Proceedings

of the Workshop
Modeling Wheat
Response to High
Temperature

P.D. Alderman, E. Quilligan, S. Asseng, F. Ewert, and M.P. Reynolds (Editors)

CIMMYT, El Batan, Texcoco, Mexico
June 19-21, 2013
Proceedings
of the Workshop on
Modeling Wheat Response to High Temperature
P.D. Alderman, E. Quilligan, S. Asseng, F. Ewert, and M.P. Reynolds
Editors

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Abstract: The abstracts herein are of presentations by experts participating in the workshop “Modeling Wheat Response to High Temperature”. Sponsored by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and in collaboration with the University of Florida, University of Bonn, and the Agricultural Model Intercomparison and Improvement Project (AgMIP).
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Workshop Program  
Modeling Wheat Response to High Temperature (June 19-21, 2013)  
CIMMYT, El Batan, Texcoco, Mexico

Wednesday 19th June

8:00-8:30am  Registration, Borlaug Building, outside Sasakawa room

8:30-12:30  Welcome and Client Perspectives on Wheat Modeling (Chair Matthew Reynolds)

- Welcome Address (Matthew Reynolds and Senthold Asseng)
- Beyond modelling wheat physiology: what do system agronomists need? (Santiago Lopez-Ridaura)
- A Breeders’ wish list for the Wheat AgMIP modeling initiative (Karim Ammar)
- Modeling wheat cultivars for global warming: A gap analysis (Matthew Reynolds)
- Global Futures (Daniel Mason-D’Croz)
- CGIAR Research Program on Climate Change, Agriculture and Food Security (Andy Jarvis)

1:30-5:00  Wheat Physiological Response to High Temperature (Chair Vara Prasad)

- Exposing wheat to a wide range of temperatures: The Hot Serial Cereal Experiment (Bruce Kimball)
- Ecosystem warming affects mass and energy exchange processes in spring wheat (Gary Wall)
- What physiological traits should we focus on in breeding for heat tolerance? (Mariano Cossani)
- How high temperature affects wheat growth and development (Karine Chenu)
- Impact of season-long and short-episodes of high temperature stress on growth and development of wheat (Vara Prasad)

5:00-7:00  Reception at CIMMYT Guest House

Thursday 20th June

8:00-2:00  Documentation of wheat model temperature algorithms (Chair Jeff White)

- APSIM-Wheat-E (Enli Wang)
- APSIM-Nwheats (Senthold Asseng)
- AQUACROP (L. Garcia-Vila)
- APSIM-wheat (Peter Thorburn)
- CropSyst (Claudio Stöckle)
- DSSAT-CROPSIM-wheat (L.A. Hunt)
- EPIC wheat (Kaiguang Zhao)
- FASSET (J. Doltra)
- GLAM-wheat (Ann-Kristin Koehler)
- HERMES (Kurt Christian Kersebaum)
- InfoCrop (S. Naresh Kumar)
- LINTUL (Joost Wolf)
- Lobell (David Lobell)
- LPJmL (Katharina Waha)
- MCWLA-Wheat (Fulu Tao)
• MONICA (Class Nendel)
• Expert-N (Christian Biernath)
• O’Leary-model (Garry O’Leary)
• SALUS (Bruno Basso)
• Simplace (Ehsan Rezaei)
• SiriusQuality (Pierre Martre)
• STICS (G. De Sanctis)
• WheatGrow (Yan Zhu)
• WOFOST (Taru Palosuo)

2:00-8:00  *Excursion to Teotihuacan and dinner at La Gruta restaurant*

**Friday 21st June**

8:30-12:00  *Sources of errors in simulating the HSC dataset (Chair Peter Thorburn)*

• Causes of errors (Senthold Asseng)
• Model Improvement Discussion (Peter Thorburn)

1:00-5:00  *AgMIP Wheat Closed Session (Chair Senthold Asseng)*

• Outlining HSC simulation paper
• Next Steps for AgMIP-Wheat: the International Heat Stress Genotype Experiment (Phillip Alderman)
### List of participants

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Climate change is happening all around us. Since 1980, average maximum temperatures during the growing season have increased between 0.6 and 3 °C for major wheat producing areas in the Indo-Gangetic Plains (IGP) and other parts of Asia (Lobell and Gourdji 2012). While many uncertainties remain regarding the extent and impact of climate change, there is broad agreement among climate scientists that temperatures around the globe will continue to increase. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report showed a general trend of warming over Sub-Saharan Africa, IGP, and Latin America over the next 100 years, based on results from 21 climate models (IPCC 2007). Further, Battisti and Naylor (2009) suggest that there is a high probability (>90%) that by the end of this century, growing season temperatures will exceed the most extreme seasonal temperatures recorded in the past century. For the IGP, current climate projections show increases of 0.6-3.1 °C beyond current temperatures by 2050 (New et al. 2012). These temperature increases are particularly concerning when you consider that more than half of wheat production areas worldwide already experience heat-stress-inducing temperatures during some part of the growth cycle (Cossani and Reynolds 2012). All of these findings point to the need to understand the effects that rising temperatures will have on wheat growth in the future.

The CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) and the Agricultural Model Intercomparison and Improvement Project (AgMIP) are two important international research efforts seeking to understand how climate change will affect agriculture. The approach in both CCAFS and AgMIP is fundamentally collaborative, seeking to link scientists and research institutions around the world to enhance understanding of climate change and identify strategic points for adaptation and mitigation. The CCAFS perspective is presented in more detail by A. Jarvis (these proceedings). AgMIP focuses on bringing together climate, crop, and economic modeling communities with cutting-edge information technology, to produce improved crop and economic models and provide the next generation of climate impact projections for the agricultural sector. These foci will allow AgMIP to substantially improve the characterization of world food security due to climate change and to enhance adaptation capacity in both developing and developed countries.

One key goal of the AgMIP Wheat team and the CCAFS-funded research within CIMMYT’s wheat physiology group is to improve wheat crop modeling for climate impact and mitigation assessments. The previous AgMIP Wheat pilot phase identified simulation of temperature effects as one of the largest limitations in modeling climate change impacts (Asseng et al. 2013). Thus, the objectives of this workshop include:

1) Comparing the accuracy of wheat models in development, growth, and yield formation for wheat grown in a wide range of temperature regimes.
2) Documenting and comparing temperature algorithms for models used in AgMIP Wheat.
3) Identifying promising avenues for improving representation of temperature effects within wheat models.

4) Determining new directions for wheat modeling research and development.

We trust that the body of knowledge represented in these proceedings will enhance our understanding of wheat responses to high temperatures and facilitate further discussions on improving our modeling of wheat growth under climate change.

References


Beyond modeling wheat physiology: What do system agronomists need?

Santiago Lopez-Ridaura¹, Charles Bielders², Ivan Ortiz-Monasterio¹, and Bruno Gerard¹

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Agronomic research often looks at the interaction between crops or crop varieties, the biophysical environment where they grow, and the management carried out to obtain the desired goods and services from those crops. Although empirical research has dominated in the history of agronomy, crop models have helped in the last decades to integrate knowledge and information, and formalize the main processes governing crop growth and development.

Crop specific models (i.e. wheat) have contributed greatly to comprehending the potential for crop production as well as yield variability under specific environmental and management conditions, understanding the factors responsible for the yield gap (and their inter-linkages), and providing guidelines for improved crop production. However, from an agronomic perspective, there is a great need to improve models to formalize complex cropping systems rather than single crops. This would help agronomists guide and interpret their experimental results, understand the main factors affecting cropping systems performance, design alternative cropping systems, and explore their performance under changing climatic and management conditions.

This paper highlights some of the main model improvements agronomists need from modeling colleagues to tackle the relevant questions for their work at different scales (from the plant to the cropping and farming systems), with special emphasis on wheat-based cropping systems.

Main Challenges: The agronomic needs

At the plant(s) level

Crop models have given special attention to the formalization of physiological processes of crop growth and development, which have been useful for breeders and agronomists in developing new cultivars, their recommendation domains, and optimum management techniques. However, important processes relevant for agronomists are still not fully captured by models.

Extreme heat stress has important implications for wheat grain yield because of its effects on spikelet sterility and limited grain filling. Some studies comparing empirical with modeled data have shown the underestimation of yield losses by models by up to 50% (Lobell et al. 2012). Formalizing these processes, together with the effect of severe drought at different phenological stages of crop growth, would be an important contribution of modeling to agronomic research on wheat.
Carbohydrates remobilization and nutrient translocation under different environmental conditions are also some of the issues that must be addressed by modeling as they influence grain yield and harvest index, as well as the main determinants for grain quality at harvest (e.g. protein content and hardness).

Current models seldom, if ever, allow investigation of the interactions between plants within a field, as occur for instance when changing planting geometries (i.e. in the case of irregularly spaced rows – planting on beds). These interactions occur above ground but also below ground, through competition of individual plants for light, water, and nutrients. To capture such effects, there will be a need to improve the representation of root system physiology and development, which is generally much less well represented in crop models than the above ground plant processes.

Finally, the dynamics of pest and diseases, influenced by temperature and relative humidity levels but also strongly affected by crop management, are processes that need further integration in crop models.

*Plant and soil*

Managing soils and soil fertility has a strong impact on crop development and productivity. Agronomists have for a long time worked, under experimental conditions, on the effects of different tillage, fertilization and irrigation practices (as well as crop protection methods) on the performance of crops. Models can capture some of the processes related to soil-plant interaction. However, there are still numerous important processes poorly formalized by models.

Water dynamics along the soil profile, together with nutrient availability, which are major factors driving crop development have been formalized in models. However, the effect on crop growth of processes such as soil salinization and compaction under different tillage techniques are seldom integrated into models although those processes are of great importance in most wheat growing regions of the world.

Nutrient uptake and conversion efficiencies for N, and sometimes for P, are well formalized in models, but the interaction between different nutrient levels and water availability, especially when multiple deficiencies are encountered, are still to be strengthened in the crop-soil models. In the case of N, more work needs to be done to improve simulations of nitrous oxide emissions in relation to water and N management. In addition, estimates of ammonia volatilization associated with the use of urea fertilizer not incorporated (a common practice in many agricultural systems in the developing world) should be integrated in crop models, particularly in high pH soils. Phosphorus, for example, plays an important role in early root growth, and this process need to be well formalized within models.

Depending on the crop and site, it is also important to understand the availability and use efficiency of additional macronutrients (K, Ca, Mg, and S) and micronutrients, notably Zinc and Boron in the case of wheat, as they play an important role in crop growth and grain production and quality. A study in the Indo Gangetic Plains, a major wheat production region, showed that more than 50% of cereal fields were Zn deficient (Singh 2004).

The influences of soil pH for both extreme soil acidity and alkalinity and rhizosphere bio-chemical conditions on the development of crops, especially in early growth stages, and on the acquisition of soil
nutrients, are important processes still not fully integrated into crop-soil models. Finally, the dynamics of beneficial (micro-)organisms (e.g. mycorrhizae) or soil borne diseases (including nematodes and insects) and their yield enhancing/reducing effects have also been neglected or simplified in models and further work is needed to formalize those processes under different environmental conditions and management practices.

Finally, most models currently assume the soil profile to be laterally homogeneous, for instance in terms of soil structure, moisture distribution, or nutrient distribution. Although this assumption covers a broad range of field conditions, there are many instances where this assumption is not applicable. Reduced tillage practices, for instance, generate highly heterogeneous profiles with a direct effect on root distribution and water distribution. Banded or hill-placed fertilization creates heterogeneous nutrient distribution, whereas furrow or drip irrigation and many water harvesting techniques generate heterogeneous moisture distribution. The capacity of crop models should be enhanced to cover these widely occurring conditions.

**Cropping systems**

The combination and sequencing of crops with different management practices and under different environmental conditions are of great influence on the productivity, stability, and sustainability of cropping systems. Long term on-station and on-farm trials are commonly set up by agronomists to understand the overall performance of cropping systems. However, only a few options can be evaluated in such an empirical way. Cropping systems models can be of great help to explore different (current and alternative) cropping systems and to understand the interactions between different crops and management techniques under different environmental conditions.

Especially relevant for agronomic research and development would be the availability of cropping systems models that are able to capture, on a multi-year basis, the interactions occurring in crop rotations, intercropping, green manures, and cover crops, and their effect on the long term performance of the cropping systems, and the inter-annual variability of this performance, under different environmental and management conditions.

The current expansion of conservation agriculture will require models that are better able to predict the performance of a cropping systems for different sequences of crops and specific management techniques (such as residue management, tillage, sowing and harvesting dates, and long term soil nutrients and organic matter dynamics). This will allow us to explore options for increased productivity and sustainability of cropping systems, especially in the context of large inter-annual variability of rainfall levels and rainfall distribution as well as temperature changes.

