}	GR~Ta(0,10,-,40)	TT~Ta(0,24,-,35)	TT~Ta(0,29,-,40)	Rr~Ta(0,24,-,35)	-	Tx>33
MONICA	TT-Ta(0,∞,–,–)	TT-Ta(1, ∞,–,–)	TT-Ta(9,∞,–,–)	V~Ta(-4,0,3,18)	Ps~Ta(-4,21,-,40)	Gr~(Tx,Tn), Mr~(Tx,Tn)	-	-	TT-Ta(9,∞,-,-)	Rr-Ta(0,20,-,∞)	-	-
OLeary	TT-Ta(2,∞,–,–)	TT-Ta(2,∞,–,–)	TT-Ta(8,∞,–,–)	-	RUE-Ta(0,10,25,35)	-	GR~Q_{10}^{T}	-	-	Rr~Ta(-1,20,-,37)	-	-
SALUS	TT-Ta(0,26,-,∞)	TT-Ta(0,26,-,∞)	TT-Ta(0,26,-,∞)	V-Ta(-∞,7,-,18)	-	-	-	-	TT-Ta(0,8,26,35)	TT-Ta(0,8,26,35)	-	-
SIMPLACE<LINTUL2-CC-HEAT>	-	TT-Ta(1,32,-,40)	TT-Ta(9,32,-,40)	V~Ta(-4,4,10,17)	RUE-Ta(-4,7,17,32)	-	-	-	TT-Ta(-∞,10,30,∞)	-	-	Tx>34
Sirius	TT-Ts(0,∞,-,-)	TT-Ts,Thc(0,∞,-,-)	TT-Th(0,∞,-,-)	V-Ts,Thc(0,11,-,18)	RUE-Th(-2,18,-,38)	-	-	TT-Th(0,∞,-,-)	TT-Th(0,∞,-,-)	TT-Th(0,∞,-,-)	-	-
SiriusQuality	TT-Ts(0,∞,-,-)	TT-Ts,Thc(0,∞,-,-)	TT-Th(0,∞,-,-)	V-Ts,Thc(0,15.5,-,48.5)	RUE~Ts,Thc(0,18,-,50)	-	-	TT-Ts,Thc(0,∞,-,-)	TT-Ts,Thc(0,∞,-,-)	TT-Ts(0,∞,-,-)	-	-
STICS	TT-Ts(0,∞,-,-)	TT-Tc(0,33,-,∞)	TT-Tc(0,33,-,∞)	-	RUE~Tc(0,12,17,40)	-	GR-Tmc/Txc(0,-,-,38)	TT-Tc(0,40-,∞)	TT-Tc(0,40-,∞)	Rr-Tc(0,40,-,∞)	-	Tc~$Q10^{Tc}$
WheatGrow	TT~Th(0,20,-,32)	TT~Th(3.3,22,-,32)	TT~Th(5.1,25,-,35)	V~Th(-1,1,10,18)	Ps~Ta(0,12,27,45)	Mr~$Q10^{Ta}$	-	-	-	Rr-Ta(0,26,50,60)	-	-
WOFOST	TT-Ta(-10,30,-,∞)	TT-Ta(0,30,-,∞)	TT-Ta(0,30,-,∞)	-	Ps-Ta(-2,15,25,38)	Mr~$Q10^{Ta}$	-	-	TT-Ta(0,35,-,∞)	-	-	-

Ta, mean daily air temperature; Tx, daily maximum air temperature; Tm, daily minimum air temperature; Th, hourly or subdaily air tempeature; Tc, canopy temperature; Txc, daily maximum canopy temperature; Tmc, daily minimum canopy temperature; Thc, subdaily canopy temperature; Ts, soil temperature; TT, thermal time; RUE, Radiation use efficiency.

[a] TT-T or TT~T(T1,T2,T3,T4), Thermal time (TT) changes linearly (-) or curvilinearlly (~) with temperature (T), with a base temperature of T1, optimal temperature between T2 and T3, and an upper most temperature of T4. Tx-(ws,vpd).

[b] V-T or V~T (T1,T2,T3,T4) - Vernalization is linearly (-) or curvilinearly (~) related to temperature with the cardinal tempearatures T1,T2,T3, and T4.

[c] RUE-T or RUE~T(T1,T2,T3,T4), RUE approach linearly (-) or curvilinearly (~) related to tempeature, with the cardinal tempearatures T1,T2,T3, and T4; TE-T or TE~T(T1,T2,T3,T4), transpiration efficiency approach linearly (-) or curvilinearly (~) related to tempeature; Ps-T or Ps~T(T1,T2,T3,T4) photosynthesis rate linearly (-) or curvilinearly (~) related to tempeature; Ps~T (complex), photosynthesis is simulated as function of temperature in a complex manner.

