

The uncertainty of crop yield projections is reduced by improved temperature response functions

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Increasing the accuracy of crop productivity estimates is a key element in planning adaptation strategies to ensure global food security under climate change. Process-based crop models are effective means to project climate impact on crop yield, but have large uncertainty in yield simulations. Here, we show that variations in the mathematical functions currently used to simulate temperature responses of physiological processes in 29 wheat models account for >50% of uncertainty in simulated grain yields for mean growing season temperatures from 14 °C to 33 °C. We derived a set of new temperature response functions that when substituted in four wheat models reduced the error in grain yield simulations across seven global sites with different temperature regimes by 19% to 50% (42% average). We anticipate the improved temperature responses to be a key step to improve modelling of crops under rising temperature and climate change, leading to higher skill of crop yield projections.

Process-based modelling of crop growth is an effective way of representing how crop genotype, environment and management interactions affect crop production to aid tactical and strategic decision making¹. Process-based crop models are increasingly used to project the impact of climate change on crop yield². However, current models produce different results, creating large uncertainty in crop yield simulations³. A model inter-comparison study within the Agricultural Model Inter-comparison and Improvement Project (AgMIP)⁴ of 29 widely used wheat models against field experimental data revealed that there is more uncertainty in simulating grain yields from the different models than from 16 different climate change scenarios³. The greatest uncertainty was in modelling crop responses to temperature^{3,5}. Similar results were found with rice and maize crops^{6,7}. Such uncertainty should be reduced before informing decision making in agriculture and government policy. Here, we show contrasting differences in temperature response functions of key physiological processes adopted in the 29 crop models. We reveal opportunities for improving simulation of temperature response in crop models to reduce the uncertainty in yield simulations.

We aim to reassess the scientific assumptions underlying model algorithms and parameterization describing temperature-sensitive physiological processes, using wheat, one of the most important staple crops globally, as an example. We hypothesized that: (1) the difference among models in assumed temperature responses is the largest source of the uncertainty in simulated yields; and (2) the uncertainty in the multi-model ensemble results can be reduced by improving the science for modelling temperature response of physiological processes.

Temperature affects crop performance primarily through its impact on (1) the rate of phenological development from seed germination to crop maturity, including the fulfilment of cold requirement (vernalisation); (2) the initiation and expansion of plant organs; (3) photosynthesis and respiration, considered either separately or combined as net biomass growth simulated using radiation use efficiency (RUE)⁸; and (4) the senescence, sterility or abortion of plant organs. All 29 models simulate these processes, except for sterility and abortion, in response to temperature change.

Here, we compare the temperature functions of these four categories of physiological processes built into the 29 wheat models

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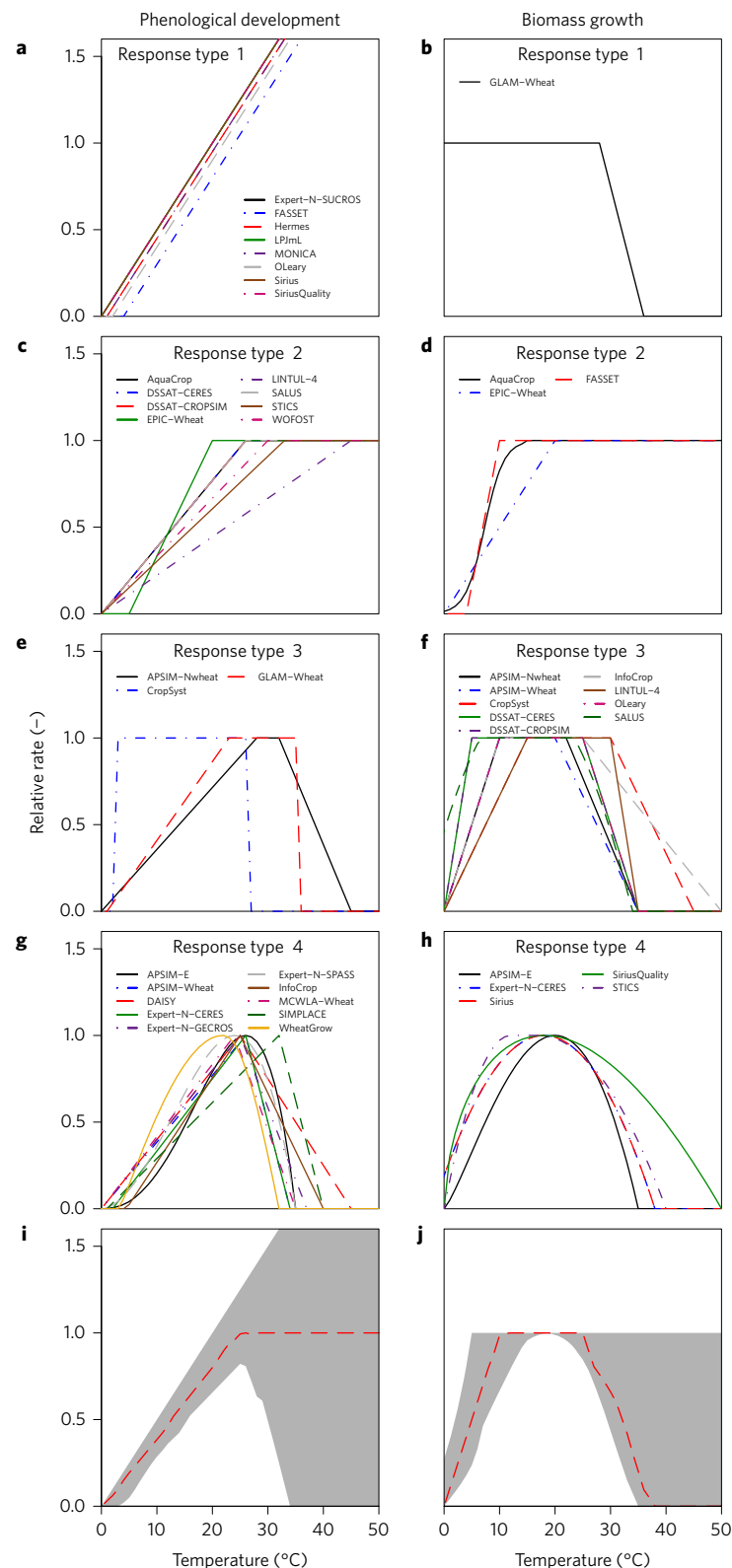


Figure 1 | Temperature response functions in 29 wheat simulation models. a,c,e,g,i, Phenological development (preflowering). **b,d,f,h,j,** Biomass growth (or RUE). **a,b,** Type 1, linear with no optimum or maximum temperature. **c,d,** Type 2, linear or curvilinear with an optimum but no maximum temperature. **e,f,** Type 3, linear with range of optimal temperatures. **g,h,** Type 4, linear or curvilinear with three cardinal temperatures. **i,j,** Summary of temperature responses of all models, with red lines representing the median and shaded area the 10% and 90% percentiles for the 29 models. In **a-j** rates are normalized to 20 °C. Models are listed in Supplementary Table 1.

and identify the representative response types. We analyse how different temperature response functions affected simulations of wheat growth compared to observations in a field experiment^{8–10},

in which well-fertilized and irrigated wheat grew under contrasting sowing dates and temperature environments (Hot Serial Cereal (HSC) experiment). We further evaluate the impact of the different