**The role of models in designing innovative cropping and farming systems**

Cropping systems models can play an important role in agronomic research and development, especially in the context of climate change and climate variability. Models might allow agronomists to understand and predict the performance of different cropping systems under a wide range of environmental and management conditions. This would help identify the recommendation domains for technological
innovations in time and space, improve targeting of technologies for different conditions, and design alternative cropping systems that improve the sustainability of rural households.

Together with insights from other disciplines, cropping systems models might strongly contribute to farm scale analysis by providing guidelines on promising activities and the best allocation of resources available at the farm (Rodriguez et al. 2007; Giller et al. 2006). At the landscape level, it would also be of great interest to develop models that take into account the redistribution of essential drivers of soil fertility and crop productivity, such as the redistribution of water, sediment, nutrients, and carbon through runoff and erosion. Similarly, at the village or regional scales, redistribution of organic inputs (e.g. feces, manure, and crop residue) should be taken into account.

Cropping systems models might be of great value when integrated within prospective ex-ante analysis of technological and policy interventions, notably when attempting to generate technologies and policies to cope the future climate situations (Lopez-Ridaura and Gerard 2012). By integrating cropping systems models into this wider agronomic research context, we might increase the chances of success of technical recommendation and the adoptability assessment of different alternative cropping systems.

Finally, to truly contribute to the decision and discussion support systems for improved technology and policy development, the inclusion of farmers and other stakeholders in the parameterization, validation, and use of cropping systems models would certainly increase their usefulness for future agronomic research.

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A Breeders’ wish list for the Wheat AgMIP modeling initiative

Karim Ammar, Matthew Reynolds, Ravi Singh, Enrique Autrique, Susanne Dreisigacker, Javier Peña, and Hans Braun

Global Wheat Program, CIMMYT

The Global Wheat Program at CIMMYT coordinates a breeding program with arguably the broadest scope of any worldwide, and its historical and present successes are extensively documented. One key activity is the continuous effort to maintain genetic resistance to the most prevalent diseases of wheat, such as the rusts, which has permitted sustained productivity on over 100 million hectares in the developing world, while maintaining steady yield potential progress (Braun et al. 2010). Genetic gains in yield during the post Green-Revolution period, as shown by evaluations of CIMMYT international yield trials at thousands of sites worldwide, have been achieved at rates of 0.5-1% from 1995 to 2010 (Ammar et al. 2008; Manes et al. 2012; Sharma et al. 2012).

Successful breeding relies on the integration of different layers of information pertaining to measurable or selectable traits, and in some cases, to the genetic basis underlying these traits (if it is known); mainly in relation to the following factors:

• Adaptation of vegetative and reproductive growths to different target latitudes and altitudes so that sensitive growth stages occur when the weather is most favorable;

• Development of plant types that balance favorable expression of yield components with lodging resistance;

• Accumulation of genes for disease resistance;

• Combination of grain compositional traits satisfying diverse grain processing characteristics and consumer preferences;

• Adaptation to specific cropping systems, such as conservation agriculture or different irrigation practices;

• Increased genetic yield potential per se;

• Adaptation to low and unpredictable rainfall;

• Resilience to cooler and warmer climates.

If modeling tools are to be useful for breeders, they need to provide either new information or information presented in a novel integrative fashion, not achieved through traditional phenotyping, in a user-friendly format. This information could assist in breeding decisions, from the planning of crosses based on parental lines genetics to the selection phase in segregating populations, and finally during the fixed line testing final step. In doing so, it is important that modelers and tool developers distinguish and prioritize their work based on the level of complexity of the range of traits managed by breeders. A good first step in building a viable relationship between modelers and breeders would be to start with a
“proof of concept”, addressing traits of relatively simple inheritance and relatively known genetic basis, such as:

5) Flowering time; assumed to be determined to a large extent by allelic composition and interactions at the Ppd and Vrn genes. This trait can be modeled based on the known and readily determined allelic composition at the few loci involved. The resulting knowledge on optimal allelic combinations to achieve optimal flowering windows (at specific locations) could be helpful in designing targeted crosses (White et al. 2008).

6) Simulation models have already been developed to determine traits that confer lodging resistance under rainfed (high rainfall) wheat conditions in the UK (Berry et al. 2007); but they have not been developed for irrigated wheat regions. The risk of lodging increases with yield potential, unless tradeoffs are made between investments in reproductive structures versus root and stem strength (Foulkes et al. 2010).

7) Many disease resistance genes have been identified. Major effect genes are not a problem for breeding programs, but accumulating several genes of minor and partial individual effects, for a more durable resistance, presents a challenge. Modeling, combined with studies quantifying the effects of these minor genes on pathogen progression, could provide breeders with a tool to plan various gene accumulation scenarios and pick the one that is most effective and easy to achieve.

8) Many quality traits and genes have also been identified. Models could provide useful tools for identifying different genetic and trait pathways that achieve acceptable functional processing and end product characteristics, based on the wealth of empirical data that is generated each year. Such tools could be used in designing crosses as well as progeny selection strategies.

Modeling for more complex traits will certainly require a more involved approach, which may be best done subsequently to those cited above. This said, it is important to point out that, to date, very little effort has been put into breeding for specific cropping systems. However, simple environmental models could be used to show, for example, how practices like residue management and zero tillage affect water or nutrient availability, and soil temperature, which would in turn infer modified breeding approaches.

Improving yield potential, drought, and heat adaptation are highly complex problems. The role of modeling for these targets is addressed by Reynolds and Alderman (these proceedings).
References


Crop simulation models can accurately predict the response of a generic crop to a range of environmental factors, such as temperature or water availability, but their ability to target suites of adaptive traits or genes to different stress profiles is still a work in progress (Chenu et al. 2009). Notwithstanding that, and the promise of molecular breeding to identify solutions based on gene modeling (Heffner et al. 2009), genetic gains have been made using stress adaptive traits to select parents and progeny (Reynolds et al. 2009). This analysis considers some of the key structure-function relationships of wheat, in order to pinpoint processes that are bottlenecks for adaptation of wheat to warmer climates, and for which simulation models could be developed.

Growth analysis and other phenotyping approaches typically consider the following structural components of a cereal plant: spikes, leaf canopy, stems, and roots; as well as the integrated function of the whole plant (Table 1). In this analysis, the principal functions for each organ are listed and classed under one of the following main categories: reproduction, metabolism, transport and storage, structural integrity, and signaling (Table 1a). All organs have functions that span more than one of these categories; we list the primary function for each organ, as well as a number of secondary functions. For example, the primary function of spikes, leaf canopy, stems, and roots is considered to be: reproduction, carbon assimilation, transport, and uptake of water and nutrients, respectively. At the whole plant level, the primary ‘function’ is a plastic response to environmental constraints reflected in overall plant size and relative allocation of resources to different plant organs.

Table 1a. Simplified structure-function matrix of wheat.

<table>
<thead>
<tr>
<th>Type of function</th>
<th>Reproduction</th>
<th>Transport &amp; storage</th>
<th>Signalling</th>
<th>Metabolism</th>
<th>Structure</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Wheat organ</th>
<th>Function</th>
<th>Secondary</th>
<th>secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spikes</td>
<td>Reproduction</td>
<td>Starch synthesis</td>
<td>Photosynthesis</td>
</tr>
<tr>
<td>Canopy</td>
<td>Photosynthesis</td>
<td>N store</td>
<td>Evaporative cooling</td>
</tr>
<tr>
<td>Stems</td>
<td>Transport</td>
<td>Reserves</td>
<td>Structural integrity</td>
</tr>
<tr>
<td>Roots</td>
<td>Absorb water &amp; nutrients</td>
<td>Signaling (PGRs)</td>
<td>Structural integrity</td>
</tr>
<tr>
<td>Whole Plant</td>
<td>Plasticity</td>
<td>Triage to maximize HI</td>
<td>Respiration</td>
</tr>
</tbody>
</table>
The next step in the analysis estimates the principal bottlenecks within this framework. For spikes, the bottleneck is the abortion of kernels at supra-optimal temperature; for photosynthetic canopy it is likely to be photo-inhibition due to excess light, in combination with impaired metabolism; for stems the hydraulic resistance at high transpiration rate is likely to become rate limiting; and likewise for roots, a limited capacity for water uptake to match evaporative demand at high VPD may cause stomatal closure (Cossani and Reynolds 2012). At the whole plant level, the primary bottleneck is expected to be an overly conservative response to stress, reducing harvest index and perhaps growth of roots or other organs, probably mediated by plant growth regulators such as ethylene, intended to promote survival over seed fecundity.

Table 1b. Bottlenecks for wheat adaptation to heat stress.

<table>
<thead>
<tr>
<th>Wheat organ</th>
<th>Primary</th>
<th>secondary</th>
<th>secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spikes</td>
<td>kernel abortion</td>
<td>heat sensitive enzymes</td>
<td>RUE</td>
</tr>
<tr>
<td>Canopy</td>
<td>Photoinhibition</td>
<td>LAI</td>
<td>TE</td>
</tr>
<tr>
<td>Stems</td>
<td>hydraulic resistance</td>
<td>transport/storage</td>
<td>competing sinks</td>
</tr>
<tr>
<td>Roots</td>
<td>exploration capacity</td>
<td>adaptation to soil</td>
<td>competing sinks</td>
</tr>
<tr>
<td>Whole Plant</td>
<td>Conservative response</td>
<td>signaling geared to survival</td>
<td>thermostability</td>
</tr>
</tbody>
</table>

The main purpose of this analysis – with input from the Wheat AgMIP group – is to identify for each of these processes; where reasonably functional models already exist, where model development is needed, and where basic research is required in order to develop parameters for new models. We therefore, offer Table 1c blank for your inputs

Table 1c. Gap analysis of modeling or research needs

<table>
<thead>
<tr>
<th>Wheat organ</th>
<th>Functional models, modeling needs, or research gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spike</td>
<td></td>
</tr>
<tr>
<td>Canopy</td>
<td></td>
</tr>
<tr>
<td>Stems</td>
<td></td>
</tr>
<tr>
<td>Roots</td>
<td></td>
</tr>
<tr>
<td>Whole plant</td>
<td></td>
</tr>
</tbody>
</table>

References

Achieving sustainable agriculture and poverty alleviation faces many obstacles including climate change, natural resource availability, a growing global population, and increasing demand for goods and services due to economic growth in the developing world. Selecting appropriate technologies and policies to achieve these goals will require robust tools and accurate local and global data. The Global Futures program was launched in 2009 to address the challenge of sustainable agriculture in an uncertain future, and has been supported with major funding from the Bill & Melinda Gates Foundation and the Climate Change, Agriculture and Food Security (CCAFS) CRP. The project brings together researchers from many CGIAR centers, including IFPRI, and leading public and private institutions, to provide policy makers with tools for optimizing the use of limited resources and prioritizing investments in agricultural research and policy reforms.

This research assess how changes in global trading regimes, mandates for biofuels and energy prices, land degradation, and climate change affect human wellbeing. Additionally, it considers how these trends affect developing countries’ progress towards achieving the Millennium Development Goals of reducing hunger, malnutrition, and poverty. To achieve its goals, the project is enhancing IFPRI’s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). IMPACT is a flexible suite of economic models that generate scenarios of future production, consumption, and trade of key agricultural commodities. It provides a flexible framework for incorporating the results of multiple specialized models, to assess the effects of climate change, water availability, and other major trends. The work pursued under the Global Futures project builds on previous research, by expanding the platform for economic and biophysical modeling of agricultural technology provided by IMPACT, through use of improved:

- Detailed Spatial Data
- Local variables on climate, soil characteristics, and crop varieties
- Measurements on changes on human welfare
- Comparison capability to determine the benefits and costs of potential agricultural investments

Review of Phase 1

The first phase of Global Futures (2009-2013) consolidated and refined an analytical framework and suite of models to help scientists and leaders within eight CGIAR centers (including IFPRI) to answer the question: “If an investor provides a specified level of investment to CGIAR, how should it be spent to provide the greatest return on investment?” The program focused on applying the improved suite of models and data to a series of priority technologies for key food security commodities.
Global Futures project scientists worked with breeders, plant physiologists, and agronomists to identify potentially promising technical traits and design virtual crops in DSSAT to test the effects of breeding these traits under a variety of environmental conditions (climate change, weather, soil quality/composition, water availability, etc.). These test results were then used as inputs in IMPACT, to assess the potential effects of these promising technologies on agricultural markets and food security.