[d] Pr~Td, photorepiration is simulated as a curvilinear function of daytime temperature (Td), Mr~Ta, maintenance respiration is simulated as a curvilinear function of daily mean temperature (T), Mr~Q_{10}^{T} - maintenance respiration is simulated as a function of temperature using a Q10 approach, Gr~T, growth respiration as a function of T.

[e] GR-T or GR~T(T1,T2,T3,T4), grain growth rate is a linearly (-) or curvilinearly (~) related to temperature T with the cardinal tempearatures T1,T2,T3, and T4; HI-T(T1,T2,T3,T4), grain growth is simulated with harvest index that is affected by temperature T, GR~Q_{10}^{T} - grain growth rate is simulated using a Q10 function of T.

[f] TT-T or TT~T(T1,T2,T3,T4), leaf area growth is related to thermal time accumulation calcualted as a linear or curvilinear funtion of temperature with the cardinal tempearatures T1,T2,T3, and T4; La-T or La~T(T1,T2,T3,T4), leaf area growth is a linear or curvilinear function of temperature.

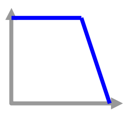
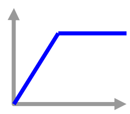
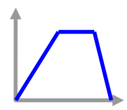
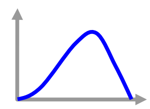
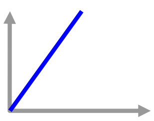
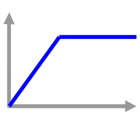
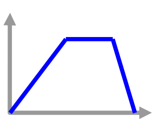
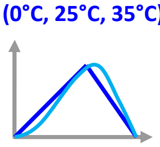
[g] TT-T or TT~T(T1,T2,T3,T4) - leaf senescence follows thermal time TT calculated as a linear or curvilinear function of temperature with the cardinal tempearatures T1,T2,T3, and T4, T> Tv - Leaf senescence is enhanced when certain temperature goes beyond the defined threshold Tv, $(Q10)^{Tc}$ - leaf senescense follows a Q10 function of Tc.

[h] Rr-T or Rr~T(T1,T2,T3,T4), root depth/length growth follows a linear (-) or curvilinearly (~) function of temperature with the cardinal tempearatures T1,T2,T3, and T4.

[i] PLN~T - Pollination is affected by extreme temperature, HI - harvest index is affected by extreme temperatures.

[j] T>Tv - leaf senescence is enhanced when temperature is above a certain threshold temperature Tv.