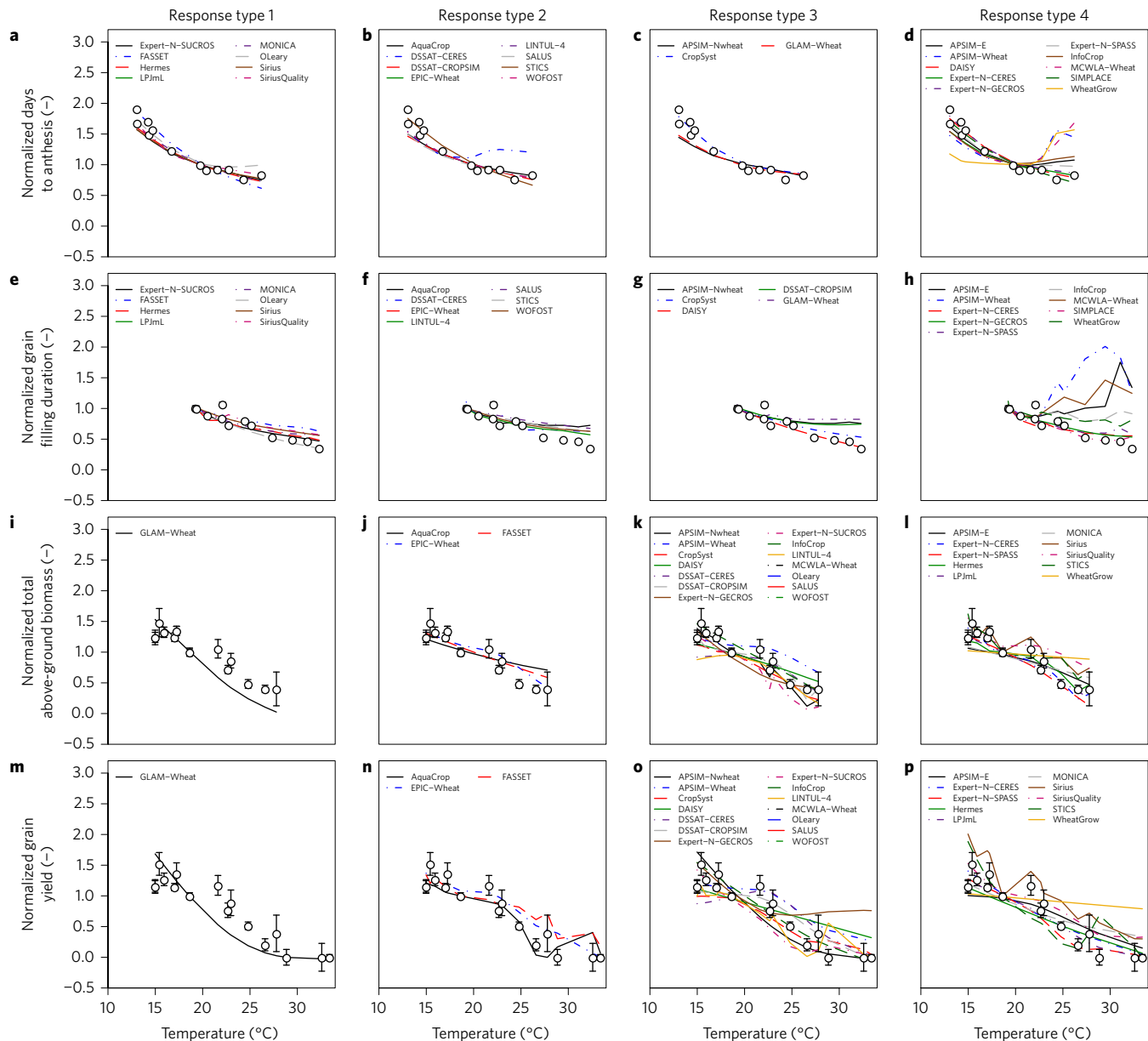


Figure 2 | Comparison of multi-model simulations against observations and average growing season temperature. a–d, Simulated days from sowing to anthesis. **e–h,** Simulated days from anthesis to maturity. **i–l,** Simulated final total above-ground biomass. **m–p,** Simulated final grain yield. The data were standardized to 20 °C and plotted against the mean average daily temperature from sowing to anthesis (**a–d**), from anthesis to maturity (**e–h**) and from sowing to maturity (**i–p**). Models were grouped according to their temperature response types for phenological development (**a–h**) or biomass growth (**i–p**), as defined in Fig. 1. Simulated and experimental data are for the HSC experiment⁸. Symbols with error bars are experimental means ± 1 s.d. for $n = 3$ independent replicates.

response types by implementing them in two models (APSIM and SiriusQuality) and analysing their results against the HSC data and an additional global dataset from the International Heat Stress Genotype Experiment (IHSGE)⁸ carried out by the International Maize and Wheat Improvement Center (CIMMYT). More importantly, we derive, based on newest knowledge and data, a set of new temperature response functions for the key physiological processes of wheat and demonstrate that when substituted in four wheat models the new functions reduced the error in grain yield simulations across seven global sites with different temperature regimes covered by the IHSGE data.

Results

Contrasting temperature functions in 29 models. A wide range of temperature responses was observed in the 29 models

(Supplementary Tables 1 and 2) which we grouped into four major types (types 1–4) according to how phenological development and biomass growth (RUE) are treated (Fig. 1 and Supplementary Table 3)—that is, whether increasing or decreasing slopes are linear or curvilinear, whether base (T_{\min}), optimum (T_{opt}) or maximum (T_{\max}) temperatures are defined and whether T_{opt} is a range or a point. The simplest type is a linear increase in developmental rate with temperature from a base temperature (T_{\min}) around 0 °C assuming no temperature optimum (T_{opt}) or maximum (T_{\max}) (type 1 phenology, Fig. 1a) and a linear decline of biomass growth rate above a certain temperature assuming no T_{\min} (type 1 biomass, Fig. 1b). For both processes, the second type defines both T_{\min} and T_{opt} , but assumes no T_{\max} , thus simulating an increasing rate with temperature below T_{opt} and a constant maximum rate above T_{opt} , respectively (type 2,

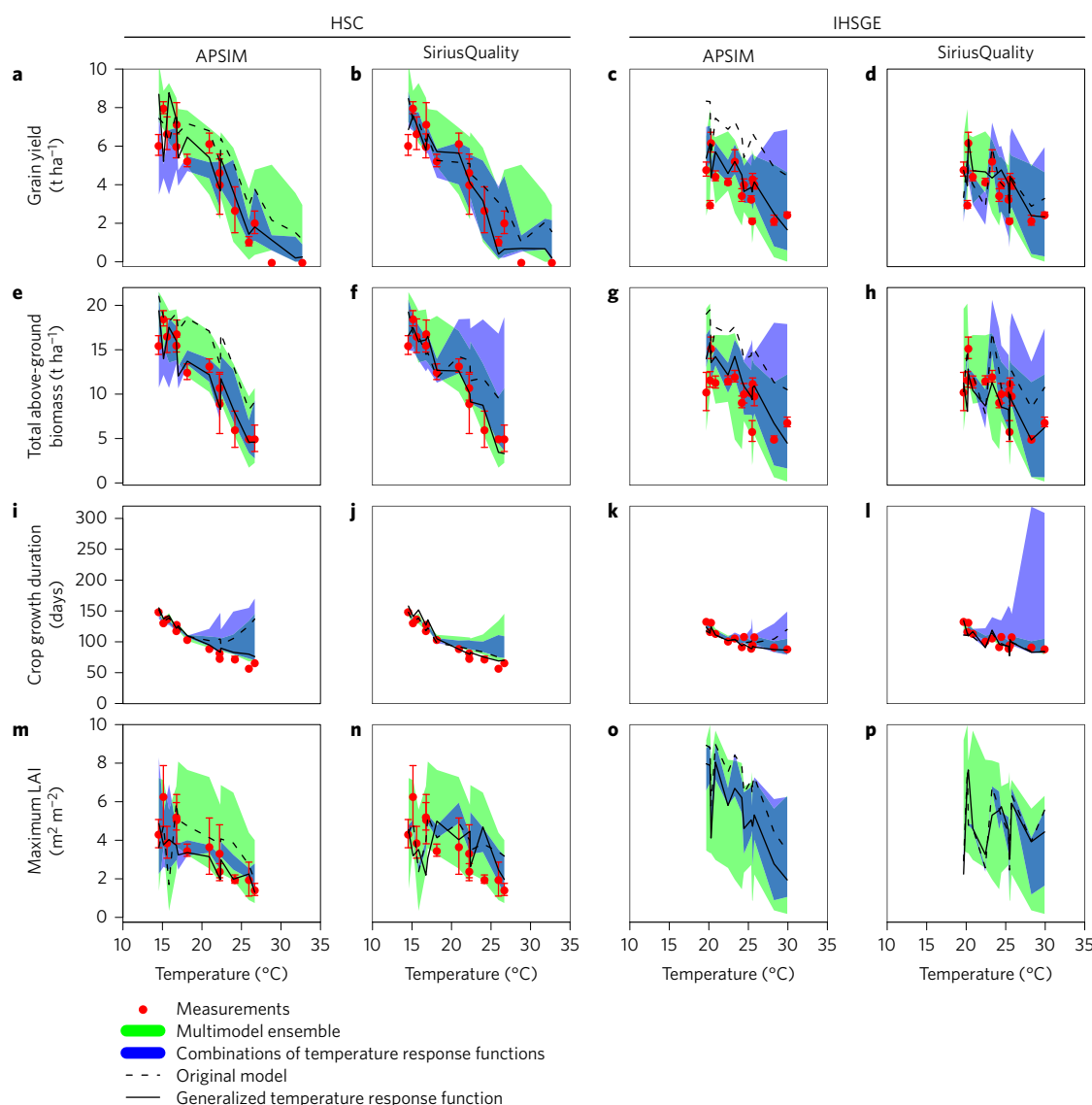


Figure 3 | Uncertainty in simulated wheat responses due to variations in the temperature response functions of phenological development and biomass growth (RUE). **a–p**, Comparisons are between observed and simulated grain yield (**a–d**), total above-ground biomass (**e–h**), crop growth duration (**i–l**) and in season maximum LAI (**m–p**) for the HSC and IHSGE data sets. Temperature on the x axis refers to average growing season temperature. Simulations were executed with the wheat models APSIM and SiriusQuality. Red circles show the measurements (mean \pm 1 s.d. for $n = 3$ independent replicates). Green areas show uncertainty in simulated values (10th–90th percentile range) from the 29 models of the AgMIP-Wheat multi-model ensemble⁸. Blue areas show the range of simulated values when using APSIM or SiriusQuality combined with the 20 combinations of the 4 or 5 types of response functions for phenological development and biomass growth, respectively, using the cardinal temperatures reported in Supplementary Table 3. Dashed black lines show the simulated values by the original APSIM and SiriusQuality models. Solid black lines show the simulated values by APSIM or SiriusQuality with the improved temperature response functions for phenological development and biomass growth.