Throughout Phase 1, much progress has been made in improving the technical capacity of the models and modeling framework for use in Global Futures. CGIAR researchers have collaborated with crop modelers to develop virtual crops for groundnuts, maize, rice, wheat, soybeans, potatoes, sorghum, and cassava. Between 20 and 30 priority technologies have been identified and parameterized by the CGIAR centers. Additionally, IFPRI undertook extensive work on developing a new version of IMPACT (IMPACT 3). This work has focused on building better integration with IMPACT-Water, spatial data, and crop models to meet the demands of Global Future and our CGIAR partners, and includes:

- Expanded food security indicators to include population at risk of hunger
- Development welfare/benefit-cost module to compare welfare changes between technologies
- Financial calculations to determine returns on investments in agriculture technologies
- Development of technology adoption module to model adoption pathway of new technologies
- Update of the base year from 2000 to 2005
- Disaggregation of model regions from 116 to 159 countries
- Disaggregation of commodities by adding 14 new crops
- Improved flexibility in modeling prices to allow the specification of tariffs and taxes
- Ability to include traded and non-traded commodities

**Next Steps: Phase 2**

The proposed Global Futures Strategic Foresight Program Phase 2 (GF/SF; 2013-2016) will deepen and institutionalize the project into a constituent program of the CRP on Policies, Institutions, and Markets (PIM) as the Strategic Foresight Program. The global research program will focus on continued development and application of a suite of models for long term scenario and foresight analyses of global, national, and subnational agricultural development and food security.

Phase 2 work builds on the collaborative cross-CGIAR work completed in Phase 1 to better institutionalize open and transparent quantitative methods for ex-ante evaluation of investments and policy reform. The original eight CGIAR centers that participated in Phase 1 will be joined by three new CGIAR centers, and will pursue the following objectives in Phase 2:

- Testing the parameterized technologies from Phase 1 in IMPACT 3
- The development of additional new virtual cultivars
- Completing work on livestock modeling
- Incorporating work land use modeling
- Incorporating new climate data, and GHG emissions
- Continuing to improve and develop new crop models in DSSAT
Perspectives on wheat modeling from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Jarvis

CCAFS / CIAT
Exposing wheat to a wide range of temperatures: The Hot Serial Cereal Experiment

Bruce A. Kimball¹, Jeffrey W. White¹, Gerard W. Wall¹, and Michael J. Ottman²

¹USDA-ARS, Arid-Land Agricultural Research Center, Maricopa; ²University of Arizona, School of Plant Sciences, Tucson

In order to determine the likely effects of global warming on field-grown wheat (*Triticum aestivum* L.), a “Hot Serial Cereal” experiment was conducted. Named “Cereal” for the crop (wheat); “Serial” because the wheat was planted about every six weeks for two years, and “Hot” because infrared heaters were deployed on six of the planting dates in a T-FACE (temperature free-air controlled enhancement) system, which warmed the canopies of the Heated plots. The infrared heater system followed the design of Kimball et al. (2008), which features six heaters deployed in a hexagonal pattern around a 3 m diameter plot, at a height of 1.2 m above the top of the wheat canopy (Ottman et al. 2012). The target amount of warming for the Heated plots, above un-heated Reference plots, were 1.5 and 3.0 °C during day and night, respectively. The actual average temperature increases were 1.3 and 2.7 °C, respectively (Fig. 1). Air temperatures ranged from -3 to +42 °C, exposing the wheat to a very wide range of temperatures (Fig. 2).

![Figure 1. Frequency distribution of 10-minute-average wheat canopy temperatures from day- and nighttime set points. The data are from six crops planted in fall, winter, and spring, during two years of the Hot Serial Cereal Experiment.](image-url)
A drip irrigation system provided weekly replacement of evapotranspiration (corrected for rain). Ample nitrogen was also supplied. The Heated plots received 10% more supplemental irrigation water than the Reference plots, which was an amount calculated to simulate future global warming at constant relative humidity (Kimball 2005, 2011).

We took the following measurements during the Hot Serial Cereal Experiment: daily weather data; daily weather data with air temperatures adjusted to the difference between Heated and Reference canopy temperatures; hourly weather data and canopy temperatures of Heated and Reference plots; heater output; biomass of various above-ground organs at three intervals; final grain yield and yield components; leaf appearance rates and phenology; canopy reflectance and normalized difference vegetation index (two to five times per week); photosynthesis, stomatal conductance, and plant water status one or two times per crop in Heated and Reference plots; and soil respiration and soil temperatures on a limited scale.

When plotted against growing-degree-days computed from canopy temperatures, vegetation index curves from Heated and Reference plots coalesced (Kimball et al. 2012), which gives us confidence that the infrared-heater treatment simulates natural warming. Infrared warming increased leaf-level net assimilation rate by 5%, but had only a nominal effect on stomatal conductance (Wall et al. 2011). The warming also dried the soil between rows, compared to that in Reference plots, resulting in a decrease in soil respiration (Wall et al. 2013). A regression-based analysis of simulations with the CSM-CROPSIM-CERES model showed that effects of T-FACE on phenology were similar to what would be expected from equivalent changes in air temperature (White et al. 2011). Leaf appearance rates exhibited a base temperature of 1.9 °C and a lower optimum temperature of 22.2 °C (White et al. 2012). Warming had no detectable effect on grain yield for normal winter planting dates (Ottman et al. 2012). However, for
spring plantings, when temperatures were above optimum, warming exacerbated an already decreased grain yield. Supplemental heating had the greatest effect in the early fall plantings when mid-season frost destroyed the yield of unheated plots, whereas yield of Heated plots was about half that of mid-winter planted wheat.

Combined use of T-FACE and planting date treatments provided a highly effective means of exposing wheat to a wide range of temperatures under agronomically relevant conditions, from which plant responses to temperature could be obtained.

References

Ecosystem warming affects mass and energy exchange processes in spring wheat

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Global warming will likely affect mass and energy exchange processes of hard red spring wheat (*Triticum aestivum* L. cv. Yecora Rojo), such as that grown in the semiarid desert region of the southwest USA. We aimed to test the hypotheses that infrared (IR) warming will alter the microclimate in a similar way to the expected future trajectory of climate change (*Hypothesis 1*); and that such an alteration will affect soil respiration and the vertical distribution of gas exchange properties and water relations of a wheat crop (*Hypothesis 2*).

A temperature free-air controlled enhancement (T-FACE) apparatus, utilizing IR heaters (Kimball 2005, 2011; Kimball et al. 2008), maintained canopy air temperature above 3.0 m diameter Heated plots (see Ottman et al. 2012) of wheat at 1.3 and 2.7 °C (0.2 and 0.3 °C below the targeted set-points of Reference plots with dummy heaters) during daytime and nighttime, respectively (Wall et al. 2011). Control plots had no apparatus. During 2007-09, wheat was sown under the three warming treatments (Control, Heated, or Reference), approximately every six weeks. Three replicates were planted in a 3x3 Latin square (LSQ) design for six plantings during fall (early planting), mid-winter (normal planting), or spring (late planting); a natural temperature variation treatment (i.e. Control) consisted of three replicates for nine plantings, covering all seasons of the year. Weekly replacement of evapotranspiration (corrected for rain) and ample nitrogen were supplied via a drip irrigation system. The Heated plots received 10% more supplemental irrigation water than the Reference plots, which was an amount calculated to simulate future global warming at constant relative humidity (Kimball 2005, 2011).

Overall, soil temperature (*Tₛ*) and volumetric soil-water content (*θₛ*) were 1.3 °C warmer and 14% lower, respectively, in Heated, compared to Reference plots (Fig. 1). Under ample soil water supply with high *θₛ*, midday soil CO₂ efflux (*Φₛ*) was 10% greater in Heated [4.1 μmol (CO₂) m⁻² s⁻¹], compared to Reference plots [3.7 μmol (CO₂) m⁻² s⁻¹]. In contrast, as the soil dried and *θₛ* decreased to a greater degree in Heated plots (compared to Reference plots), a 10% decrease in *Φₛ* occurred in Heated plots, compared to Reference plots. IR warming dried the soil in the intrarow space in Heated plots, which decreased *Φₛ* in comparison to Reference plots (Wall et al. 2013). Higher *Tₛ* and lower *θₛ* were observed in Heated plots, compared to Reference plots, therefore IR warming affected the microclimate in a similar way to the expected future trajectory of climate change (*accept Hypothesis 1*).
Fig. 1. (a) Midday soil temperature ($T_s$) for 10 survey sampling dates during the 14th planting of the Hot Serial Cereal (HSC) experiment; (b, c) Midday maximum soil CO$_2$ efflux ($\Phi_s$), and volumetric soil-water content ($\theta_s$) for three sampling dates during the 9th planting (b), and 10 sampling dates during the 14th planting (c) of the HSC experiment. Significant effects given as *, **, ***, and ns for $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, and not significant, respectively (ne for effect not estimated). Significance also denoted with † and ‡ for $P > 0.05$ and $P \leq 0.1$, and $P > 0.1$ and $P \leq 0.3$, respectively. Each mean datum was derived from three repeated measures across three replications (i.e. $n = 9$). Vertical bars are one standard error of replication mean (i.e. $n = 3$). This figure was derived from more than 234 measurements.

The vertical distribution of foliage elements, from the top to the bottom of the wheat canopy, were designated as Flag, Flag-1 (F-1), Flag-2 (F-2), and Flag-3 (F-3) leaves. Leaf-level gas exchange properties and water relations for each fully expanded (ligule emerged) sunlit leaf type on day of experiment (DOE) 379 are given as follows: leaf-level net assimilation rate ($A$), and internal CO$_2$ concentration in the substomatal cavity ($C_i$) (Fig. 2); stomatal conductance ($g_s$) to water vapor, and leaf temperature inside a cuvette ($T_L$) (Fig. 3); and, total ($\Psi_w$), osmotic ($\Psi_o$) and turgor ($\Psi_p$) potentials, and relative water content ($RWC$) (Fig. 4).
Fig. 2. Mean ±standard error (SE) midday (solar noon) net assimilation rate \( A \) and internal CO\(_2\) concentration in the substomatal cavity \( (C_i) \) for fully expanded (ligule emerged) sunlit Flag, Flag-1 (F-1), Flag-2 (F-2) and Flag-3 (F-3) leaves on day of experiment (DOE) 379. Symbols in the legend refer to Heated and Reference treatments – the sources of variance in ANOVA (i.e. means based on \( n = 8 \) or \( n = 12 \); SE of mean based on \( n = 2 \) or \( n = 3 \)).

\[ C_i \text{ [mol (CO}_2\text{) mol air}^{-1}\text{]} \]

\[ A \text{ [\mu mol (CO}_2\text{) m}^{-2}\text{ s}^{-1}\text{]} \]

Fig. 3. Mean ±standard error (SE) midday (solar noon) stomatal conductance to water vapor \( (g_s) \), leaf temperature inside a cuvette \( (T_L) \) for fully expanded (ligule emerged) sunlit Flag, Flag-1 (F-1), Flag-2 (F-2) and Flag-3 (F-3) leaves on day of experiment (DOE) 379. Symbols in the legend refer to Heated and Reference treatments – the sources of variance in ANOVA (i.e. means based on \( n = 8 \) or \( n = 12 \); SE of mean based on \( n = 2 \) or \( n = 3 \)).

\[ g_s \text{ [mol (H}_2\text{O) m}^{-2}\text{ s}^{-1}\text{]} \]

\[ T_L \text{ (^0C)} \]

Fig. 4. Mean ±standard error (SE) midday (solar noon) total \( (\psi_w) \), osmotic \( (\psi_o) \), and turgor \( (\psi_p) \) potentials, and relative water content \( (RWC) \) for fully expanded (ligule emerged) sunlit Flag, Flag-1 (F-1), Flag-2 (F-2) and Flag-3 (F-3) leaves on day of experiment (DOE) 379. Symbols in the legend refer to Heated and Reference treatments – the sources of variance in ANOVA (i.e. means based on \( n = 8 \) or \( n = 12 \); SE of mean based on \( n = 2 \) or \( n = 3 \)).

\[ \psi \text{ (MPa)} \]

\[ RWC \text{ (%)} \]
Generally, leaf-level ecophysiological parameters (i.e. $A$, $C_i$, $g_s$, $\Psi_w$, $\Psi_r$, $\Psi_p$; Figs. 2-4) were greater in the Flag leaf at the top of the canopy and decreased thereafter to the F-3 leaf at the bottom of the canopy, whereas the inverse occurred for $T_i$ and $RWC$ (Figs. 3, 4). Overall, IR warming increased leaf-level $A$ by 5%; characteristic of an increase in metabolic rates to higher temperature. Whilst the Flag leaf and those lower in the canopy had warmer $T_i$ and slightly higher $A$ in Heated plots (compared to Reference plots), across the vertical profile, the middle leaf in the canopy (F-2) exhibited the greatest response in $A$ to IR warming at comparable $g_s$, which is indicative of an increase in intrinsic water use efficiency. Nevertheless, seasonal oscillations in the IR warming response on $A$ occurred (data not shown). Stomatal conductance in Flag and F-1 leaves was slightly greater in Heated compared to Reference plots. This minor treatment response in $g_s$ may have occurred despite the well-watered wheat crop and the supplemental irrigation that minimized plant-to-air water vapor pressure differences between IR-warmed and non-warmed plots (Wall et al. 2011). A slight decrease in the internal water status of the crop was observed in Heated compared with Reference plots, as evidenced by more negative $\Psi_w$ and $\Psi_r$. In contrast, $\Psi_p$ was similar to slightly greater in Heated, compared with Reference plots, indicative of a possible increase in osmotic adjustment (Fig. 4). Nevertheless, no distinguishable difference in $RWC$ content between Heated and Reference plots was detected (Fig. 4). IR warming decreased leaf water status and provided thermal protection during freeze events (data not shown) (Wall et al. 2011). In short, IR warming altered soil respiration in an agricultural soil and the vertical distribution of gas exchange properties and water relations of a wheat crop (accept Hypothesis 2). The alterations in mass and energy exchange due to IR warming reported herein may possibly explain the observed differences in crop phenology (White et al. 2011, 2012; Kimball et al. 2012) and total biomass production and yield (Ottman et al. 2012) between Heated and Reference plots.