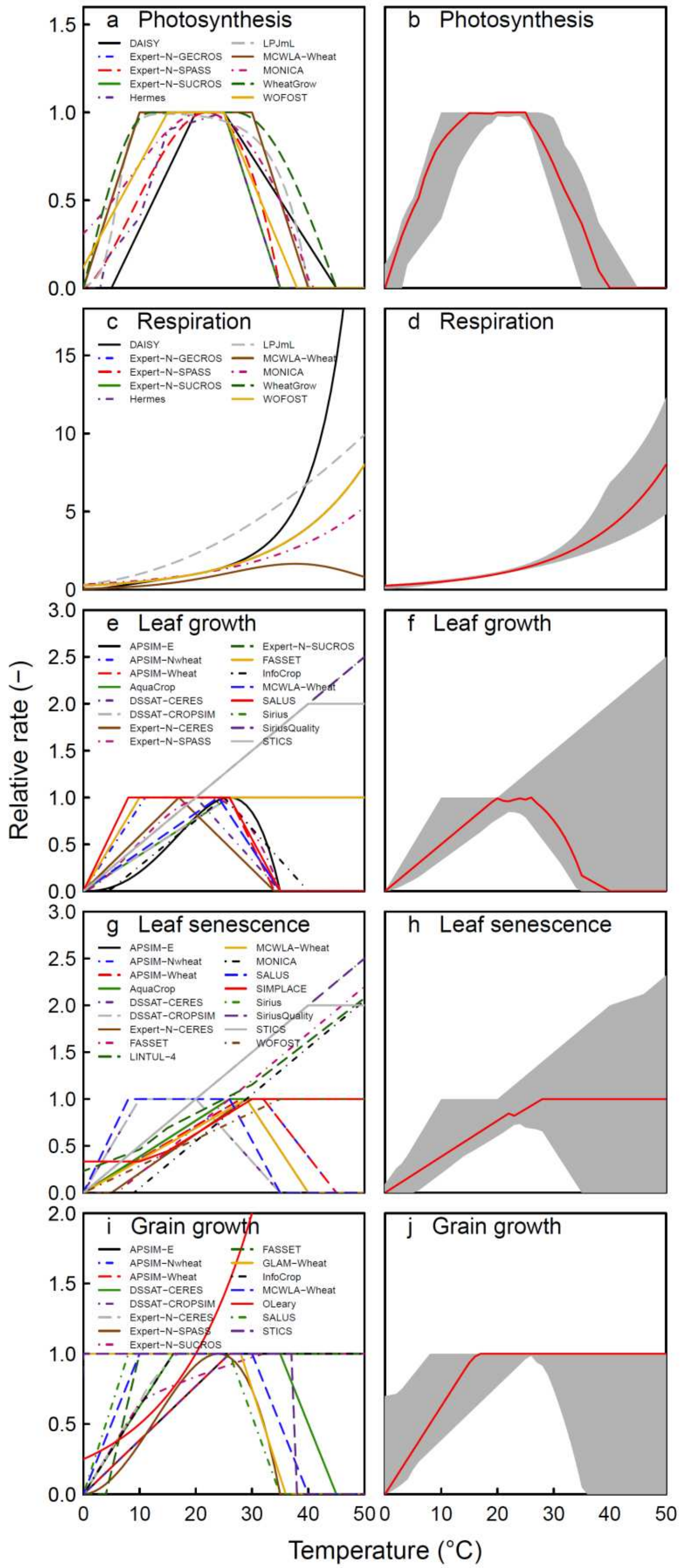
Supplementary Table 3 | The four main temperature response types for pre-anthesis phenological development and radiation use efficiency (RUE) used in the wheat models analysed in this study. For the models that explicitly simulate photosynthesis and respiration, they are grouped based on the temperature response types used for phenological development. The numbers in brackets indicate the cardinal temperatures implemented in APSIM and *SiriusQuality* models to test the impact on simulated phenology, biomass and grain yield. The models in which the new temperature response function were evaluated are highlighted in bold font.

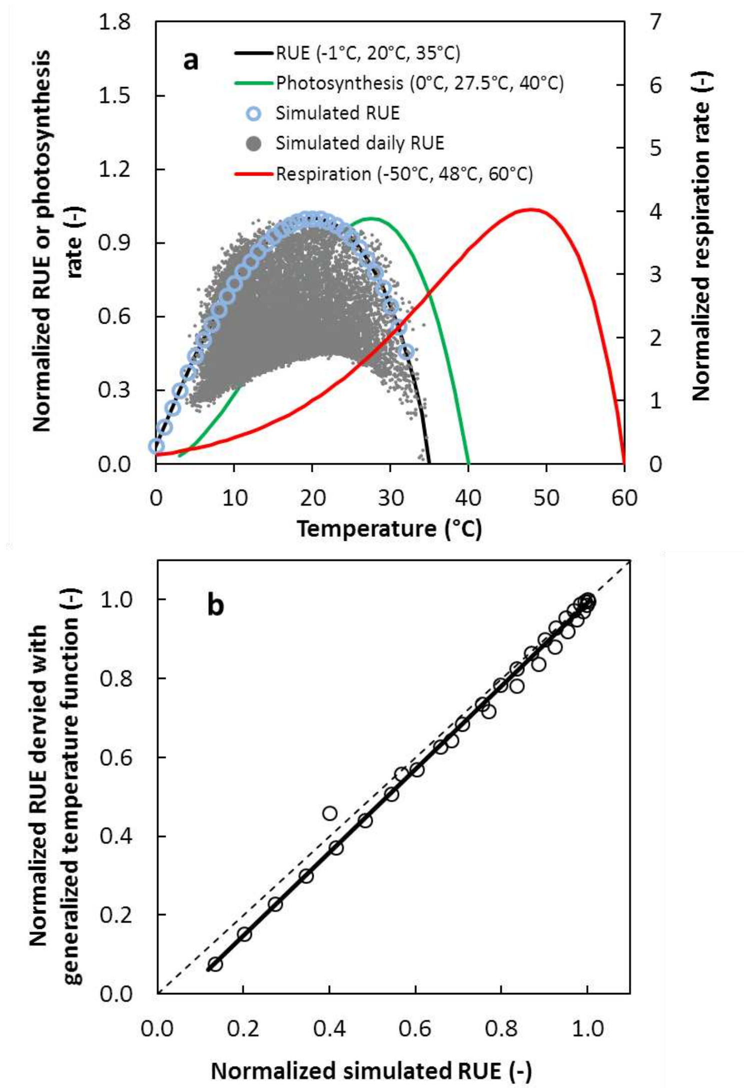
RUE / **Pre-anthesis phenological development**	**Type 1 – No reduction towards base temperature** **(∞, ∞, 25°C, 35°C)** 	**Type 2 – No maximum temperature** **(0°C, 20°C, ∞, ∞)** 	**Type 3 – A range of optimal temperatures** **(0°C, 15°C, 20, 35)** 	**Type 4 - Minimum, optimum and maximum temperatures** **(0°C, 20°C, 35°C)** 	**Phosynthesis and Respiration**
Type 1 - No optimum and maximum **(0°C, ∞, ∞, ∞)** 		FASSET	O'Leary	SIRIUS ***SiriusQuality***	HERMES LPJmL MONICA Expert-N-SUCROS
Type 2 - No maximum temperature **(0°C, 25°C, ∞, ∞)** 		Aquacrop EPIC-Wheat	**SALUS** DSSAT-CERES DSSAT-CROPSIM LINTUL-4	STICS	WOFOST
Type 3 - A range of optimum temperatures **(0°C, 25°C, 35°C, 45°C)** 	GLAM-Wheat		APSIM-Nwheat Cropsyst Expert-N-CERES		
Type 4- Min, optimum & max temperature **(0°C, 25°C, 35°C)** 			APSIM-Wheat InfoCrop MCWLA-Wheat	**APSIM-Wheat-E** Expert-N-CERES	Expert-N-SPASS Expert-N-GECROS DAISY SIMPLACE **WheatGrow**