Fig. 1c,d). Most models define the three cardinal temperatures, simulating an increasing rate with temperature from T_{\min} to T_{opt} and a decreasing rate from T_{opt} to T_{\max} (Fig. 1e–h). Some of the models in this category define T_{opt} as a range (type 3, Fig. 1e,f), while the rest define it as a single value (type 4, Fig. 1g,h). Some models implement linear responses to temperature between the cardinal temperatures, the others curvilinear.

For both phenology and biomass growth, most models agree on a T_{opt} when the rate is maximum (Fig. 1), except for models that lack a T_{opt} (Fig. 1a). At temperatures lower or higher than T_{opt} , the uncertainty in the simulation of phenological development and biomass increases, particularly at higher temperatures. Response types for photosynthesis were consistent, but different cardinal temperatures were used, introducing uncertainty (Supplementary Fig. 1a,b). The simulated temperature responses of respiration differ widely from

each other (Supplementary Fig. 1c,d). When such estimates of respiration and photosynthesis are combined to simulate growth, any uncertainty is compounded at high temperatures. For leaf growth and senescence, contrasting temperature responses were deployed, with much greater uncertainty at temperatures above 25–30 °C (Supplementary Fig. 1e–h). For grain growth, the differences in temperature responses are even greater, generating increased uncertainty above 24 °C (Supplementary Fig. 1i,j).

Model performance against HSC data. Simulation results of the 29 models against the HSC experiment were analysed by grouping all the models based on the four temperature response types and cardinal temperatures deployed for simulating phenology and biomass growth. The results were standardized at 20 °C to remove any systematic bias and compare their response to temperature (Fig. 2).

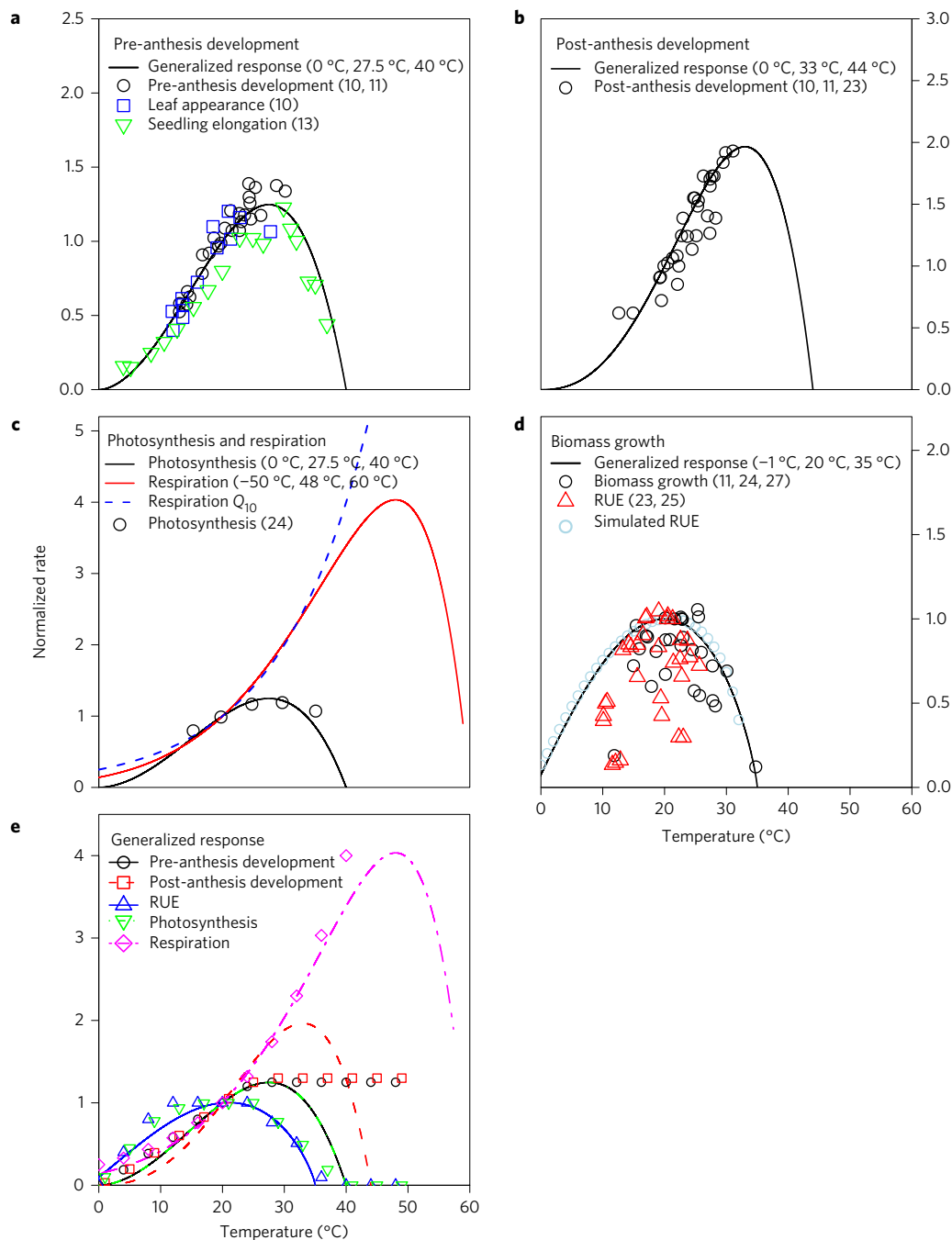


Figure 4 | Derived temperature responses of various physiological processes. a–d, The relative rates of pre- (**a**), and post- (**b**) anthesis development, photosynthesis and respiration (**c**) and biomass growth or RUE (**d**), calculated with data from the literature (symbols), were compared with those estimated using the derived temperature response functions (solid lines). In **c**, a Q_{10} value of 2 was used for response, shown with the dashed line. In **d**, daily RUE (light blue circles) was calculated with the SPASS photosynthesis and plant growth model using daily weather data covering temperature range of -5°C to 36°C . The numbers in the brackets in the legends for the response lines indicate the minimum (T_{\min}), optimum (T_{opt}) and maximum (T_{\max}) temperatures. The numbers in the brackets in the legends for the data symbols indicate the literature reference source of data. In **e**, the derived responses (lines) were compared with the medians of the temperature responses calculated from all 29 models (symbols). All data were normalized at 20°C and all curves were generated using the $f(T)$ function equation¹⁵ and the cardinal temperatures shown. For all processes, $\beta = 1.0$ except for RUE where $\beta = 0.8$.

For phenology, the models agreed most closely with each other at a mean growing season temperature around 20°C and matched the observed anthesis and maturity dates well (Fig. 2a–h). At lower and higher temperatures, the simulated results departed from each other and did not match the observed dates. Three type 4 response models (with three cardinal temperatures, Fig. 1g) with low T_{opt} and T_{\max} severely underestimated the preflowering development rate at temperatures above 25°C and thus predicted

durations longer than were observed (Fig. 2d). For postflowering development, 20 out of the 29 models predicted the physiological maturity to be later than was observed at temperatures above 25°C (Fig. 2e–h), particularly the models that have a T_{\max} around 35°C (Fig. 2h).

For total above-ground biomass and grain yield, the models with type 2 response for biomass growth (no reduction at higher temperatures) tended to overestimate biomass at high temperatures

(Fig. 2j). For type 3 (with an optimal temperature range, Fig. 2k) and type 4 (Fig. 2l) responses, the models that have a higher T_{opt} and T_{max} for either RUE (Fig. 1f,h) or photosynthesis (Supplementary Fig. 1a) also overestimated biomass at temperatures above 25 °C (Fig. 2k,l). The simulated responses for grain yield for the HSC experiment varied in a similar way to those for biomass (Fig. 2m–p). These findings indicate that improved modelling of temperature responses of phenological development, biomass growth (RUE), photosynthesis and respiration rates is necessary to reduce uncertainty in simulation of grain yield.