IR warming with T-FACE proved to be an effective experimental methodology to expose a wheat crop to a huge range of natural and artificially imposed temperature regimes in order to investigate the impact of global climate change on agronomic cropping and natural ecosystems.

References
What physiological traits should we focus on in breeding for heat tolerance?

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Global Wheat Program, CIMMYT, Mexico

Most of simulation models predict the worst impacts of rising temperatures at low latitudes, where approximately 100 million ha of wheat are currently cultivated. Therefore, adaptation of wheat productivity to future climate scenarios constitutes one of the priorities in ensuring food security worldwide. Wheat adaptation to hot environments requires efforts in developing adapted germplasm, as well as the study of associated changes in management of natural resources, such as water and nutrients. Due to the still incomplete understanding of the genetic basis of heat adaptation, physiological traits (PTs) constitute one of the best available tools for genetic improvement of crops for heat adaptation. Conceptual models, based on PTs, are proposed as alternatives to deal with the adverse future conditions. For instance, the conceptual model for heat (Fig. 1) considers the use efficiency and the capture of radiation, and the posteriori translocation of the biomass to the grains. A cumulative gene action is expected to be obtained by using conceptual models to design strategic crossing of complementary PTs and obtaining new adapted germplasm. The traits most amenable to high throughput phenotyping (HTP) would also help breeders to incorporate physiological characteristics into progeny selection routines.

![Heat conceptual model](image.png)

**Heat conceptual model**

(YIELD = \( Li \times RUE \times HI \))

- **Photo-Protection (RUE)**
  - Leaf morphology: -wax/pubesence
  - Anti-oxidants
  - Pigments (chlorophyll a:b; carotenoids)

- **Efficient Metabolism (RUE)**
  - Membrane thermostability
  - Starch synthase
  - Spike/awn photosynthesis
  - Dark respiration rate
  - \( CO_2 \) fixation

- **Light interception (Li)**
  - Early ground cover
  - Stay green

- **Partitioning (HI)**
  - Pollen fertility
  - Floret survival
  - Stem carbohydrates storage and its remobilization

To increase light interception, early ground cover (EGC) and stay green (SG) constitute the main targets for improvement, and HTP approaches are available. The main genotypic characteristics of EGC are relatively heritable, and easy to incorporate in breeding using aerial or field platforms. In terms of SG, the optimal pattern of senescence for improving grain yield under heat stress has not yet been
identified, and simulation models could play an important role in identifying it. Canopy architecture is another trait influencing light distribution and could improve RUE. Modeling studies, focused on spatial arrangements of crop rows or in leaf angle, may provide agronomic strategies that would benefit RUE. Crop biomass depends on the ratio between photosynthesis and respiration. Improving photosynthetic capacity through increased affinity of Rubisco for CO₂ versus oxygen, and a better catalytic rate, are being currently investigated by the wheat yield consortium (Reynolds et al. 2012). Exploration of the genetic variability of Rubisco’s kinetic properties in related species and improvements in its thermal stability, while being (long term) largely transgenic goals, are expected to have a large impact on wheat productivity in hot environments (Parry et al. 2011). Research is especially needed in context-specific expression, chloroplast transformation, post-translational modification, enzyme activity regulation, and developing HTP for Rubisco kinetic properties. Spike photosynthesis also constitutes a target for improving RUE, given the high percentage of radiation intercepted by the spikes. Better understanding of CO₂ assimilation/recycling within the spike is needed, as well as development of HTP tools. At the moment, canopy temperature constitutes a surrogate of photosynthetic capacity and is a HTP tool integrating several physiological mechanisms related to photosynthesis. The challenge for modelers is to incorporate spike photosynthesis into current models to understand how it contributes to the source/sink balance under abiotic stress.

Respiration generally consumes between 30-80% of C produced by photosynthesis per day, and is highly affected by temperature and phenology. High respiration rates can lead to cell damage and affect pollen viability. Field trials show that, while yield was negatively associated with mean temperatures in hot environments, night temperature explained most of the variation (Reynolds et al. 1994). Simulation exercises, including changes in minimum temperatures and how the ratio between photosynthesis and respiration is affected, could help to improve the understanding of this issue.

Photo-protective molecules like carotenoids, flavonoids, glutathione, ascorbate, and tocopherols have important roles in cell metabolism; acting in membranes like energy receptors, quenching or chemically scavenging reactive oxygen species or neutralizing free radicals. Research for crop improvement in this area in terms of simulation modeling is scarce. Currently, spectral radiometry constitutes a HTP approach to screen for these molecules. Wax is another important PT; the beginning of wax deposition occurs with critical stages for yield determination, and suggests adaptive advantages under abiotic stress. Wax characteristics in plant organs have a relatively simple genetic basis, but further research is needed to quantify the costs/benefits of different quantities and types of wax in plant tissues across target environments. RUE may also be affected by non-stable membranes at high temperatures. Membrane lipid composition affects its stability, but more research is needed to explain genetic variation in MT and its relationship with saturation/unsaturation of fatty acids. How the reproductive growth is affected by heat stress is obviously crucial to determining grain sink strength, while the ability to synthesize and accumulate starch at high temperature will determine final yield. The sensitivity of grain set to heat stress due either to lack of carbohydrate supply or other conservative responses associated with plant growth regulators such as ethylene can lead to relatively low HI. The incorporation of the relationships between grain abortion, pollen survival, or ovary development with minimum/maximum temperatures into model routines would be very useful to characterize future scenarios.
Heat stress could jeopardize grain yield through seed filling if adequate stored assimilates, mainly water soluble carbohydrates (WSC), are not available for remobilization to the grain. Genetic diversity of stem WSC in wheat ranges from 10% to almost 50% of total stem dry weight at its peak, and has been associated with differential regulation of some carbohydrate metabolic genes at the transcript level. Rht1 and Rht2 dwarfing genes are generally associated with a reduction in WSC storage capacity of stems due to shorter peduncles (Borrell et al. 1993). A better understanding of how much height is desirable under different temperatures would be an excellent complement for breeding. Even when assimilate supplies are not limiting, starch accumulation in wheat grains can be reduced by heat stress. Decreases in grain weight are expected as a consequence of high temperatures through its effect on: i) potential grain weight; ii) accelerating development of the grain; iii) reduction in the duration of grain filling; and iv) the capacity of the grains to upload available carbohydrates. Although starch enzyme activity is reduced under hot temperatures, genetic variability exists in terms of tolerance to short periods of high temperature during grain filling. Adaptation to warm night temperatures will be a high priority in humid wheat environments, and low respiratory costs and heat-stable starch synthesis remain key targets to improve RUE and HI.

Additionally, research in the area of plant signaling would play a key role in the future. High ethylene generation was associated with grain abortion and yield reduction of wheat (Hays et al. 2007). The role of abscisic acid, and its interactions with other plant signals related to floret fertility, needs also to be clarified to avoid the risk of hot temperatures.

To date, simulation modeling has delivered mainly agronomic solutions for adapting crops to stress. However, models could complement breeding programs to help with: a) characterization of multiple target environments; b) assessment of putative traits by simulating genotype by environment interaction; and c) testing of alternative breeding schemes and predicting genetic gains. Furthermore, simulation of crop management practices on heat stress could be explored. For example, conservation agriculture that offers a number of opportunities in terms of buffering crops to a range of stresses (Hobbs and Govaerts 2010).

References


How high temperature affects wheat growth and development

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High temperature and heat-shock events can severely reduce wheat yields by shortening the crop cycle and by affecting different physiological processes influencing grain set and grain filling. Global warming has already increased mean temperatures and the frequency of heat events, and these trends are predicted to escalate in the future. We conducted several growth-chamber and glasshouse experiments at different temperatures to quantify the effect of heat on wheat growth and development for contrasting genotypes. Plants were subjected to increased temperature over their entire cycle, or for a restricted period of time at different developmental stages. Higher temperatures accelerated plant development and reduced yield components through decreased pollen viability, reduced carbon assimilation, and accelerated senescence. Genetic variability in heat responses was notable for plant growth, pollen viability, leaf senescence, and carbon allocation among organs. Heat stress around flowering greatly impacted yield, affecting grain set and grain size to different extents depending on the timing of the event. The application of these results in improving crop-model capability for assessing impacts of future climate will be discussed.
Impact of season-long and short-episodes of high temperature stress on growth and development of wheat

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High temperature (heat) stress is one of the most important environmental factors, influencing an array of physiological, growth, developmental, reproductive, and yield processes of wheat. A comprehensive understanding of the effects of high temperature stress is critical for evaluating the impacts of climate change and climate variability on crop production. This research aimed to: (a) quantify impact of season-long and short-episodes of high (day and night) temperature stress on different plant processes in controlled environments, and (b) determine the sensitivity of reproductive stages of crop development to short episodes of high temperature stress. Several studies were conducted in controlled environments to quantify the impacts of high temperature stress on wheat. These studies showed that both season-long and short-episodes of high temperature stress significantly influenced growth, development, and yield processes. Season-long high temperature stress, from seedling establishment to physiological maturity, resulted in decreased biomass production, grain number, individual grain weight, and yield. Plants were generally more sensitive to high temperature stress during the reproductive stages of development, particularly during gametogenesis and flowering. Stress during these two stages decreased percent seed-set and grain number. High temperature stress during the post-anthesis stages decreased grain filling duration and grain weight. After identifying the sensitive stages of development to high temperature stress, we imposed more targeted stress treatments to determine the cumulative impact of short episodes of high temperature stress on grain number and grain weight. Mean daily high temperatures >30 °C for short periods (5 d), when imposed from start of heading, caused a linear decrease in grain number; and when the stress was imposed after seed-set, it caused a quadratic decrease in grain weight. High nighttime temperatures >20 °C during the reproductive phase decreased grain filling duration and grain weight. There were genetic differences in responses to high temperature stress, suggesting opportunities for breeding. Several crop simulation models are used to quantify the impact of stresses on growth, development, and yield traits of wheat, and it is critical that these models have accurate and quantitative temperature response functions. Basic knowledge on the sensitivity of different growth stages, and the response of various components of yield to high temperature stress, can help to improve the accuracy and functionality of crop simulation models. Mechanistically improved and tested crop simulation models may accurately quantify the impacts of both season-long and short-episodes of stress events on growth, development, and yield processes. Such improved models can enhance our capacity not only to predict crop performance in future climates, but also to identify traits that can potentially be improved/exploited to obtain higher and more stable crop yields under current and future climates.

**Keywords:** temperature stress, growth, development, reproductive success, yield
Improving APSIM for simulation of temperature response of wheat (APSIM-WheatE)

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The Agricultural Production systems SIMulator (APSIM; Wang et al. 2002; Keating et al. 2003) has become one of the most widely used models for simulating performance of cropping systems, and their responses to climate change. The APSIM-Wheat model (Wang et al. 2003) simulates growth and development of wheat crops in response to environmental and management conditions. In the current version of APSIM-Wheat (v7.4), wheat temperature responses are simulated as linear increases or decreases between defined cardinal (base, optimum, maximum) temperatures for each process, including:

1) **Thermal time and phenology** – The optimum temperature for development is 26 °C; development rate (or thermal time) decreases linearly to zero at temperatures of 0 and 34 °C (Fig 1a). Daily thermal time (DTT) is calculated using 3-hourly temperatures estimated from daily maximum and minimum temperatures.

2) **Emergence** – Shoots elongate towards the soil surface at a rate of 1.5°Cd/mm depth, after a lag phase of 40 °Cd, in response to daily thermal time (as calculated above).