Supplementary Table 4 | Parameters used for simulating the response of radiation use efficiency to temperature in the SPASS photosynthesis model[69].

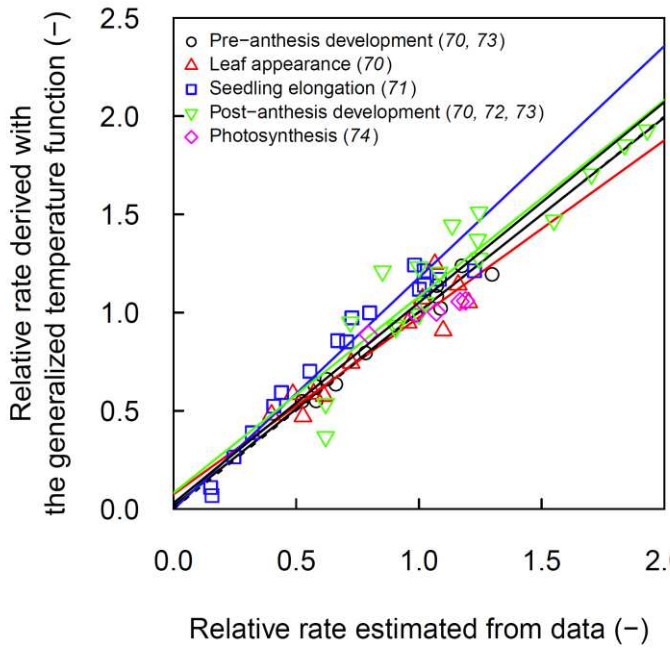
Parameter	Value	Unit	Explanation
AMAX	40	kg CO_2 ha^{-1} h^{-1}	Maximum photosythesis rate of leaf
EFF	0.6	g CO_2 J^{-1}	Light use efficiency at low light
K_L	0.7	m^2 ground m^{-2} leaf	Radiation extinction coefficient of leaf canopy
Γ	73.6	mg CO_2 m^3 air	CO_2 compensation point
DarkResp	0.03	g CO_2 g^{-1} d^{-1}	Maintenance respiration at 20°C
Temperature	-5 to 35	°C	Temperature range simulated
Radiation	10 to 32	MJ d^{-1}	Radiation range simulated
CO_2	736	mg CO_2 m^3 air	Atmospheric CO_2 concentration
LAI	3	m^2 leaf m^{-2} ground	Leaf area index
Biomass	3	t ha^{-1}	Total above ground biomass
Root	0.2	-	Partition of photosynthate to root

Supplementary Figure 1 | Temperature response functions in 29 wheat simulation models. (**a** and **b**) photosynthesis. (**c** and **d**) respiration. (**e** and **f**) leaf area growth. (**g** and senescence) senescence.Grain growth (**i** and **j**). Models are listed in Supplementary Table 1. (**b**, **d**, **f**, **h**, and **j**) Summaries of temperature responses from all models with red lines representing the median and shaded areas the 10% and 90% quantiles.