Impact of temperature response functions. While the impact of the temperature functions in different models may be compounded by interactions with other simulated processes, we further evaluated the impact of the different temperature response types (Supplementary Table 3) by implementing 20 combinations of temperature response types in the APSIM and SiriusQuality models to simulate the HSC data and the additional IHSGE data from CIMMYT^{8,11,12}. This change caused the two models to predict different grain yields as a result of differences in simulated growth duration, leaf area index (LAI) and biomass (Fig. 3). Differences in simulated grain yield were greater than 100%, particularly at low and high temperatures (Fig. 3). The range of simulated grain yield caused by different combinations of temperature response functions in APSIM and SiriusQuality was on average 52% (65%) and 64% (78%) of the uncertainty of the whole ensemble of 29 models for the HSC (IHSGE) data, respectively, highlighting the significant impact of temperature response functions alone on simulated wheat growth in the absence of water and nutrient stresses.

New temperature response functions. A recent synthesis of available data on phenological development and tissue expansion indicated that rates of preanthesis phenological development, tissue expansion and cell division of crop plants all followed a common Arrhenius-type response curve, and for wheat the response curve has a T_{min} of 0 °C, T_{opt} of 27.7 °C and T_{max} of 40 °C^{13,14}. We used this information to derive and unify the modelling of the temperature response for wheat phenological development and initiation and expansion of leaves, nodes, tillers, stem, grain and roots using a non-linear function ($f(T)$ ¹⁵ (Fig. 4a and equation 1). If such a temperature response represents the crop's development of sink capacity¹³, leaf photosynthesis under current CO₂ levels, typical radiation and stress-free conditions should closely follow this response, with T_{opt} around 27.7 °C (Fig. 4c), although the T_{opt} of C₃ crops such as wheat may increase under higher CO₂ concentrations and light intensities when photorespiration is suppressed¹⁶.

Data on Q_{10} (the factor by which the rate of a process increases when temperature is raised by 10 °C) for various species living in a wide temperature range¹⁷ enabled us to derive cardinal temperatures for respiration using the $f(T)$ equation (Fig. 4c). This new function can accurately simulate the decline in Q_{10} with increasing temperature (Fig. 5), and is similar to that estimated for *Eucalyptus pauciflora*¹⁸. This clearly demonstrates the need to replace the traditional constant Q_{10} approach to better quantify the temperature response of respiration. The rates of postanthesis development calculated with data from experiments in outdoor climate chambers¹⁹ and the HSC experiment, together with the $f(T)$ equation, enabled derivation of the cardinal temperatures of postanthesis development (Fig. 4b). The rate of postanthesis development increases with temperature up to 25–30 °C^{20,21}.

We used the derived response functions for photosynthesis and respiration combined with the Soil Plant Atmosphere Systems Simulation (SPASS) canopy photosynthesis and growth model²² to generate the temperature response for RUE (Supplementary

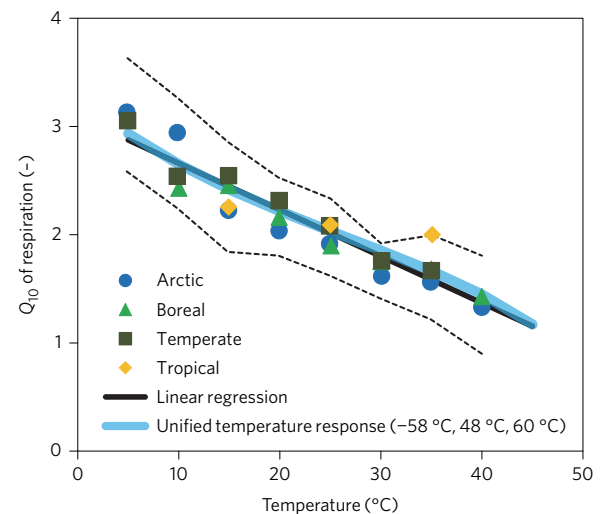


Figure 5 | Comparison of Q_{10} for respiration derived from the temperature response function in Fig. 4c to the temperature dependence of the Q_{10} of foliar respiration rates¹⁷. Closed symbols are mean Q_{10} of foliar respiration rate of species of arctic (circles, 49 species), boreal (triangles, 24 species), temperate (squares, 50 species) and tropical (diamonds, 3 species) biomes taken from literature¹⁷. Black dashed lines indicate ± 1 s.d. of all observations across biomes¹⁷. A single linear regression was fitted to all experimental data (solid black line). The Q_{10} of the respiration rate derived using the non-linear function equation $f(T)$ (equation 1), together with parameters in Fig. 4c, is shown (thick blue line). Data are reproduced with permission¹⁷.

Fig. 2a, Fig. 4d). The emergent response showed a T_{opt} of 20 °C, T_{min} of –1 °C and T_{max} of 35 °C under moderate to high radiation, but T_{opt} shifted towards lower temperatures under low radiation (data not shown), giving a wider T_{opt} range (Supplementary Fig. 2a). The same $f(T)$ equation with these derived cardinal temperatures for RUE (Fig. 4d) is able to explain 99% of the variance of the emergent responses generated from the SPASS model (Supplementary Fig. 2b).

The derived temperature response functions captured real responses well, compared to the preanthesis developmental rates reported¹³ and calculated from the HSC experimental data (Fig. 4a), postanthesis developmental rates estimated from an additional data set for a winter wheat cultivar grown in outdoor climate chambers²³ (Fig. 4b) and measured leaf photosynthesis rates²⁴ (Fig. 4c). Pooling all data, the derived response functions explained 84% (for postanthesis development) to 95% (for seedling elongation) of the variation in the rates calculated from measured data (Supplementary Fig. 3). The derived temperature function for RUE (Fig. 4d) matched the response of maximum net biomass growth rates calculated from the HSC and that of the maximum RUE calculated from LAI, biomass and radiation interception for two additional data sets for winter wheat grown in the field in the North China Plain (NCP)²⁵ and in outdoor climate chambers¹⁹. A comparison of the net biomass growth rate and RUE for the NCP and outdoor climate chamber experiments (Supplementary Fig. 4) demonstrated that under the current CO₂ level, RUE for biomass growth under conditions free of other stresses follows the temperature response shown in Fig. 4d, representing the upper boundary of the calculated RUE across a wide temperature range, and is consistent with previous studies²⁴. Except for the responses of daily biomass growth and RUE where daily average temperatures are used, use of subdaily temperatures and canopy temperatures may further improve the simulated response.

Improvement in wheat yield simulations. Implementation of the derived temperature response functions in APSIM and

Table 1 | Model improvement statistics for simulation of days to maturity, above-ground biomass, grain yield and grain number in the independent IHSGE data after implementation of the new temperature response functions of phenological development and biomass growth (RUE) in four wheat models: APSIM, SiriusQuality, SALUS and WheatGrow.

Model	Grain yield		Total above-ground biomass		Days to maturity		Grain number	
	Original model	Improved model	Original model	Improved model	Original model	Improved model	Original model	Improved model
RMSE	(t ha⁻¹)	(t ha⁻¹)	(t ha⁻¹)	(t ha⁻¹)	(d)	(d)	(grain m⁻²)	(grain m⁻²)
APSIM	2.99	1.23	5.91	2.38	12.3	8.3	4,647	3,732
SiriusQuality	1.05	0.67	2.89	1.84	11.1	11.8	4,046	2,886
Salus	2.00	0.88	2.56	1.85	10.1	10.7	NA	NA
WheatGrow	2.43	1.98	5.47	2.95	1.4	3.6	NA	NA
EF	(—)	(—)	(—)	(—)	(—)	(—)	(—)	(—)
APSIM	−1.91	−0.09	−1.53	0.32	−0.10	0.62	−1.63	−0.78
SiriusQuality	−0.02	0.66	−0.14	0.46	0.32	0.41	−1.52	−0.06
Salus	0.05	0.56	0.53	0.63	0.37	0.62	NA	NA
WheatGrow	−1.73	−0.58	−1.48	−0.71	0.99	0.93	NA	NA

NA, not available. Grain number was not simulated by the two models.

SiriusQuality improved the simulation of wheat phenological development, biomass growth and grain yield across growing temperatures from 15 to 32 °C compared with data from both HSC experiments and the independent IHSGE global experiment (Fig. 3). For HSC, only the postanthesis development rates were used to derive $f(T)$ so that data can be considered as semi-independent. Compared with the original models, the root mean squared relative error (RMSRE) of the models for grain yield with the derived temperature responses was reduced by 58% (from 58 to 24%) and 53% (from 53 to 25%) for APSIM and SiriusQuality, respectively, against the HSC data. The error reduction for the IHSGE data set was 60% (from 100 to 39%) and 39% (from 31 to 19%) for APSIM and SiriusQuality, respectively.