3) **Root front advance** – The rate of rooting front/depth advance is modeled using daily average air temperature. The base, optimum, and maximum temperatures are 0, 25, and 35 °C, respectively (Fig 1b).

4) **Vernalization** – Simulated with 3-hourly temperatures, with base, optimum, and maximum temperatures of 0, 2, and 15 °C, respectively (Fig 1d).

5) **Phyllochron** – Development of each leaf ligule requires 75 °Cd of thermal time, except for the last one, which appears much quicker.

6) **Biomass growth** – Temperature effects on radiation use efficiency (RUE) and biomass growth is simulated with daily average temperature, with base, optimum, and maximum temperatures of 0, 10-20, and 35 °C (Fig 1c).

7) **Grain filling rate** – Grain demand for biomass increases linearly with daily average temperature, from zero at 0 °C to the maximum demand at 26 °C (Fig 1e).

8) **Grain N filling rate** – Grain N demand increases linearly with daily average temperature, from zero at 0 °C to the maximum demand at 25 °C (Fig 1f).

9) **Frost damage** – All leaves will be senesced by frost if daily minimum temperature goes below -5 °C.

10) **Plant death at high temperatures** – Death of the wheat crop increases from zero at a weighted 3-day soil temperature of 55 °C, to 100% at 60 °C.

Application of APSIM-Wheat in the North China Plain, where winter temperatures are much lower than in Australia, reveals that the model tends to overestimate both phenology advances and biomass growth during early stage of the winter wheat crop (Chen et al. 2010). We therefore need to improve the temperature response functions in APSIM-Wheat.
The curvilinear temperature response function in the wheat phenology (Wang and Engel 1998) and SPASS-Wheat model (Wang and Engel 2002) was found to be superior to other temperature functions in simulating response of wheat plants to temperature (Streck et al. 2003; Xue et al. 2004). It has been successfully applied for modeling leaf development and phenology of wheat (Streck et al. 2003; Xue et al. 2004), maize (Streck et al. 2008b), rice (Streck et al. 2008a), and potato crops (Streck et al. 2012).

The Wang-Engel (WE) temperature function constructs a curvilinear response based on the base, optimum, and maximum temperatures 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 the base and maximum temperature (Equation 1):

\[
f(T) = \frac{2(T-T_{\min})^{a}(T_{\text{opt}}-T_{\min})^{a}-(T_{\max}-T_{\min})^{2a}}{(T_{\text{opt}}-T_{\min})^{2a}}; \quad \alpha = \ln2/\ln[(T_{\max} - T_{\min})/(T_{\text{opt}} - T_{\min})] \quad (1)
\]

We therefore used the WE temperature model to modify the temperature functions in APSIM-Wheat for:

1) Thermal time, with base, optimum, and maximum temperatures of 0, 25, and 35 °C (Fig 1a).
2) RUE, with base, optimum, and maximum temperatures of 0, 20, 35 °C (Fig 1c).
3) Frost damage, with critical temperature changed from -5°C to -15°C.

The modified model, APSIM-WheatE, was used to simulate the phenological development, leaf area index, and biomass growth of winter wheat in the North China Plain. Comparing the simulation results from both the original and modified models against measured data showed improvements in the modeling of both phenology and biomass growth dynamics, particularly for the early stage of the wheat growth period after wintering up to jointing. The modified model is also used for simulating the Hot Serial Cereal (HSC) experiment within the AgMIP-Wheat project. Further, we have tried to use the WE function to modify the temperature responses of rate of rooting front advance (Fig 1b) and vernalization (Fig 1d). These will be tested in future simulations.

References


Temperature routines in Nwheat

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University of Florida, USA

Nwheat model

The Agricultural Production Systems SIMulator (APSIM) for wheat (APSIM-Nwheat version 1.55s; Keating et al. 2001) is a crop simulation model consisting of modules that incorporate aspects of soil, water, nitrogen, crop residues, and crop growth and development, and their interactions within a crop/soil system that is driven by daily weather data (Keating et al. 2003). The Nwheat model in the APSIM framework has evolved from experiences in Australia with the CERES family of crop and soil models (Ritchie et al. 1985; Jones and Kiniry 1986), and the PERFECT model (Littleboy et al. 1992). Modifications include: replacement of the original crop water deficit routine with an approach based on a critical fraction of available soil water (Stapper 1984); inclusion of a leaf sheath biomass pool with resultant modification of partitioning to the remaining leaf blade and stem biomass pools; inclusion of high temperature stress effects on leaf senescence; modification of the root elongation rates; frost damage; tillering; specific leaf area; radiation use efficiency; carbohydrate partitioning; and the deletion of respiration and root exudation subroutines.

APSIM-Nwheat has been extensively tested against a range of field measurements from many different environments (Asseng et al. 1998b, 2000, 2001a, 2001b, 2004), including a wheat experiment with temperature as the variable (Asseng et al. 2004). Nwheat is now also available as a test-version in DSSAT (Jones et al. 2003).

Temperature routines and inputs

In the Nwheat model, air temperature affects several processes, including leaf area growth, photosynthesis, senescence, root depth elongation, phenology, and soil carbon and nitrogen transformation processes. Temperature inputs for Nwheat are the daily minimum and maximum air temperature [°C].

Temperature effects on phenology

Nwheat uses the phenology routines from CERES (Ritchie 1991). The phenology in Nwheat controls the life cycle of the simulated wheat crop. It starts and terminates various growth processes and determines changes in carbon partitioning between different parts of a crop. For example, the phenology routine sets the end of leaf growth and at the same time terminates carbon partitioning to leaves; it also switches on the carbon flow to the grain at the beginning of grain filling and turns it off when crop maturity is reached. Phenology in the crop model is described as different growth stages after Jones and Kiniry (1986). Table 1 shows the growth stages, the requirements to reach the following growth stage, and a linear translation into a decimal code (DC) or Zadoks-scale (Tottman and Makepeace 1979).

The phenological development of the crop is mainly driven by temperature, but for some specific genotypes, it is further influenced by day length. Day length is generated from the longitude of the site and the day of the year.
Each day, the phenology routines calculate the thermal time (in degree days) from daily mean temperature (the average of minimum and maximum temperature). Thermal time is calculated using the relationship in Figure 1 to obtain the daily value of thermal time (in growing degree days) for the day. These daily thermal time values are accumulated into a thermal time sum, which is used to determine the duration of each phase.

Figure 1. The effect of average daily temperature on rate of thermal time accumulation in NWheat.

The duration of crop phases is measured in terms of degree days, as outlined in Table 1. The germination to emergence phase includes an effect of sowing depth on the thermal time target. The thermal time target equals a lag period before coleoptile growth starts, plus a coleoptile elongation rate that determines the thermal time taken to reach the soil surface before the crop emerges. The phase between emergence and the end of tillering is determined by a thermal time target, modified by a cultivar’s photoperiod (day length) sensitivity and vernalization requirement.

Table 1. Internal phenological stages with requirements to reach a growth stage and their corresponding decimal code (DC) or Zadoks-scale (Tottman and Makepeace 1979).

<table>
<thead>
<tr>
<th>APSIM-NWheat growth stage</th>
<th>Requirements</th>
<th>Model internal stage</th>
<th>DC</th>
<th>Zadoks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination</td>
<td>A minimum soil water content is required</td>
<td>0</td>
<td>0</td>
<td>Germination</td>
</tr>
<tr>
<td>Emergence</td>
<td>$40 + 1.02 \text{ DTT} \times \text{sowing depth from sowing}$</td>
<td>1</td>
<td>10</td>
<td>Emergence</td>
</tr>
<tr>
<td>End juvenile</td>
<td>$400 \text{ DTT from stage 1}$ ($p1v, p1d$ extend that period)</td>
<td>2</td>
<td>20</td>
<td>Begin tillering</td>
</tr>
<tr>
<td>End vegetative</td>
<td>3 phint from stage 2</td>
<td>3</td>
<td>55</td>
<td>End leaf growth</td>
</tr>
<tr>
<td>End ear</td>
<td>2 phint from stage 3</td>
<td>4</td>
<td>59</td>
<td>End ear growth</td>
</tr>
<tr>
<td></td>
<td>80 DTT from stage 4</td>
<td>anthesis</td>
<td>65</td>
<td>Anthesis</td>
</tr>
<tr>
<td>Start grain filling</td>
<td>120 DTT from stage anthesis</td>
<td>5</td>
<td>72</td>
<td>Begin grain filling</td>
</tr>
<tr>
<td>Maturity</td>
<td>p5 from stage 5</td>
<td>6</td>
<td>91</td>
<td>Physiological maturity</td>
</tr>
</tbody>
</table>

Note: DTT is the daily thermal time after Figure 1.
Other growth phases are multiples of the phyllochron interval (in degree days per leaf initiated), fixed degree day targets, or genotypic specific parameters input by users (e.g. p5 is the degree days from the start of grain filling to maturity; Table 2).

Table 2. Genetic phenology coefficients in Nwheat.

<table>
<thead>
<tr>
<th>Genetic coefficients</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity to vernalization</td>
<td>p1v</td>
<td>1 (low) − 5 (high)</td>
</tr>
<tr>
<td>Sensitivity to photoperiod</td>
<td>p1d</td>
<td>1 (low) − 5 high)</td>
</tr>
<tr>
<td>Thermal time (base 0°C) from start of grain filling to maturity</td>
<td>p5</td>
<td>600–800°C-days</td>
</tr>
<tr>
<td>Phyllochron interval</td>
<td>phint</td>
<td>70–120°C-days/leaf appearance</td>
</tr>
</tbody>
</table>

**Temperature effects on photosynthesis**

Nwheat uses the radiation use efficiency concept (the net above-ground biomass accumulation per unit intercepted radiation, based on a radiation dependent function, after CERES-Wheat; Ritchie et al. 1985). If the weighted mean temperature \(0.25 T_{min} + 0.75 T_{max}\) is below or above an optimum range, photosynthesis is reduced by the factor \(F_{Photo1}\):

\[
F_{Photo1} = 1 - 0.0025 \times ((0.25T_{min} + 0.75T_{max}) - 18)^2
\]

In Nwheat, elevated atmospheric CO\(_2\) increases radiation use efficiency depending on temperature. It also increases transpiration efficiency, but independently of temperature (Reyenga et al. 1999).

\[
F_{Photo2} = (C_e - \Gamma) \frac{(C_{350} + 2\Gamma)}{((C_e + 2 \Gamma)(C_{350} - \Gamma))}
\]

where \(F_{Photo2}\) is the ratio of the light limited photosynthetic response at the enhanced CO\(_2\) concentration, compared to the current level (350 ppm; assumed to be the CO\(_2\) concentration when the model was developed) for scaling RUE. \(C_{350}\) = current CO\(_2\) concentration (=350 ppm) and \(C_e\) = elevated CO\(_2\) concentration (ppm). The temperature dependent CO\(_2\) compensation point (\(\Gamma\)) is calculated as \(\Gamma = (163 - T)/(5 - 0.1T)\); where \(T = \) temperature (°C), after Bykov et al. (1981; Fig. 2).

**Figure 2. CO\(_2\) Factor (\(F_{Photo2}\)) for photosynthesis as a function of average daily temperature and atmospheric CO\(_2\).**
Temperature effects on respiration

Respiration is not directly considered as a separate process, but indirectly by considering net-photosynthesis only in the radiation use efficiency calculation.

Temperature effects on growth and senescence

Several growth processes, as well as leaf senescence, are affected by temperature in the Nwheat model. Leaf area growth is reduced if the mean daily temperature is $<11\, ^\circ\text{C}$ or $>24\, ^\circ\text{C}$ (Fig. 3).

![Figure 3. Reduction factor of leaf area growth as a function of daily mean temperature.](image)

The most drastic impact of temperature in the Nwheat model is when maximum temperatures rise above $34\, ^\circ\text{C}$ (Porter and Gawith 1999) and thus hasten leaf senescence by 3-fold at just above $34\, ^\circ\text{C}$ and 6-fold at $40\, ^\circ\text{C}$ (Fischer 1980; van Herwaarden et al. 1998; Porter and Gawith 1999; Shah and Paulsen 2003; Wollenweber et al. 2003; Zhao et al. 2007), by multiplying the calculated senesced leaf area under normal development by a heat stress factor, $F_{\text{heat}}$ (Fig. 4a, b, and eq. 3,4):

$$F_{\text{heat}} = 4 - \left(1 - \frac{(T_{\text{max}} - 34)}{2}\right)$$

(3)

$$F_{\text{heat}} = 1 \quad \text{if} \quad T_{\text{max}} \leq 34\, ^\circ\text{C}$$

(4)

![Figure 4. a) Factor to accelerate canopy senescence as a function of daily maximum temperature (Equations 3 and 4 in text). b) Example of simulated relative leaf area index with no day of maximum temperature $>34\, ^\circ\text{C}$ (uppermost line) and an increasing number of days with maximum temperature of $>34\, ^\circ\text{C}$ starting from the day of flowering to all days $>34\, ^\circ\text{C}$ (lowermost line). From Asseng et al. (2011).](image)
The heat stress function in Nwheat is based on a number of glasshouse and field experiments showing accelerated senescence when temperatures are >34 °C (Fischer 1980; van Herwaarden et al. 1998; Porter and Gawith 1999; Shah and Paulsen 2003; Wollenweber et al. 2003; Zhao et al. 2007). Figure 4b illustrates a simulation where heat events were added to a dataset free of such heat events, and shows the reduction of LAI caused by adding heat events after anthesis (Asseng et al. 2011).