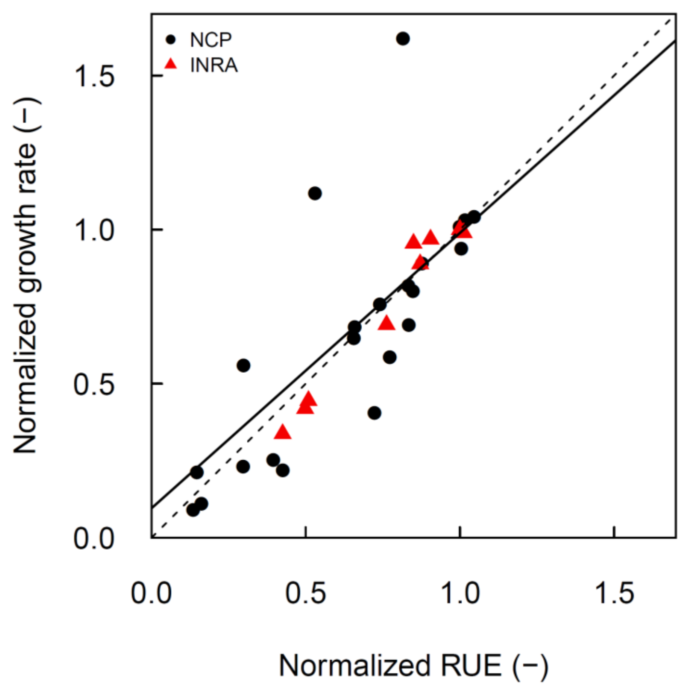




Supplementary Figure 2 | Radiation use efficiency (RUE) temperature dependency derived from photosynthesis and respiration. (**a**) RUE temperature response functions averaged under low (10 MJ m^{-2} d^{-1}; circles) and high (30 MJ m^{-2} d^{-1}; blue circles) conditions, and RUE under various (grey dots) radiation conditions calculated with the SPASS photosynthesis and plant growth model[69]. Red and green solid lines are the derived temperature response functions for photosynthesis and respiration rates used in SPASS to calculate daily RUE, respectively. The temperature responses for photosynthesis (green line), respiration (red line), and RUE (black line) were produced using the cardinal temperatures shown in parenthesis with β = 1.0 for photosynthesis and respiration and 0.8 for RUE. The black line roughly captures the envelope of the simulated daily RUE response to temperature by the SPASS model. (**b**) Comparison of normalized RUE calculated using the derived temperature response function shown in (**a**) with mean daily RUE calculated using the SPASS model for temperatures ranging from 0°C to 32°C. Solid and dashed lines are the standardized linear regression (y = -1.0556 [1.0305, 1.0814] x - 0.0643 [-0.0844, -0.0441], r^2 = 0.99, $P < 2.22 \times 10^{-16}$) and the 1:1 line, respectively. All rates were normalized at 20°C.



Supplementary Figure 3 | Performance of the improved temperature response functions in capturing the phenological development, tissue expansion, and photosynthesis rates derived from experimental data. The numbers in the brackets in the legend indicate the literature sources[70-74] of the data. Solid lines are standardized regressions for pre-anthesis development rate (black; y = 0.83 [0.734, 0.943] x + 0.15 [0.045, 0.2598], $r^2 = 0.90$, $P < 9.59 \times 10^{-14}$), leaf appearance rate (red; y = 0.91 [0.734, 1.120] x + 0.07 [-0.102, 0.233], $r^2 = 0.88$, $P < 6.56 \times 10^{-6}$), seedling elongation rate (blue; y = 1.18 [1.058, 1.315] x - 0.002 [-0.0985, 0.0946], $r^2 = 0.95$, $P < 2.94 \times 10^{-11}$), and post-anthesis development rate (green; y = 0.95 [0.822, 1.099] x + 0.14 [-0.056, 0.329], $r^2 = 0.84$, $P < 6.77 \times 10^{-13}$). The dashed line is the 1:1 line. All rates were normalized at 20°C.