The improved temperature functions were tested further using two additional models (system approach to land use sustainability (SALUS) and WheatGrow) with the multi-environment IHSGE experimental data (Table 1). Improvements in simulating total biomass and grain yields were demonstrated in all four models, with a reduction in root mean squared error (RMSE) by 28–60% for biomass and 19–59% for grain yield. Less improvement was achieved for modelling phenological development for both models, possibly due to an over-fitting of the original models as phenological data were provided to modellers and models were not fully recalibrated after the implementation of the improved equations. The four improved models had a larger modelling efficiency for both total biomass and grain yield (Table 1), indicating that they better captured the variations of these variables to temperature. We conclude that the common equation $f(T)$ with different parameters for different processes is able to simulate the temperature responses of major physiological processes in wheat and may be potentially applied to other crops to increase certainty in simulating crop yield under climate change^{13,14}.

Discussion

With the increased applications of process-based crop models to address genotype × environment × management interactions as they impact on yield under climate change, the science underpinning a model for simulation of crop growth processes and yield needs to be critically examined to ensure high scientific rigor and simulation certainty. Our analyses revealed contrasting differences in the type of mathematical equations used to simulate temperature responses of the key physiological processes of wheat. Such differences are a major cause for large uncertainty in simulated wheat yields across different temperature environments. They also reflect the insufficient understanding of how key physiological processes respond to temperature at the time when the models were originally developed, many of which were only based on

limited data and local conditions. We demonstrated that by updating the temperature response functions based on newest science and data, crop models can better capture the impact of temperature change on growth processes and grain yield, unveiling a major step to improve modelling of crops under rising temperature and climate change, leading to higher skill of crop yield projections.

AgMIP has enabled a worldwide comparison of agricultural models against global datasets. The inter-comparison of 29 wheat models showed that uncertainty in simulated wheat yield from different models increases with rising temperature, which provides the background and forms the basis for our current study. Previous results from a multi-model ensemble approach for wheat^{3,5}, rice, maize and potato crops^{6,7,26} indicated that the mean simulated crop yield of a multi-model ensemble agreed reasonably well with observations, pointing to the use of a multi-model ensemble approach as an effective way of quantifying and reducing uncertainty in crop yield projections under climate change. However, such agreement will ultimately depend on how the response functions for all major physiological processes compare among the models and how closely they are to the ‘true’ response to environmental variables like temperature. Although the multi-model ensemble approach provides one useful way of uncertainty quantification, it is expensive and difficult to apply in terms of labour, timing and expertise. In addition, the ensemble approach itself does not necessarily lead to improvement in process understanding, unless a further step is taken to increase the rigor of science underpinning the process submodules by improving algorithms in comparison to data, as demonstrated here.

Further analysis of our newly derived response functions reveals that the median responses from all 29 models closely matched the derived temperature responses for preanthesis phenological development from 0 to 30 °C, and for biomass growth rates, RUE and respiration in the range of 0 to 35 °C. However, for postflowering phenological development, the ensemble median only matched the derived responses up to 25 °C, while the median model photosynthesis response matched the derived temperature response of RUE rather than that of photosynthesis (Fig. 4e). The deviations of temperature response functions for various processes in individual models from the newly derived functions based on experimental data imply that there is no guarantee for the multi-model ensemble median or mean to provide the best yield predictor, particularly at high temperatures. Our results highlight the importance of careful ex-ante screening and evaluation of the individual models for their robustness to simulate temperature responses before they are selected in a multi-model ensemble for the purpose of reducing uncertainty in assessment of climate change impact.

Our analyses identified several key knowledge gaps. Very limited data are available to quantify wheat response to extreme temperatures, at both low and high temperature ranges. Further research is needed for the postanthesis development rate under high temperatures, where models disagree with each other and few data are available. The models that simulate photosynthesis tend to underestimate T_{opt} for this process and thus need to be reparametrized. There is still a lack of measurement data to quantify how net biomass growth rate responds to temperature, and to verify simulated RUE response to temperature. More generally, variations in vapor pressure deficit among environments could introduce noise in the temperature response due to differences in evaporative cooling confounding the association between air and actual plant temperature and thereby reduce the certainty of prediction. Pollination, sterility or abortion of plant organs as affected by abnormal temperatures have rarely been simulated, but can become important under rising temperature and thus need more attention. While our current analyses focus only on temperature, interactions with other climate drivers will also need to be addressed, for example, interactions with photoperiod on flowering, with radiation on growth rate, and with CO_2 concentration change under stressed and non-stressed conditions.

Methods

Inter-comparison of temperature responses in wheat crop models. Twenty-nine physiologically based wheat crop models previously used in the AgMIP-Wheat project⁸ (Supplementary Table 1, Supplementary Dataset) were compared in terms of how the key temperature-responsive physiological processes are simulated. The different approaches used in the models are summarized in Supplementary Table 2 and Extended Database 1. The algorithms used in these models were extracted and the temperature response equations for key developmental and growth processes were categorized based on whether the cardinal temperatures (minimum T_{min} , optimum T_{opt} and maximum T_{max}) are defined and if so how. For phenology and biomass four temperature types were identified (Fig. 1, Supplementary Fig. 1 and Supplementary Table 3).

Comparison of model performance against data from the HSC experiment. The 29 wheat models were tested against field data from an HSC experiment in which the spring wheat cultivar Yecora Rojo was grown with different sowing times and artificial infrared heat treatments under field conditions at Maricopa, Arizona, United States (33.07° N, 111.97° W, 361 m above sea level (a.s.l.))^{9,27}. Yecora Rojo is of short stature, requires little to no vernalisation, has a low photoperiod sensitivity and matures early²⁸. All crops were well watered and fertilized with temperature being the most variable factor.

The inter-comparison of model performance was part of the AgMIP-Wheat project, with four steps and different levels of available information for model calibration⁸. The results used in this study (Figs 2 and 3) were simulation results from all models that were calibrated against observed phenology (flowering and maturity dates) from all treatments, together with the in-season and final, total above ground, leaf, stem, grain dry mass and nitrogen and LAI from the highest yielding treatment, that is, simulation step D “Blind test with calibrated highest yield”⁸.

The HSC data set was also used to assess the uncertainty in the multi-model ensemble due to different types of temperature response functions for phenological development, LAI, biomass growth and grain yield (see below).

Evaluation of wheat models against global multi-site experiments. The 29 wheat models were also evaluated against data from the IHSGE carried out by CIMMYT (therefore referred to as IHSGE dataset) that had seven temperature environments, including time-of-sowing treatments^{11,12}, in the absence of water and nutrient stresses and free of pests and diseases. The IHSGE experiments included two spring wheat cultivars (Bacanora 88 and Nesser) grown during the 1990–1991 and 1991–1992 winter cropping cycles at hot, irrigated and low latitude sites in Mexico (Ciudad Obregon, 27.34° N, 109.92° W, 38 m a.s.l.; and Tlatizapan, 19.69° N, 99.13° W, 940 m a.s.l.), Egypt (Aswan, 24.1° N, 32.9° E, 200 m a.s.l.), India (Dharwar, 15.49° N, 74.98° E, 940 m a.s.l.), the Sudan (Wad Medani, 14.40° N, 33.49° E, 411 m a.s.l.), Bangladesh (Dinajpur, 25.65° N, 88.68° E, 29 m a.s.l.) and Brazil (Londrina, 23.34° S, 51.16° W, 540 m a.s.l.)^{11,12,29}. Experiments in Mexico included normal (December) and late (March) sowing dates. Bacanora 88 has moderate vernalisation requirement and low photoperiod sensitivity and Nesser has low to no vernalisation requirement and photoperiod sensitivity. All experiments were well watered and fertilized, with temperature being the most important variable. Variables measured in the experiment included plants m^{-2} , total above-ground biomass at 50% anthesis, days to 50% anthesis, days to physiological

maturity, final total above-ground biomass, grain yield, spikes m^{-2} , grains spike⁻¹ and average single grain mass at maturity.

Model inter-comparison was carried out using standardized protocols and one step of calibration⁸. These experimental data were not publicly available and were therefore used in a blind test. Sowing dates, anthesis and maturity dates, soil type characteristics and weather data for all sites, years and cultivars were supplied to the modellers. Crop growth data were supplied only for one site (at Obregon) in one year; all other crop growth data were held back and not supplied to modellers. The IHSGE dataset was also used to assess the uncertainty of the multi-model ensemble due to different types of temperature response functions for phenological development, LAI, biomass growth and grain yield (see below). None of these data were used to derive the improved temperature response functions.