The potential grain-filling rate routine in Nwheat (Asseng et al. 2002) is based on the CERES wheat model (Ritchie et al. 1998; Lobell and Ortiz-Monasterio 2007), which is in turn based on data and a model by Vos (1981). The Vos model produces similar results to the grain-filling model for wheat developed by Wang and Gifford (1995; Fig. 5).

![Figure 5. Factor for potential kernel growth rate demand as a function of daily mean temperature (Equations 5-7 in text). Lines indicate a range of different scenarios depending on the diurnal temperature range. The T_min numbers next to some curves indicate the constant minimum temperature in the calculation of this curve following equation 5-7. From Asseng et al. (2011).](image)

In Nwheat, dry matter accumulation in the grain is driven by potential accumulation per kernel (Fig. 5), expressed as demand functions, and actual supply. A dry matter accumulation temperature factor (FT,DM, 0...1) for single kernel (K) growth is calculated as:

\[
F_{T,DM} = 0.065 \times T_{mean} \quad T_{mean} \leq 10 \, ^{\circ}C
\]  
(5)

\[
F_{T,DM} = 0.65 + (0.079-0.0033 \times (T_{max} - T_{min})) \times (T_{mean} - 10)^{0.8} \quad T_{mean} \geq 10 \, ^{\circ}C
\]  
(6)

\[
0 \leq F_{T,DM} \leq 1.
\]  
(7)

Extremely high maximum temperatures will also reduce potential kernel growth rate demand, as indicated by a number of curves with fixed minimum temperatures, and average temperature on the x-axis driven entirely by T_max in Figure 5.

The dry matter demand (DM) for grain-growth rate per day (DM_{pot} in g m^{-2} d^{-1}) is the product of F_{T,DM}, a user-specified cultivar-specific parameter (Table 3) for maximum daily kernel growth rate (DM_{max} in mg kernel^{-1} d^{-1}) and the number of kernels per unit area (K).

\[
DM_{pot} = DM_{max} \times F_{T,DM} \times K \times 10^{-3}
\]  
(8)
Table 3. Genetic coefficients of the wheat module.

<table>
<thead>
<tr>
<th>Genetic coefficients</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum kernel growth rate</td>
<td>Fillrate</td>
<td>2.0–2.5 mg/kernel/day</td>
</tr>
<tr>
<td>Potential final dry weight of a single stem (excluding grain)</td>
<td>stmwt</td>
<td>1.0–4.0 g/stem</td>
</tr>
</tbody>
</table>

The supply of dry matter for grain filling in the model is derived from current photosynthesis and retranslocation from pre-stored dry matter. Photosynthesis during grain filling is a function of weather conditions and LAI, which itself is a function of environmental effects (e.g. water, N supply, and temperature) and phenological stage. Grain N accumulation in the model can hold back DM if not enough N is available in the crop to maintain a minimum N concentration in the grain. Maximum grain weight is capped at 55 mg/kernel.

Mean daily temperature affects potential dry matter accumulation of the grain only below 23 °C; a continuous increase of potential N accumulation occurs above this temperature. A dry matter accumulation temperature factor ($F_{T,DM}$, 0...1) for single kernel growth, after Ritchie et al. (1985), is calculated as:

$$
F_{T,DM} = \begin{cases} 
0.065 \times T_{mean} & T_{mean} \leq 10°C \\
0.65 + (0.079 - 0.0033 \times (T_{max} - T_{min})) \times (T_{max} - 10)^{0.8} & 10°C < T_{mean} \leq 23°C \\
1 & T_{mean} > 23°C 
\end{cases} 
$$

The potential kernel N accumulation ($\Delta KN_{pot}$, in g N kernel$^{-1}$ d$^{-1}$) for a single kernel, after Ritchie et al. (1985), is calculated as:

$$
\Delta KN_{pot} = \begin{cases} 
0.49 \times T_{mean} & T_{mean} \leq 10°C \\
4.83 + 1.06 \times T_{mean} + 0.25 \times (T_{max} - T_{min}) & T_{mean} > 10°C 
\end{cases} 
$$

The inconsistency (a 4-fold increase) of the potential kernel N accumulation function at 10 °C in the original CERES-Wheat model (Ritchie et al. 1985) seems to be unrealistic and will need further investigation.

In the model, the potential amount of carbohydrate available for remobilization to grain is defined as 75% of biomass growth between 150 degree days (°C-d) before grain filling to the commencement of grain filling. Frost stress starts below –6°C ($T_{min}$) and reduces the leaf area. Note that any effect of frost during anthesis on kernel number is currently not considered in the model.
Temperature effects on evapotranspiration

Potential evapotranspiration ($E_{\text{pot}}$) is calculated as in the CERES model (Ritchie et al. 1985), using the Priestley and Taylor (1972) approach ($E_{\text{to}}$ – reference evapotranspiration) as a function of solar radiation, soil and crop albedo, and air temperature, with corrections for advection occurring above 24 °C. Actual evapotranspiration is the sum of actual soil evaporation and actual plant transpiration.

In contrast to the CERES model, in which water uptake demand is based on solar radiation and LAI, in APSIM-Nwheat, transpiration and water uptake demand are linked to biomass production via a transpiration efficiency coefficient (0.006 kg/m²/mm Pa) and vapor pressure deficit (after Monteith 1988). Vapor pressure deficit is calculated after Tanner and Sinclair (1983) as a function of maximum and minimum temperatures. The potential crop transpiration demand is calculated as:

$$E_{\text{p}} = G_t * \frac{0.006}{0.75 * (6.1078 * \exp(17.269 * T_{\text{max}}/(237.3 + T_{\text{max}}))) - (6.1078 * \exp(17.269 * T_{\text{min}}/(237.3 + T_{\text{min}})))}$$  \hspace{1cm} (11)

where $E_{\text{p}}$ (in mm) is the simulated potential crop transpiration demand and $G_t$ (in g/m²) is the simulated actual crop growth rate on a daily basis. Simulated actual water uptake is then a function of potential uptake demand, the distribution of root length density, and available soil water in the different soil layers. The soil water balance, including the ET dynamics, has been tested against several field data sets (Asseng et al. 1998a; Probert et al. 1998; Asseng et al. 2000; Asseng et al. 2001a).

Temperature effects on root growth

In Nwheat, the expansion of the root system is divided into two processes: root elongation to depth, and root length density development within soil layers. Root elongation to depth occurs at a rate of 2.2 mm°C·day and can be reduced through a soil layer specific hospitality factor (or multiplier) for root depth elongation (RDHF, values of 0–1), crop water stress and soil layer water content in the deepest root layer.

References


Accounting for the effects of temperature in AquaCrop

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Temperature affects three processes in AquaCrop simulations: crop development, biomass accumulation, and harvest index; the latter due to the simulated effects of extreme temperatures on pollination. AquaCrop has the following developmental stages: planting, emergence, maximum canopy expansion, flowering, onset of canopy senescence, and physiological maturity. The time required from sowing to each particular stage is computed as growing degree days (GDD; °C day). These are calculated by subtracting the base temperature (T<sub>base</sub>) from the average air temperature. Base temperature is the temperature below which crop development does not progress. In AquaCrop, an upper threshold temperature (T<sub>upper</sub>) is also considered. The upper temperature threshold specifies the temperature above which crop development no longer increases with an increase in air temperature.

Three GDD computation methods are proposed in AquaCrop, although Method 3 is the default method. The first two methods are those proposed by McMaster and Wilhelm (1997) for calculating average air temperature. In Method 1, the average air temperature (T<sub>avg</sub>) is given by:

\[
T_{avg} = \frac{(T_x + T_n)}{2}
\]  

where T<sub>x</sub> and T<sub>n</sub> are the daily maximum and minimum air temperatures, respectively. The average temperature (T<sub>avg</sub>) is then calculated and checked to see if it lies between T<sub>base</sub> and T<sub>upper</sub>. If T<sub>avg</sub> is less than T<sub>base</sub>, then T<sub>avg</sub> is taken as T<sub>base</sub> (i.e. 0 °C day for that day). If T<sub>avg</sub> is greater than T<sub>upper</sub>, then T<sub>avg</sub> is taken as equal to T<sub>upper</sub> and the growing degrees for that day are at their maximum (T<sub>upper</sub> - T<sub>base</sub>). In Method 2, the comparison between T<sub>x</sub>, T<sub>n</sub> and T<sub>base</sub> and T<sub>upper</sub> occurs before the calculation of T<sub>avg</sub> and are adjusted if they drop below T<sub>base</sub> or exceed T<sub>upper</sub>. The average temperature in Method 2 is therefore given by:

\[
T_{avg} = \frac{(T_x^* + T_n^*)}{2}
\]  

where T<sub>x</sub>* and T<sub>n</sub>* are the adjusted maximum and/or minimum air temperatures. The following rules also apply: T<sub>x</sub>* is the maximum air temperature (T<sub>x</sub>* = T<sub>x</sub>). If T<sub>x</sub> is greater than T<sub>upper</sub>, then T<sub>x</sub>* = T<sub>upper</sub>. If T<sub>x</sub> is smaller than T<sub>base</sub>, then T<sub>x</sub>* = T<sub>base</sub>. T<sub>n</sub>* is the minimum air temperature (T<sub>n</sub>* = T<sub>n</sub>). If T<sub>n</sub> is greater than T<sub>upper</sub>, then T<sub>n</sub>* = T<sub>upper</sub>. If T<sub>n</sub> is smaller than T<sub>base</sub>, then T<sub>n</sub>* = T<sub>base</sub>.

In Method 3, the one recommended for use in AquaCrop, the comparison to T<sub>base</sub> and T<sub>upper</sub> also occurs before average temperature is calculated, as in Method 2. However, the check only occurs for the maximum air temperature. Average temperature in Method 3 is also given by Equation 2, but where T<sub>x</sub>* is the adjusted maximum air temperature and T<sub>n</sub> the minimum air temperature (i.e. not adjusted). The Method 3 rules are: T<sub>x</sub>* is the maximum air temperature (T<sub>x</sub>* = T<sub>x</sub>). If T<sub>x</sub> is greater than T<sub>upper</sub>, then T<sub>x</sub>* =
$T_{upper}$. If $T_x$ is smaller than $T_{base}$, then $T_x = T_{base}$. $T_n$ is not adjusted. However if $T_n$ exceeds $T_{upper}$, $T_n$ will be set equal to $T_{upper}$. Once $T_{avg}$ is calculated, it is checked to see if the average air temperature is above the base temperature. If $T_{avg}$ is less than $T_{base}$, then $T_{avg}$ is taken as $T_{base}$ (resulting in 0 °C day on that day).

Temperature also affects biomass accumulation and, indirectly, harvest index. Under low temperatures, biomass accumulation is slowed, relative to the rate of transpiration, because of the direct effects of cold on growth and photosynthesis. In AquaCrop, a $K_s$ coefficient is used, which varies between an upper threshold (1) and a lower threshold (0), defined in terms of GDD (Fig. 1).

![Air temperature stresses](image)

**Figure 1.** AquaCrop display showing the direct effects of temperature on biomass production for a cold-sensitive crop.

Extreme low and high temperatures also affect pollination. Figure 2 shows the two logistic curves that determine the degree of pollination failure based on crop-specific temperature thresholds that the user may set for specific conditions, although default values are incorporated in the model.
Figure 2. AquaCrop display showing the direct effects of low and high temperatures on pollination.

Only the upper threshold for the minimum air temperature ($T_{n,\text{cold}}$) and the lower threshold for the maximum air temperature ($T_{n,\text{heat}}$), at which pollination starts to fail, are crop parameters. $T_{n,\text{cold}}$ can range from 0 to +15 °C and $T_{n,\text{heat}}$ from +30 to +45 °C. In AquaCrop, it is assumed that full stress is reached ($K_s = 0$) at 5 °C below (cold stress) or above (heat stress) the specified threshold air temperature.