Supplementary Figure 4 | Relationship between net biomass growth rate and radiation use efficiency. Data are from the NCP[75] (black circles) and outdoor semi-controlled environment[72] (red triangle) experiments. There was no difference in the slope (P = 0.20) and intercept (P = 0.97) among datasets, therefore, a single standardized regression was fitted to all data (solid line; y = 0.8934 [0.7814, 1.0214] x + 0.0958 -0.0078, 0.1837], r^2 = 0.65, $P = 4.42 \times 10^{-8}$). Dashed line is the 1:1 lines. All rates were normalized at 20°C.

Supplementary Literature Cited

1 Zhao, Z. *et al.* Modelling to increase the eco-efficiency of a wheat–maize double cropping system. *Agriculture, Ecosystems & Environment* **210**, 36-46 (2015).

2 Keating, B. A. *et al.* An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267-288 (2003).

3 Wang, E. *et al.* Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy* **18**, 121-140 (2002).

4 Chen, C., Wang, E. & Yu, Q. Modeling Wheat and Maize Productivity as Affected by Climate Variation and Irrigation Supply in North China Plain. *Agronomy Journal* **102**, 1037-1049 (2010).

5 Asseng, S. *et al.* Performance of the APSIM-wheat model in Western Australia. *Field Crops Res.* **57**, 163-179 (1998).

6 Asseng, S. *et al.* Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. *Field Crops Research* **85**, 85-102 (2004).

7 Steduto, P., Hsiao, T., Raes, D. & Fereres, E. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal* **101**, 426-437 (2009).

8 Stockle, C., Donatelli, M. & Nelson, R. CropSyst, a cropping systems simulation model. *European Journal of Agronomy* **18**, 289-307 (2003).

9 Hansen, S., Jensen, H., Nielsen, N. & Svendsen, H. Simulation of nitrogen dynamics and biomass production in winter-wheat using the Danish simulation model DAISY. *Fertilizer Research* **27**, 245-259 (1991).

10 Hansen, S., Abrahamsen, P., Petersen, C. T. & Styczen, M. DAISY: model use, calibration, and validation. *Transaction of the ASABE* **55**, 1317-1335 (2012).

11 Hoogenboom, G. & White, J. Improving physiological assumptions of simulation models by using gene-based approaches. *Agronomy Journal* **95**, 82-89 (2003).

12 Jones, J. *et al.* The DSSAT cropping system model. *European Journal of Agronomy* **18**, 235-265 (2003).

13 Ritchie, J. T., Godwin, D. C. & Otter-Nacke, S. *CERES-wheat: A user-oriented wheat yield model. Preliminary documentation*. 252 (1985).

14 Hunt, L. A. & Pararajasingham, S. CROPSIM-wheat - a model describing the growth and development of wheat. *Canadian Journal of Plant Science* **75**, 619-632 (1995).

15 Kiniry, J. *et al.* EPIC model parameters for cereal, oilseed, and forage crops in the northern great-plains region. *Canadian Journal of Plant Science* **75**, 679-688 (1995).

16 Williams, J., Jones, C., Kiniry, J. & Spanel, D. The EPIC crop growth-model. *Transactions of the ASAE* **32**, 497-511 (1989).

17 Izaurralde, R. C., McGill, W. B. & Williams, J. R. in *Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate* (eds M.A. Liebig, A.J. Franzluebbers, & R.F. Follett) 409-429 (Elsevier, 2012).

18 Priesack, E., Gayler, S. & Hartmann, H. The impact of crop growth sub-model choice on simulated water and nitrogen balances. *Nutrient Cycling in Agroecosystems* **75**, 1-13 (2006).

19 Ritchie, S., Nguyen, H. & Holaday, A. Genetic diversity in photosynthesis and water-use efficiency of wheat and wheat relatives. *Journal of Cellular Biochemistry*, 43-43 (1987).

20 Biernath, C. *et al.* Evaluating the ability of four crop models to predict different environmental impacts on spring wheat grown in open-top chambers. *European Journal of Agronomy* **35**, 71-82 (2011).

21 Stenger, R., Priesack, E., Barkle, G. & Sperr, C. (Land Treatment collective proceedings Technical Session, New Zealand, 1999).