Evaluation of the impact of various temperature response functions on simulation results. In order to demonstrate the impact of the temperature response types used in different wheat crop models on simulated phenology, total above-ground biomass and grain yield, the four major types of temperature responses summarized from the models (Supplementary Table 3) were implemented in the APSIM and SiriusQuality models. These two models were chosen because they were built with different types of temperature response functions (Supplementary Table 3) and use different approaches to simulate phenology (progress to flowering by calculating the duration of phases between significant events on the shoot apex versus tracks development through leaf appearance, using the prediction of final main stem leaf number), canopy expansion (branching versus individual phytomer-based approaches) and biomass growth (radiation use efficiency of whole canopy versus individual canopy layers). For phenology, we also separated the response type 4 into linear and curvilinear responses, resulting in a total of 20 temperature (4 × 5) response type combinations for models using RUE (Supplementary Table 3). The two modified models were executed against the HSC and IHSGE experimental data. For any given observed grain yield, the simulated yield ranges from the multi-model ensemble (of the 29 wheat models), the APSIM and SiriusQuality models (each with the 20 combinations of temperature response functions), were calculated. The ratios of the simulated ranges of the APSIM and SiriusQuality with the 20 combinations of temperature response functions to those of the multi-model ensemble were used to estimate how much variations in the multi-model ensemble ranges were explained by each of the models together with the variations in temperature functions.

New temperature response functions of wheat physiological processes derived based on data. The Wang–Engel curvilinear temperature response function used to model wheat phenology¹³ in the SPASS-Wheat model³⁰ was found to be accurate and flexible in simulating the temperature responses of wheat plants^{31,32}. It has been successfully applied in modelling leaf development and phenology of wheat^{31,32}, maize³³, rice³⁴ and potato crops³⁵.

The Wang–Engel temperature function constructs a curvilinear response based on T_{min} , T_{opt} and T_{max} of the simulated process. These three cardinal temperatures determine the shape of the response curve, so they have clear biological meanings. Once the cardinal temperatures are known, no extra parameters are needed in the model. It simulates the effect (0–1) of temperature between T_{min} and T_{max} as:

$$f(T) = \left(\frac{2(T - T_{\text{min}})^{\alpha}(T_{\text{opt}} - T_{\text{min}})^{\alpha} - (T - T_{\text{min}})^{2\alpha}}{(T_{\text{opt}} - T_{\text{min}})^{2\alpha}} \right)^{\beta};$$

$$\alpha = \frac{\ln 2}{\ln \left(\frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{opt}} - T_{\text{min}}} \right)}, \beta = 0 \sim 1 \quad (1)$$

An extra shape factor β was added here in equation (1) to account for temperature responses with more extended T_{opt} (for example, for RUE at low radiation). For all processes, $\beta = 1.0$ was used to describe temperature responses, except for RUE where $\beta = 0.8$ was used to reflect the different shape of the RUE response curve compared to other physiological processes.

The cardinal temperatures derived for using equation (1) to simulate temperature responses of various processes are given in Fig. 4. For phenological development, the cardinal temperatures were derived from published data on seedling elongation and preanthesis development¹³ and postanthesis development^{10,23} (see below). For photosynthesis under current CO_2 , the cardinal temperatures of preanthesis phenological development were used assuming it mimics the development of sink capacity. For respiration rate, equation (1) with $\beta = 1.0$ was used to derive the average Q_{10} (the factor by which the respiration rate increases when temperature is raised by 10 °C) of respiration rate at different temperatures from 5 to 45 °C with 5 °C interval. A genetic algorithm was applied to optimize the three cardinal temperatures (T_{min} , T_{opt} and T_{max}) to match the derived average Q_{10} to the Q_{10} estimated at the corresponding temperatures known from the literature¹⁷ (Fig. 5). Finally, for RUE the cardinal temperatures were derived from simulation results using the SPASS canopy photosynthesis and growth model, together with the derived temperature functions for photosynthesis and respiration (see below). All rates were normalized at 20 °C.

Calculation of pre- and postanthesis development rates from data. Preanthesis development rates were calculated from the HSC experiment. The rates of leaf emergence were estimated as the slope of the decimal number of emerged leaves (Haun index³⁶) measured at least twice a week against days from seedling emergence³⁷. The rate of development towards anthesis was calculated as the reciprocal of the duration from emergence to anthesis. The rates of seedling elongation for seven spring wheat cultivars grown in growth chambers with different temperature were also obtained from a recent data synthesis¹³.

Postanthesis rate of development was calculated as the reciprocal of the time from anthesis to physiological maturity from the HSC data¹⁰ and experiments carried out at INRA Clermont-Ferrand, France (44.78° N, 3.17° E, 329 m a.s.l.) with the winter wheat cultivar Thésée, grown during the 1993–1994 and 1997–1998 winter cropping cycles in outdoor climate chambers under well-watered and fertilized conditions with postanthesis mean daily temperature ranging from 12.6 to 24.7 °C²³. In the HSC experiment, physiological maturity was judged when the endosperm of grains became firm and almost dry. In the INRA experiments, physiological maturity was calculated as the time when 95% of final grain dry mass was reached by fitting a three-parameter logistic function equation to grain dry mass data plotted against the number of days after anthesis²³.

The calculated postanthesis rate of development from the HSC data was the only data used for derivation of temperature response functions shown in Fig. 4. No data from the IHSGE dataset were used in the derivation of temperature functions. Therefore, for model testing, the IHSGE dataset is fully independent data, while the HSC dataset is semi-independent.

Derivation of the emergent temperature response for RUE using a canopy photosynthesis and growth model. Simplified versions of the canopy photosynthesis and growth submodels in the SPASS-Wheat model³⁰, together with the derived temperature response functions for photosynthesis and respiration rates (Fig. 4c), were used to calculate the net biomass growth rate of a wheat canopy and derive the cardinal temperatures and shape parameter of the RUE temperature response function (Supplementary Fig. 2). The model integrates leaf level photosynthesis rate to canopy level. It also calculates the growth and maintenance respiration, then the net assimilation and net biomass growth. All the parameter values used in the simulations are given in Supplementary Table 4.

We assumed a wheat canopy at an early developmental stage with an LAI of 3 m² m⁻² and a total above-ground biomass of 3 t ha⁻¹. For any new growth, 20% of assimilate would be partitioned to roots and 80% to the above ground parts. In the simulations, we used 47 years (1957–2003) of daily climate data from Birchip in Victoria of Australia to simulate the daily RUE of the wheat canopy in the absence of water and nutrient stresses. This gave us a daily global radiation range from 10 to 32 MJ d⁻¹ and a daily mean temperature range of 3.6–36 °C. We also executed the model for an extra range of daily mean temperature from –5 to 5 °C to generate the daily net above-ground biomass growth rate. RUE was calculated for different daily temperatures as the net above-ground biomass growth rate divided by the radiation intercepted by the canopy.

Calculation of net biomass growth rate and radiation use efficiency under different temperatures. Net biomass growth rate was calculated from the HSC data as the ratio of total above-ground biomass at maturity divided by the number of days from crop emergence to physiological maturity. Measurement data on dynamics of LAI and total above-ground biomass from the INRA experiments described above¹⁹ and from five experiments where the winter wheat cultivars SJZ8 and SJZ15 were grown during the 2004–2005, 2005–2006, 2006–2007 and 2009–2010 winter cropping cycles at Wuqiao, NCP (37.41° N, 116.37° E, 20 m a.s.l.), with ample water and nitrogen supply²⁵, were used to calculate RUE under different temperatures.

In the INRA experiments, LAI and total above-ground biomass were measured every 4–8 days starting at anthesis. Only dates when LAI was higher than 2.5 m² m⁻² were used (that is, before the onset of the phase of rapid canopy senescence), leaving measurements from five to six dates with which to calculate the net biomass growth rate and RUE. Daily radiation interception was calculated as total incident radiation times (1-exp(-K_L × LAI)), where K_L (0.7 m² ground m⁻² green leaf) is the light extinction coefficient. RUE was calculated as the slope of total above-ground biomass versus the cumulative radiation interception and the average net biomass growth rate was calculated as the slope of total above-ground biomass versus the number of days after anthesis.

In the NCP experiments, LAI and total above-ground biomass were measured before wintering, at greening and at jointing, booting, anthesis and 10 days after flowering and at maturity. Daily increases in LAI were estimated through best fit polynomial equations to the data. Daily radiation interception was calculated as for the INRA experiments but using total incident radiation estimated from sunshine hours. The cumulative radiation interception for each period was calculated as the sum of daily radiation interception. RUE for each period (from jointing onwards) was calculated as the net biomass increase divided by the total radiation interception and the average net biomass growth rate was also calculated for each period (from jointing onwards) as the net biomass increase divided by the total number of days.

Calculation of daily mean temperature. Daily mean air temperature (T_t) in the HSC and IHSGE experiments was calculated as the sum of eight contributions of a

cosine variation between daily maximum (T_{max,daily}) and minimum (T_{min,daily}) daily air temperatures³⁸:

$$T_t = \frac{1}{8} \sum_{r=1}^{r=8} T_h(r) \quad (2)$$

$$T_h(r) = T_{\min,daily} + f_r (T_{\max,daily} - T_{\min,daily}) \quad (3)$$

$$f_r = \frac{1}{2} \left(1 + \cos \frac{90}{8} (2r - 1) \right) \quad (4)$$

where T_h(°C) is the calculated 3-h temperature contribution to estimated daily mean temperature and *r* is an index for a particular 3-h period.