References


The approach to representing temperature effects in APSIM-Wheat (v7.4)

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APSIM-Wheat is a module within the APSIM farming systems model (Keating et al. 2003). It is the module currently included in the general release of APSIM, although other wheat modules have been programmed in the APSIM simulation environment. APSIM-Wheat has developed from a combination of approaches used in previous APSIM wheat models (Meinke et al. 1997a, 1997b; Asseng et al. 1998a, 1998b; Wang et al. 2003b). The current version of the model is implemented within the APSIM-Plant model framework (Wang et al. 2003a), a generic crop template for developing crop models in APSIM.

In APSIM-Wheat, temperature directly affects phenology, biomass accumulation, and root extension, and has indirect effects on transpiration efficiency and the influence of atmospheric CO₂ concentrations on growth. There are other processes in farming systems affected by temperature (e.g. the nitrogen cycle), which are outside the domain of the wheat model. This abstract summarises the approach to representing direct effects of temperature on crop growth in APSIM-Wheat (release v7.4), which are described in more detail in the model documentation (http://www.apsim.info/Wiki/GetFile.aspx?Page=Module-Documentation&File=Crops.pdf). Some functions have been changed in v7.5. For example, in that version, high temperature accelerates leaf senescence (following the approach of Asseng et al. 2011). However, these are not detailed here as that version has not been used in the AgMIP wheat pilot to date.

Phenology

The APSIM-Wheat model simulates the growth and development of a wheat crop in a daily time-step on an area basis. Wheat growth and development in this module respond to weather (radiation, temperature), soil water, and soil nitrogen. The model uses 11 crop stages and 10 phases (i.e. the time between stages). The stages are: sowing, germination, emergence, end of juvenile, floral initiation (which equates to terminal spikelet in wheat), anthesis, start of grain filling, end of grain filling, physiological maturity, harvest ripe, and end crop. Progression from one stage to the next is determined by accumulation of thermal time (TT, degree days). Each day the phenology routines calculate that day’s TT, except for sowing to germination, which is driven by soil water content. TT is calculated from crown temperatures (Tc). Daily maximum and minimum values of Tc are calculated from maximum and minimum air temperatures, being equal to air temperatures where the maximum and minimum air temperatures are ≥ 0 °C, but a more complex function (not detailed here) of air temperature when ≤ 0 °C.

TT is calculated from a linear function with three cardinal values of Tc (Fig. 1), as used in the original routines in CERES-Wheat. These daily thermal time values are cumulated into a thermal time sum, which is used to determine the duration of each phase.
The sowing to germination phase is not affected by temperature. The phase between germination and emergence is comprised of two periods; there is an initial period (the ‘lag’ phase) of fixed thermal time (40 °Cd) during which shoot elongation is slow; this is followed by period when the rate of shoot elongation towards the soil surface is linearly related to air temperature and sowing depth, with a default rate of 1.5 °Cd mm⁻¹.

![Figure 1](image.png)

**Figure 1.** Relationship between crown temperature and thermal time used in APSIM-Wheat.

The phase between emergence and end of juvenile stages is composed of a cultivar-specific period, commonly called the basic vegetative or juvenile phase, of fixed thermal time; when development rate is not affected by photoperiod. The end of juvenile stage in wheat is currently timed as occurring on the day after emergence, since the development rate of wheat is sensitive to photoperiod from emergence. The end of the juvenile stage is included in the model to make the stages compatible with other cereal crops in APSIM that do have a definable juvenile phase.

It takes 400 °Cd to reach terminal spikelet stage after the end of juvenile stage. During this phase, the daily accumulation of TT is sensitive to photoperiod and accumulation of vernalising days (V) germination and terminal spikelet stages. The model assumes that wheat, as a long day plant, will have a longer phase (dependent upon cultivar) between the germination stage and terminal spikelet under short days. Photoperiod is calculated from day of year and latitude using standard astronomical equations accounting for civil twilight. Accumulation of vernalisation (ΔV) is simulated from daily average value of Tc and daily maximum (Tmax) and minimum (Tmin) temperatures when Tmin is less than 15°C and Tmax is less than 30°C, using the original CERES approach:

\[
\Delta V = \text{min} \{1.4 - 0.0778T_c, 0.5 + [13.44T_c(T_{\text{max}} - T_{\text{min}} + 3)^2]\}
\]

Devernalization can occur if Tmax is greater than 30°C and the accumulated vernalisation is less than 10 (vernalisation is completed at V = 25). The devernalization function is a linear one, with V reduced by half the difference between Tmax and 30°C. V is calculated by summing daily vernalization and devernalization between emergence and terminal spikelet stages. The effect of vernalization on accumulation of TT is cultivar specific.
There are fixed TT durations for the subsequent phases between the terminal spikelet stage and flag leaf (3 phyllochrons), and from flag leaf to anthesis (2 phyllochrons + 80 °Cd). From anthesis to the start of grain fill stages, the thermal duration is assumed to be 120 °Cd, based on CERES Wheat, where 200 °Cd was assumed to elapse between the end of ear growth and the start of grain filling, adjusted for the thermal duration from flag leaf to anthesis. The duration of grain filling is cultivar specific, commonly between 500 and 800 °Cd.

Between the emergence and terminal spikelet stages, daily TT can be reduced by water or nitrogen stresses, resulting in delayed phenology when the plant is under stress. However, the default parameter values in APSIM 7.4 are set so that there are no water or nitrogen stress effects on phenological development.

**Root extension rate**

Up to anthesis, root extension rate is affected by a temperature, defined by linear function with three cardinal values of the temperature factor (Fig. 2).

**Biomass accumulation**

Biomass accumulation in APSIM-Wheat is also affected by temperature, as well as light interception, radiation use efficiency (RUE), atmospheric CO₂ concentration, water stress, nitrogen stress, etc. The temperature stress-RUE function has four cardinal temperatures (Fig. 3), where the mean daily temperature is the average of Tₘₐₓ and Tₘᵢₙ.

![Figure 2. Response of root extension to mean daily temperature used in APSIM-Wheat.](image)

![Figure 3. Response of wheat radiation use efficiency to mean daily temperature used in APSIM-Wheat.](image)
Grain demand for carbon and nitrogen

The daily grain demand for carbon is calculated from grain number, grain filling rate, and temperature and nitrogen factors from anthesis to end of grain filling. The temperature factor is defined by a linear function, equal to 0 at a mean daily air temperature of 0 °C, and 1 at > 26 °C. A similar approach applies for nitrogen demand of grain, which is calculated from grain number, a potential grain nitrogen filling rate, and a temperature factor. The function defining the temperature factor of nitrogen demand is the same as that for carbon, except it equals 1 at > 25 °C (not shown).

References


Temperature Routines in CropSyst

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Temperature is an important physical variable that may affect many processes in CropSyst. For example, the calculation of crop evapotranspiration, and thus transpiration, is affected by the influence of temperature on the energy balance. Temperature also influences the soil surface energy balance, and thus the calculation of soil temperature in the soil profile, which in turn affects biological processes such as nitrogen transformation, soil organic carbon oxidation, and others. This abstract focuses on temperature routines in CropSyst that directly affect crop development, harvest index, and canopy damage by frost.

Crop development

Crop development in CropSyst is based on thermal time accumulation. The thermal time (sum of growing degree days) required for each of the phonologic stages of development must be specified. Degree days are accumulated from planting. Depending on the crop type, the following growth stages may be relevant: emergence, tuber initiation, end of canopy growth, maximum root depth, peak leaf area index (LAI), start of flowering, grain filling, and senescence, and physiological maturity.

Water stress tends to increase the crop canopy temperature, which may accelerate the accumulation of degree-days. The ‘phenological sensitivity to water stress’ parameter, which ranges from 0 to 1, allows users to determine the degree of the effect of water stress. Note that for some crops, phenology may actually be delayed by water stress (negative adjustment factor).

Thermal time accumulation

In CropSyst, thermal time accumulation is calculated hourly, using temperatures derived from the daily maximum and minimum. Degree hours are accumulated for each day and divided by 24 hours/day to
obtain growing degree days that are accumulated throughout the season. The hourly calculation of degree days requires three parameters (e.g. Purcell 2003):

\[
T_{\text{base}} = \text{Base temperature (no accumulation when } T_{\text{hour}} \leq T_{\text{base}}) \quad (1)
\]

\[
T_{\text{opt}} = \text{Optimum (maximum accumulation when } T_{\text{hour}} = T_{\text{opt}}) \quad (2)
\]

\[
T_{\text{max}} = \text{Maximum temperature (no accumulation for } T_{\text{hour}} \geq T_{\text{max}}) \quad (3)
\]

where \( T_{\text{hour}} \) is hourly temperature. The following is an example of hourly degree day accumulation for a given \( T_{\text{hour}} \), where \( T_{\text{base}} = 3 \, ^{\circ}\text{C}; T_{\text{opt}} = 25 \, ^{\circ}\text{C}; \) and \( T_{\text{max}} = 35 \, ^{\circ}\text{C}. \)

![Diagram showing degree-hours accumulation](image)

**Crop water stress adjustment**

To account for possible effects of water stress on canopy temperature, a correction is implemented by adding temperature to the \( T_{\text{max}} \) input. This is adapted from the literature relating canopy temperature measured using infrared thermometry and crop water stress (e.g. Idso 1982) and is defined as:

\[
T'_{\text{max}} = T_{\text{max}} \left[ 1 + (1.5 \cdot VPD_{\text{max}} \cdot \text{StressIndex}_{\text{water}}) \right] \cdot \text{PSWS} \quad (4)
\]

where \( T'_{\text{max}} \) is the adjusted daily maximum air temperature (\(^{\circ}\text{C})\); \( T_{\text{max}} \) is the input daily maximum air temperature (\(^{\circ}\text{C})\); StressIndex\(_{\text{water}}\) is the daily crop water stress index, ranging from 0 (no stress) to 1 (maximum stress); and VPD\(_{\text{max}}\) is the daily maximum vapor pressure deficit (kPA). PSWS is the phenologic sensitivity to water stress crop input parameter. For crops whose development is not expected to be affected by water stress, this correction can be deselected by the user (PSWS = 0).

**Temperature effect on harvest index**

CropSyst calculates yield by multiplying biomass production at physiological maturity by harvest index (HI). This is determined during grain filling using a maximum HI (\( HI_{max} \), a user-defined unstressed sink strength), a maximum translocation fraction, and the fraction of total biomass accretion obtained during grain filling (Kemanian et al. 2007). \( HI_{max} \) can be reduced by heat and cold stresses, using a linear reduction function (0 to 1), with threshold temperatures for no effect and for maximum effect. Different
thresholds and sensitivities can be used for different periods throughout the season. Based on a user-defined window of stress exposure for damage (in hours), for each day in a defined period, an average reduction factor of maximum $H_{\text{Imax}}$ is calculated for the period.

<table>
<thead>
<tr>
<th>Temperature stress period</th>
<th>Cold</th>
<th>Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current period edit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No stress threshold temperature</td>
<td>-0.50</td>
<td>31.00</td>
</tr>
<tr>
<td>Maximum stress threshold temperature</td>
<td>-2.00</td>
<td>44.00</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Hours of stress exposure for damage</td>
<td>4.00</td>
<td>4.00</td>
</tr>
</tbody>
</table>

**Temperature effect on canopy growth**

Canopy LAI development in CropSyst is linked to biomass production and partitioning to leaves, modulated by reduction or full-stop of expansion due to water stress (Stöckle et al. 2003). Thus, temperature effects on crop development and duration of development phases during the growing season will affect biomass production and LAI. Frost damage to leaves is also accounted for in the model, using an approach similar to that described for heat and cold effects on HI, but with frost impacts actuating in each day of occurrence of a frost event, based on minimum temperature.

<table>
<thead>
<tr>
<th>Frost damage to canopy</th>
<th>leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold temperature which begins to damage the plant (leaves)</td>
<td>0.00 °C</td>
</tr>
<tr>
<td>Cold temperature which is lethal to the plant (leaves)</td>
<td>-3.00 °C</td>
</tr>
<tr>
<td>Thermal time at which grain filling may continue after lethal frost</td>
<td>1150 °C-days</td>
</tr>
</tbody>
</table>

**References**


The CSM-CROPSIM Wheat model: Temperature responses

L.A. Hunt\textsuperscript{a} and J.W. White\textsuperscript{b}

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The Cropping System Model (CSM; Jones et al. 2003) has a modular structure insofar as it incorporates individual components from other models. One such component is the CSM-CROPSIM Wheat model, which describes wheat development and growth and is based upon the CROPSIM model, an early version of which was described by Hunt and Pararajaysingham (1995). CSM-CROPSIM Wheat uses the Zadok's scheme for describing the life cycle, has all variables presented in so-called genotype (cultivar, ecotype, and species) files, and conforms strictly to the principle that all process rate calculations are performed before state variables are updated.