22 Wang, E. & Engel, T. SPASS: a generic process-oriented crop model with versatile windows interfaces. *Environmental Modelling & Software* **15**, 179-188 (2000).
23 Yin, X. & van Laar, H. H. *Crop systems dynamics: an ecophysiological simulation model of genotype-by-environment interactions*. 115 (Wageningen Academic Publishers, 2005).
24 Goudriaan, J. & Van Laar, H. H. in *Current Issues in Production Ecology* 238 (Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994).
25 Berntsen, J., Petersen, B., Jacobsen, B., Olesen, J. & Hutchings, N. Evaluating nitrogen taxation scenarios using the dynamic whole farm simulation model FASSET. *Agricultural Systems* **76**, 817-839 (2003).
26 Olesen, J. *et al.* Comparison of methods for simulating effects of nitrogen on green area index and dry matter growth in winter wheat. *Field Crops Research* **74**, 131-149 (2002).
27 Challinor, A., Wheeler, T., Craufurd, P., Slingo, J. & Grimes, D. Design and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology* **124**, 99-120 (2004).
28 Li, S. *et al.* Simulating the Impacts of Global Warming on Wheat in China Using a Large Area Crop Model. *Acta Meteorologica Sinica* **24**, 123-135 (2010).
29 Kersebaum, K. Modelling nitrogen dynamics in soil-crop systems with HERMES. *Nutrient Cycling in Agroecosystems* **77**, 39-52 (2007).
30 Kersebaum, K. C. Special features of the HERMES model and additional procedures for parameterization, calibration, validation, and applications. *Ahuja, L.R. and Ma, L. (eds.). Methods of introducing system models into agricultural research. Advances in Agricultural Systems Modeling Series 2, Madison (ASA-CSSA-SSSA)*, 65-94 (2011).
31 Aggarwal, P. *et al.* InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. II. Performance of the model. *Agricultural Systems* **89**, 47-67 (2006).
32 Spitters, C. J. T. & Schapendonk, A. H. C. M. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. *Plant and Soil* **123**, 193-203 (1990).
33 Shibu, M., Leffelaar, P., van Keulen, H. & Aggarwal, P. LINTUL3, a simulation model for nitrogen-limited situations: Application to rice. *European Journal of Agronomy* **32**, 255-271 (2010).
34 Bondeau, A. *et al.* Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* **13**, 679-706 (2007).
35 Beringer, T., Lucht, W. & Schaphoff, S. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Global Change Biology Bioenergy* **3**, 299-312 (2011).
36 Fader, M., Rost, S., Muller, C., Bondeau, A. & Gerten, D. Virtual water content of temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology* **384**, 218-231 (2010).
37 Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. & Sitch, S. Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology* **286**, 249-270 (2004).
38 Rost, S. *et al.* Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research* **44** (2008).
39 Müller, C. *et al.* Effects of changes in CO2, climate, and land use on the carbon balance of the land biosphere during the 21st century. *Journal of Geophysical Research-Biogeosciences* **112** (2007).
40 Tao, F., Yokozawa, M. & Zhang, Z. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis. *Agricultural and Forest Meteorology* **149**, 831-850 (2009).

41 Tao, F., Zhang, Z., Liu, J. & Yokozawa, M. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology* **149**, 1266-1278 (2009).
42 Tao, F. & Zhang, Z. Adaptation of maize production to climate change in North China Plain: Quantify the relative contributions of adaptation options. *European Journal of Agronomy* **33**, 103-116 (2010).
43 Tao, F. & Zhang, Z. Climate change, wheat productivity and water use in the North China Plain: A new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology* **170**, 146-165 (2013).
44 Nendel, C. *et al.* The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics. *Ecological Modelling* **222**, 1614-1625 (2011).
45 Oleary, G., Connor, D. & White, D. A simulation-model of the development, growth and yield of the wheat crop. *Agricultural Systems* **17**, 1-26 (1985).
46 OLeary, G. & Connor, D. A simulation model of the wheat crop in response to water and nitrogen supply .1. Model construction. *Agricultural Systems* **52**, 1-29 (1996).
47 OLeary, G. & Connor, D. A simulation model of the wheat crop in response to water and nitrogen supply .2. Model validation. *Agricultural Systems* **52**, 31-55 (1996).
48 Latta, J. & O'Leary, G. Long-term comparison of rotation and fallow tillage systems of wheat in Australia. *Field Crops Research* **83**, 173-190 (2003).
49 Basso, B., Cammarano, D., Troccoli, A., Chen, D. & Ritchie, J. Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis. *European Journal of Agronomy* **33**, 132-138 (2010).
50 Senthilkumar, S., Basso, B., Kravchenko, A. N. & Robertson, G. P. Contemporary evidence of soil carbon loss in the US corn belt. *Soil Sci. Soc. Am. J.* **73**, 2078-2086 (2009).
51 Angulo, C. *et al.* Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe. *Agricultural and Forest Meteorology* **170**, 32-46 (2013).
52 Jamieson, P., Semenov, M., Brooking, I. & Francis, G. Sirius: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy* **8**, 161-179 (1998).
53 Jamieson, P. & Semenov, M. Modelling nitrogen uptake and redistribution in wheat. *Field Crops Research* **68**, 21-29 (2000).
54 Lawless, C., Semenov, M. & Jamieson, P. A wheat canopy model linking leaf area and phenology. *European Journal of Agronomy* **22**, 19-32 (2005).
55 Semenov, M. & Shewry, P. Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. *Scientific Reports* **1** (2011).
56 Martre, P. *et al.* Modelling protein content and composition in relation to crop nitrogen dynamics for wheat. *Eur J Agron* **25**, 138-154 (2006).
57 Ferrise, R., Triossi, A., Stratonovitch, P., Bindi, M. & Martre, P. Sowing date and nitrogen fertilisation effects on dry matter and nitrogen dynamics for durum wheat: An experimental and simulation study. *Field Crops Res.* **117**, 245-257 (2010).
58 He, J., Stratonovitch, P., Allard, V., Semenov, M. A. & Martre, P. Global sensitivity analysis of the process-based wheat simulation model *SiriusQuality*1 identifies key genotypic parameters and unravels parameters interactions. *Procedia - Social and Behavioral Sciences* **2**, 7676-7677 (2010).
59 Brisson, N. *et al.* STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* **18**, 311-346 (1998).
60 Brisson, N. *et al.* An overview of the crop model STICS. *European Journal of Agronomy* **18**, 309-332 (2003).