Evaluation of the improved temperature response functions. We tested the performance of the new temperature response functions on how accurately they capture the rates of the phenological development, tissue expansion, photosynthesis and biomass growth (RUE) measured or derived from experimental data at a range of temperatures. This was done by comparing the rates calculated using the derived functions (Fig. 4) at a given temperature against the corresponding measured rates from the experiments at the same temperature (Supplementary Figs 3 and 4). Significance of the relationship was tested and the coefficient of determination (R²) was used to see how much variation in the measurements could be explained by the new temperature functions.

Evaluation of the improved skills of four wheat models when using the new temperature responses. To test the improvement by using the improved temperature response functions, they were also implemented into the APSIM, SiriusQuality, SALUS and WheatGrow models, replacing their original functions. The simulation results were then compared with the measurements (Fig. 3, Table 1). These four models were chosen to have good representation of different temperature response functions for phenological development and biomass growth and thus to generalize the improvement in wheat model skills when they use the temperature response function we derived. One of the models (WheatGrow) uses a photosynthesis and respiration approach to model biomass growth, while the other three use a RUE approach.

Many different measures of the discrepancies between simulations and measurements have been proposed³⁹. We concentrated on three measures to highlight different aspects of the quality of simulation with the original and improved models. All measures are based on mean squared error (MSE), where the mean is over all measurements of a particular variable. The RMSE is the square root of MSE; it has the advantage to express errors in the same units as the variable. RMSE was calculated as:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (5)$$

where *y_i* is the observed value of the *i*th measured treatment, *ŷ_i* is the corresponding simulated value and *N* is the total number of treatments.

For comparing very different growth environments likely to give a broad range of crop responses, the relative error can be more meaningful than the absolute error, so the RMSRE was also calculated because of the very wide range of total above-ground biomass and grain yields in both the HSC and IHSGE datasets. RMSRE was calculated as:

$$\text{RMSRE} = 100 \times \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{y_i - \hat{y}_i}{y_i} \right)^2} \quad (6)$$

Finally, the Nash–Sutcliffe model efficiency⁴⁰ (EF) is a distance measure that compares model MSE with the MSE of using the average of measured values as an estimator. Therefore, EF is useful for making statements about the skill of a model relative to this simple reference estimator. For a model that simulates perfectly, EF = 1, and for a model that has the same squared error of simulation as the mean of the measurements, EF = 0. EF is positive for a model that has a smaller squared error than the mean of the measurements. EF was calculated as:

$$\text{EF} = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N (y_i - \bar{y})^2} \quad (7)$$

where \bar{y} is the average over the *y_i*.

Data availability. The data extracted from the models to describe their temperature functions are provided in Supplementary_Data_Set_D1 in Excel format. The experimental data used to calibrate and validate the models are available in Harvard Dataverse with the identifiers “10.7910/DVN/1WCFHK”⁴¹ for and IHSGE data and “10.7910/DVN/ECSFZG”⁴² for the HSC data.

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E.W., P.M., S.A. and F.E. motivated the study; E.W. and P.M. designed and coordinated the study, and analysed the data; E.W., P.M., Z.Z., A.M., L.L. and B.B. conducted model improvement simulations; E.W., P.M., S.A., F.E., Z.Z., A.M., R.P.R., K.A., P.D.A., J.A., C.B., D.C., A.J.C., G.D.S., J.D., E.F., M.G.-V., S.G., G.H., L.A.H., R.C.I., M.J., C.D.J., K.C.K.,

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Competing interests

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Erratum: The uncertainty of crop yield projections is reduced by improved temperature response functions

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In the original version of this Article, the author information was incorrect. Enli Wang and Pierre Martre contributed equally to this work. Davide Cammarano has a present address: James Hutton Institute, Invergowrie, Dundee DD2 5DA, Scotland, UK. Reimund P. Rötter has a former affiliation: Natural Resources Institute Finland (Luke), 00790 Helsinki, Finland. This has now been corrected.

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The uncertainty of crop yield projections is reduced by improved temperature response functions

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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.bsye.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@igsnr.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
<i>SiriusQuality</i> (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.												
Model	Development				Biomass accumulation		Canopy expansion/senescence			Heat stress response		
	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-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-Ta(0,15,30,35)	-	-	-	TT-Ta(-10,∞,-,-)	-	-	-
LPmL	-	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,Thc(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 temperature; 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 curvilinearly (~) 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 temperatures T1,T2,T3, and T4.

^c RUE-T or RUE~T(T1,T2,T3,T4), RUE approach linearly (-) or curvilinearly (~) related to temperature, with the cardinal temperatures T1,T2,T3, and T4; TE-T or TE~T(T1,T2,T3,T4), transpiration efficiency approach linearly (-) or curvilinearly (~) related to temperature; Ps-T or Ps~T(T1,T2,T3,T4) photosynthesis rate linearly (-) or curvilinearly (~) related to temperature; 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-Q₁₀^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 temperatures 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-Q₁₀^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 calculated as a linear or curvilinear function of temperature with the cardinal temperatures 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.

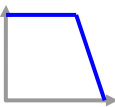
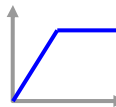
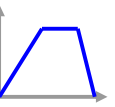
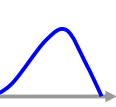
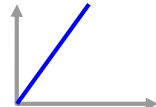
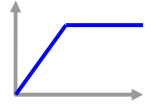
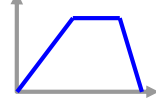
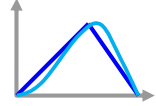
^g TT-T or TT~T(T1,T2,T3,T4) - leaf senescence follows thermal time TT calculated as a linear or curvilinear function of temperature with the cardinal temperatures T1,T2,T3, and T4, T> Tv - Leaf senescence is enhanced when certain temperature goes beyond the defined threshold Tv, (Q10)^{Tc} - leaf senescence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

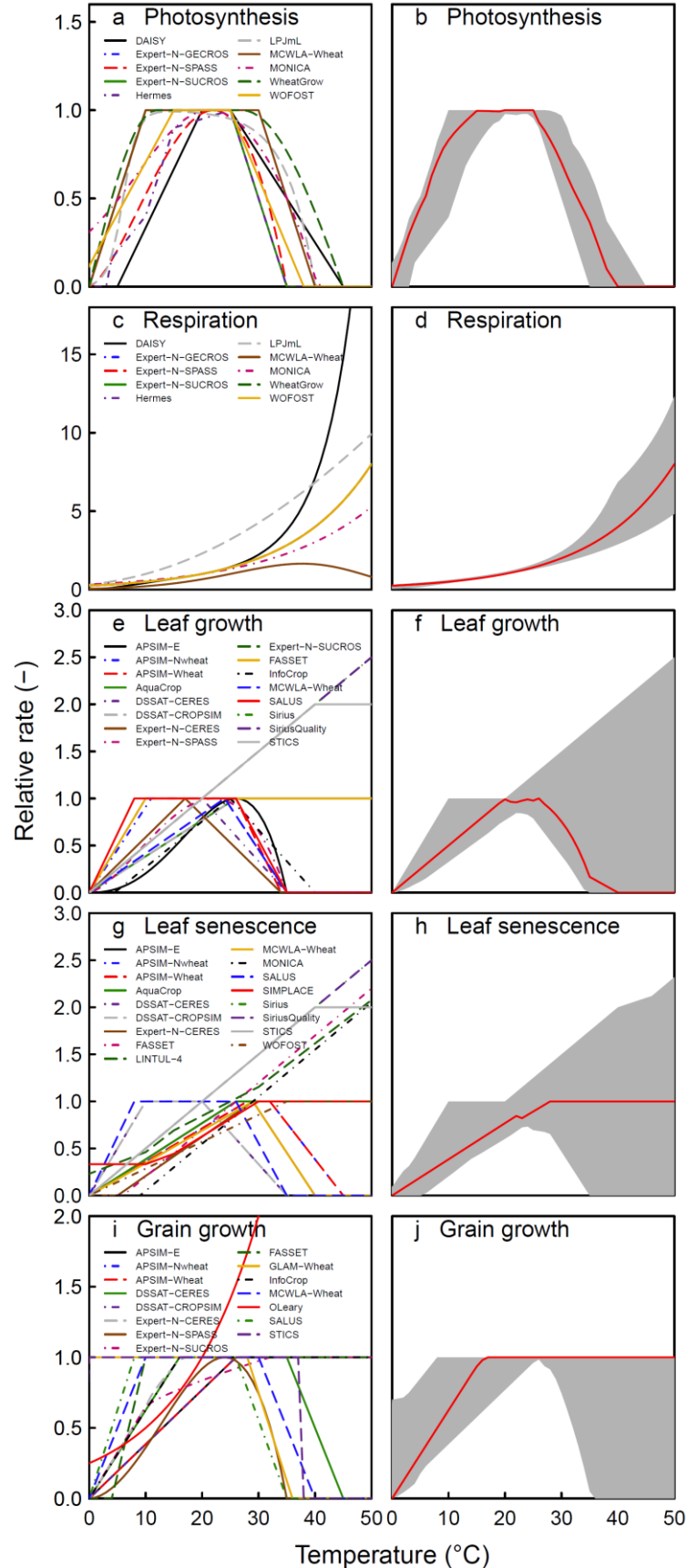
Supplementary Table 3 | The four main temperature response types for pre-anthesis phenological development and radiation use efficiency (RUE) used in the wheat models analysed in this study. For the models that explicitly simulate photosynthesis and respiration, they are grouped based on the temperature 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.