61 Cao, W. & Moss, D. N. Modelling phasic development in wheat: a conceptual integration of physiological components. *Journal of Agricultural Science* **129**, 163-172 (1997).
62 Cao, W. *et al.* Simulating organic growth in wheat based on the organ-weight fraction concept. *Plant Production Science* **5**, 248-256 (2002).
63 Yan, M., Cao, W. & C. Li, Z. W. Validation and evaluation of a mechanistic model of phasic and phenological development in wheat. *Chinese Agricultural Science* **1**, 77-82 (2001).
64 Li, C., Cao, W. & Zhang, Y. Comprehensive Pattern of Primordium Initiation in Shoot Apex of Wheat. *ACTA Botanica Sinica*, 273-278 (2002).
65 Hu, J., Cao, W., Zhang, J., Jiang, D. & Feng, J. Quantifying responses of winter wheat physiological processes to soil water stress for use in growth simulation modeling. *Pedosphere* **14**, 509-518 (2004).
66 Pan, J., Zhu, Y. & Cao, W. Modeling plant carbon flow and grain starch accumulation in wheat. *Field Crops Research* **101**, 276-284 (2007).
67 Pan, J. *et al.* Modeling plant nitrogen uptake and grain nitrogen accumulation in wheat. *Field Crops Research* **97**, 322-336 (2006).
68 Boogaard, H. & Kroes, J. Leaching of nitrogen and phosphorus from rural areas to surface waters in the Netherlands. *Nutrient Cycling in Agroecosystems* **50**, 321-324 (1998).
69 Wang, E. & Engel, T. Simulation of growth, water and nitrogen uptake of a wheat crop using the SPASS model. *Environmental Modelling and Software* **17**, 387-402 (2002).
70 White, J. W., Kimball, B. A., Wall, G. W., Ottman, M. J. & Hunt, L. A. Responses of time of anthesis and maturity to sowing dates and infrared warming in spring wheat. *Field Crops Research* **124**, 213-222 (2011).
71 Parent, B. & Tardieu, F. Temperature responses of developmental processes have not been affected by breeding in different ecological areas for 17 crop species. *New Phytologist* **194**, 760-774 (2012).
72 Triboï, E., Martre, P. & Triboï-Blondel, A.-M. Environmentally-induced changes in protein composition in developing grains of wheat are related to changes in total protein content. *Journal of Experimental Botany* **54**, 1731-1742 (2003).
73 Reynolds, M., Balota, M., Delgado, M., Amani, I. & Fischer, R. Physiological and morphological traits associated with spring wheat yield under hot, irrigated conditions. *Functional Plant Biology* **21**, 717-730 (1994).
74 Nagai, T. & Makino, A. Differences between rice and wheat in temperature responses of photosynthesis and plant growth. *Plant and Cell Physiology* **50**, 744-755 (2009).
75 Zhao, Z. *et al.* Accuracy of root modelling and its impact on simulated wheat yield and carbon cycling in soil. *Field Crops Research* **165**, 99-110 (2014).