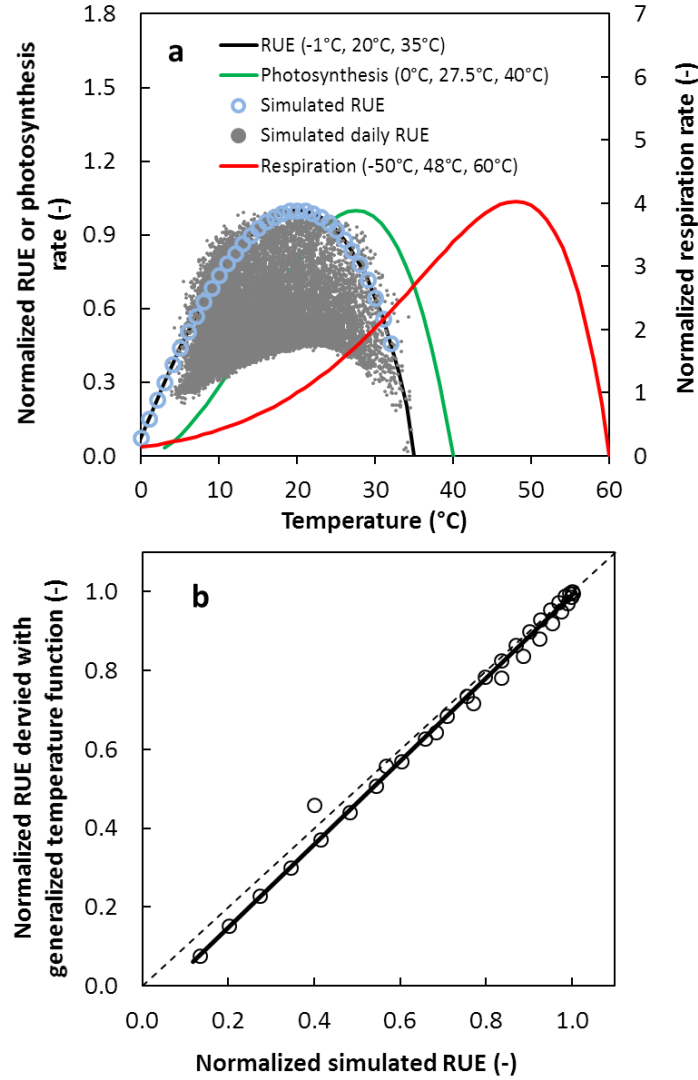
<div> <div>RUE</div> <div>Pre-anthesis phenological development</div> </div>	Type 1 – No reduction towards base temperature	Type 2 – No maximum temperature	Type 3 – A range of optimal temperatures	Type 4 - Minimum, optimum and maximum temperatures	Photosynthesis and Respiration
	$(\infty, \infty, 25^{\circ}\text{C}, 35^{\circ}\text{C})$ 	$(0^{\circ}\text{C}, 20^{\circ}\text{C}, \infty, \infty)$ 	$(0^{\circ}\text{C}, 15^{\circ}\text{C}, 20, 35)$ 	$(0^{\circ}\text{C}, 20^{\circ}\text{C}, 35^{\circ}\text{C})$ 	
Type 1 - No optimum and maximum $(0^{\circ}\text{C}, \infty, \infty, \infty)$ 		FASSET	O'Leary	SIRIUS <i>SiriusQuality</i>	HERMES LPJmL MONICA Expert-N-SUCROS
Type 2 - No maximum temperature $(0^{\circ}\text{C}, 25^{\circ}\text{C}, \infty, \infty)$ 		Aquacrop EPIC-Wheat	SALUS DSSAT-CERES DSSAT-CROPSIM LINTUL-4	STICS	WOFOST
Type 3 - A range of optimum temperatures $(0^{\circ}\text{C}, 25^{\circ}\text{C}, 35^{\circ}\text{C}, 45^{\circ}\text{C})$ 	GLAM-Wheat		APSIM-Nwheat Cropsyst Expert-N-CERES		
Type 4- Min, optimum & max temperature $(0^{\circ}\text{C}, 25^{\circ}\text{C}, 35^{\circ}\text{C})$ 			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 model⁶⁹.

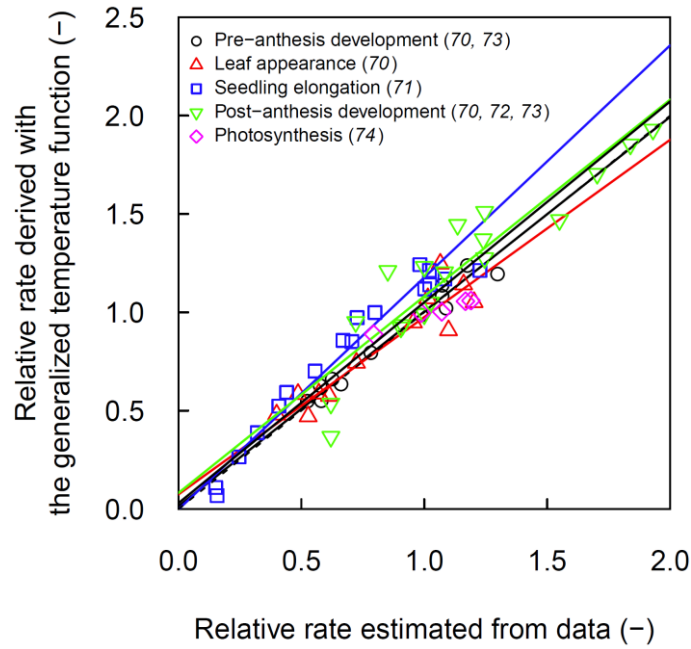
Parameter	Value	Unit	Explanation
AMAX	40	kg CO ₂ ha ⁻¹ h ⁻¹	Maximum photosynthesis rate of leaf
EFF	0.6	g CO ₂ J ⁻¹	Light use efficiency at low light
K_L	0.7	m ² ground m ⁻² leaf	Radiation extinction coefficient of leaf canopy
Γ	73.6	mg CO ₂ m ³ air	CO ₂ compensation point
DarkResp	0.03	g CO ₂ g ⁻¹ d ⁻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.

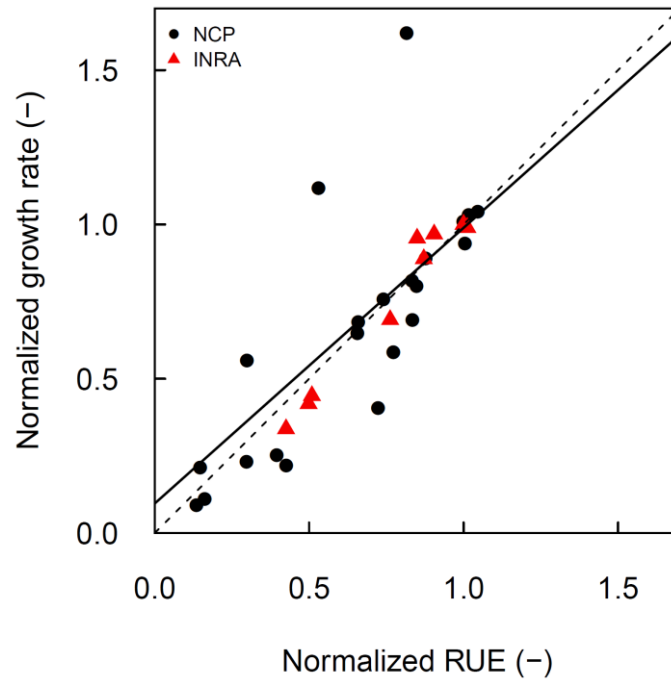




Supplementary Figure 2 | Radiation use efficiency (RUE) temperature dependency derived from photosynthesis and respiration. (a) RUE temperature response functions averaged under low (10 MJ m⁻² d⁻¹; circles) and high (30 MJ m⁻² d⁻¹; blue circles) conditions, and RUE under various (grey dots) radiation conditions calculated with the SPASS photosynthesis and plant growth model⁶⁹. 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 $\beta = 1.0$ 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 sources⁷⁰⁻⁷⁴ 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 NCP⁷⁵ (black circles) and outdoor semi-controlled environment⁷² (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.

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