The CROPSIM module in CSM is complemented by another wheat component, the CROPSIM-CERES component. This uses the scheme presented by Ritchie (1991) in the CERES model for dividing up the life cycle. CROPSIM-CERES was based on the growth and development routines of the CERES model but was re-structured to conform to the principles that all process rate calculations must be completed before variables are integrated and that all variables be presented in external files and not embedded in the code. CROPSIM-CERES shares many aspects with the CROPSIM module per se.

The overall temperature response of CSM-CROPSIM is determined by the integration of a number of individual process responses. Most of these are driven by mean air temperature, with the actual response curve detailed in terms of four cardinal temperatures: the low temperature at which activity ceases; the lowest and highest temperatures at which activity proceeds at a maximum rate; and a high temperature at and above which there is no activity. Relative activity is determined by linear interpolation between the cardinal temperatures, with the actual process rate calculated by multiplying the relative rate by the maximum process rate. All cardinal temperatures are read from a file (the SPECIES file), which contains characteristic values for all aspects that do not vary among ecotypes and cultivars. The respective processes for which the temperature response is handled as above, together with the abbreviations used for the array of cardinal temperatures, are given in Table 1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature response array</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed germination and emergence</td>
<td>TRGEM *</td>
<td>1</td>
<td>26</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Seed reserve utilization</td>
<td>TRDV1</td>
<td>0</td>
<td>26</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Reproductive development and leaf appearance</td>
<td>TRDV1</td>
<td>0</td>
<td>26</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 1. Cardinal temperatures assumed for effects on major processes in CSM-CROPSIM-Wheat.
It is possible to specify several temperature responses for different phases of the life cycle (as specified in terms of the principal phases of the Zadok’s scale), but currently the only difference is between the phases before and after the grain filling process starts. All processes are driven by mean air temperature, but if snow is present on the soil surface, temperature is assumed to be zero. Soil temperature is not currently used for the listed plant processes, and no account is taken of frozen soil. There is currently no temperature sensitivity for the photoperiod response, although a capability for this is built into the model.

The processes listed in Table 1 determine the overall responses to temperature when adequate nitrogen is available. Under nitrogen limiting conditions, the overall response of several growth (but not development) aspects may be determined by the temperature response of soil organic matter mineralization. This process is calculated for each soil layer, is driven by calculated soil temperatures, and has an exponential response to temperature (Table 2). Soil temperature is calculated using an algorithm based mainly on the average annual temperature, the average annual amplitude in average daily temperature, and the bulk density and water content of the various soil layers, with some modification for the difference between the daily maximum temperature and the long term average temperature for the day (Hillel 2004). The actual algorithm used is:

\[
ZD = -\text{DSMID}(L) / \text{DD}
\]

\[
\text{ST}(L) = \text{TAV} + (\text{TAMP} / 2.0 * \text{COS(ALX + ZD)} + \text{DT}) * \text{EXP(ZD)}
\]

where ZD is soil depth as fraction of the damping depth; DSMID is the depth to midpoint of soil layer L (cm); DD is the damping depth (mm) [From bulk densities, water contents]; ST(L) is the soil temperature for layer L; TAV is the average annual air temperature (°C); TAMP is the average annual amplitude in mean monthly temperature (°C); and ALX is the difference from hottest day (radians). DT is the difference between the last five days average temperature and the calculated normal temperature for the day:

\[
\text{DT} = \text{ATOT} / 5.0 - \text{TA}
\]
where ATOT is the sum of an array of the last 5 days adjusted temperature (°C), which considers effects of maximum temperature, solar radiation and albedo. Finally:

\[ TA = \frac{TAV + TAMP \times \cos(ALX)}{2.0} \]

The default values for TAV and TAMP are 20.0 °C and 5.0 °C. These are inappropriate for many wheat growing regions, so care should be taken to ensure that values for these parameters are provided in the daily weather files.

Table 2. Assumed effect of soil temperature (at a given depth) on nitrogen mineralization.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Temperature factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>10.0</td>
<td>0.32</td>
</tr>
<tr>
<td>20.0</td>
<td>0.73</td>
</tr>
<tr>
<td>30.0</td>
<td>1.36</td>
</tr>
<tr>
<td>40.0</td>
<td>2.18</td>
</tr>
</tbody>
</table>

CSM-CROPSIM Wheat is set up to allow easy examination of the temperature responses of different plant processes. The input files containing information on crop management have a section dealing with environmental modifications, which allows a user to set up a sequence of simulation runs with varying daily maximum and/or minimum air temperatures, but with the same general management. Changes to air temperature are not currently applied to the values used in the soil temperature algorithm, so that the rate of soil organic matter decomposition will not reflect the changed temperatures. Outputs obtained under conditions of limited nitrogen nutrition, when mineralization would be important, should thus be interpreted with caution. Outputs for reproductive development aspects, or for growth aspects obtained under adequate nitrogen nutrition, however, should be suitable for detailed scrutiny. For this, application of the approach detailed by White et al. (2005) would be useful.

References


A description of temperature routines in EPIC-Wheat

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Temperature is a fundamental forcing variable used in the EPIC model to simulate crop growth as well as biophysical and biogeochemical processes (Fig. 1). The EPIC model can directly ingest daily air temperature data or, alternatively, generate daily air temperature from monthly weather inputs. The particular generator used is a multivariate normal model that considers the serial correlation of temperature and other weather variables. Air temperature is then used to estimate daily soil temperature. The primary biophysical variables related to temperature include relative humidity, saturation vapor pressure, vapor pressure deficit, potential and actual evapotranspiration, and snow variables such as snowfall and snowmelt. In particular, five algorithms are available to calculate potential evapotranspiration (ET).

The simulation of crop growth and its underlying phenological and biogeochemical processes is based on daily heat unit accumulation. The heat unit (HU) is defined as the difference between daily mean temperature and a crop-specific base temperature $T_{\text{base}}$:

$$ HU = (T_{\text{max}} + T_{\text{min}})/2 - T_{\text{base}} $$

(1)

HU is accumulated on a daily basis and can be normalized with respect to the potential heat units of crops (PHU) to get a heat unit index (HUI), which equals 0 at planting and 1 at physiological maturity (i.e. $HUI(d) = \sum_{i=1}^{PHU} HU_i$). HUI is a key measure in predicting plant development, such as leaf area growth and senescence, optimal plant nutrient concentrations, partitioning of dry matter, and date of harvest. When predicting leaf area index (LAI) and canopy height, HUI is converted to a heat unit factor (HUF), according to crop-specific parameters $l_1$ and $l_2$:

$$ HUF = HUI/[HUI + \exp(l_1 - l_2 \cdot HUI)] $$

(2)

The optimal growth in LAI on the $d$th day, for the $i$th crop, is then calculated by:

$$ \Delta LAI_i^i(d) = (HUF_i^i(d) - HUF_i^i(d-1)) \cdot LAI_{i_{\text{max}}}^i \cdot \frac{LAI_i^i(d-1)}{TLAI_i(d-1)} $$

(3)

where $LAI_{i_{\text{max}}}$ is the maximum LAI for Crop $i$; $LAI_i^i(d-1)$ and $TLAI_i(d-1)$ are the LAI at the beginning of Day $d$ for Crop $i$ and all crops, respectively. Canopy height is estimated as:

$$ CHT(d) = H_{\text{max}} \cdot \sqrt{HUF(d)} $$

(4)

Similarly, HUI is used to estimate nutrient uptake. For example, the optimal nitrogen content for a crop on a given day can be derived as:

$$ UNO = DM \cdot (b_1 + b_2 \exp(-b_3 \cdot HUI)) $$

(5)
where DM is the accumulated biomass; and $b_1$, $b_2$, and $b_3$ are crop-specific parameters. Also, HUI serves as an important input for estimating harvest index (HI); defined as the fraction of above-ground dry biomass removed as economic yield. Given the minimum and potential values of HI for a crop (i.e. HIMN and HIP), the HI value on a given day is computed by:

$$HI = \frac{SWH}{SWH + \exp(5.56 - 0.0315 \cdot SWH)} \cdot \left(\frac{HIP - 100 \cdot HUI}{100 \cdot HUI + \exp(11.11 - 10HUI)} - HIMN\right) + HIMN$$  (6)

where SWH is the accumulated plant water use when HUI falls between 0.1 and 1.0, therefore representing the sum of actual plant ET up to Day $d$.

Actual crop growth and yield are regulated by many constraints. In particular, the temperature stress factor is computed as:

$$TS = \begin{cases} 
\sin(1.5706 \cdot RTO), & 0 < RTO < 2 \\
0, & \text{otherwise}
\end{cases}, \text{and}$$  (7)

$$RTO = \frac{(T_{mean} - T_{base})}{(T_{opt} - T_{base})}$$  (8)

where $T_{mean}$ is daily mean temperature and $T_{opt}$ is a crop-specific optimal temperature. TS, combined with other stresses from nutrient, water, and aeration (i.e. NS, WS, and AS), can be applied to limit optimal growth for computing actual growth. For example, the actual LAI increase is an adjusted version of $\Delta LAI^i(d)$:

$$\Delta ALAI^i(d) = \Delta LAI^i(d) \cdot \min(TS, NS, WS, AS)$$  (9)

Figure 1 depicts a more detailed picture of the key processes related to temperature; either air or soils. Numbers listed there indicate the indices of equations in EPIC’s theoretical documentation for calculating the relevant variables.
Figure 1. Diagram depicting how EPIC algorithms use air temperature to estimate biological (e.g. plant growth, plant temperature stress), biophysical (e.g. evapotranspiration, freezing / thawing), and biogeochemical (e.g. soil respiration) processes. Numbers on lines connecting processes and process controllers refer to equation numbers, which can be found in the APEX (EPIC) theoretical manual (Williams et al. 2008; http://apex.tamu.edu/).

References
Temperature effects on crop development in FASSET: A description of the simulated processes

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The Farm ASSeessment Tool (FASSET) crop model (Berntsen et al. 2003) is a deterministic, dynamic model programmed in C++. It simulates crop growth in terms of dry matter (DM) accumulation in a daily time-step. DM accumulation is affected by temperature, solar radiation, water and nitrogen (N) availability, and atmospheric CO₂ concentration. The FASSET model requires daily maximum and minimum temperature, precipitation, potential evapotranspiration, and global radiation values. It has been calibrated and tested for use in wheat and other arable crops in Danish cropping systems (e.g. Olesen et al. 2002; Doltra et al. 2011) and is currently being extended to other cropping systems and agroclimatic regions (Doltra et al. 2012). A detailed description of the crop model can be found in Olesen et al. (2002). Here we present the temperature algorithms and routines involved in the simulation of wheat growth.

Phenology

The developmental phase of wheat is controlled by temperature sums, which are calculated by summing mean air temperatures above a specified threshold:

\[ S_{n,i} = \sum_{j=a}^{i} (T_j - T_b)_+ \]  

where \( S_{n,i} \) is the temperature sum in period \( n \) (starting at day \( a \) and ending on day \( i \)); \( T_j \) is the daily mean air temperature at day \( j \); and \( T_b \) is the base temperature in the \( n \)th period (°C). The subscript (+) indicates that only positive values are considered. The effect of temperature on the duration of developmental phases is modified by photoperiod during the phase of emergence to anthesis.

Phenological development is regulated by growth phases. The end of a phase has a specific index \( (F) \), and each index has a corresponding temperature sum \( (S_F) \).
FASSET operates with a simple development stage index:

<table>
<thead>
<tr>
<th>Index F</th>
<th>Phase</th>
<th>Start of phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>Not sown</td>
<td></td>
</tr>
<tr>
<td>[-1;0]</td>
<td>sown but not emerged</td>
<td>Sown</td>
</tr>
<tr>
<td>[0; 1]</td>
<td>vegetative growth</td>
<td>Emerged</td>
</tr>
<tr>
<td>[1;2]</td>
<td>Reproductive</td>
<td>Anthesis</td>
</tr>
<tr>
<td>[2;3]</td>
<td>Ripening</td>
<td>End of Grain filling</td>
</tr>
<tr>
<td>3</td>
<td>Ripe</td>
<td></td>
</tr>
</tbody>
</table>

Before sowing, $F$ is -2; when the crop is sown it becomes -1; and from there it increases each day with a positive temperature sum ($S_{ni}$) according to:

$$F_{n,i} = F_{n,i-1} + \frac{S_{ni}}{S_n}$$  \hspace{1cm} (2)

where $F_{n,i}$ is the phenological index in phase $n$ on the $i^{th}$ day.

**Crop growth**

At crop emergence, the DM of the crop ($W_i$ g m$^{-2}$) is set to equal DM in the seed. Half the DM from the seed is assigned to top DM ($W_t$) and the other half to root DM ($W_r$). The amount of DM in the crop on the $i^{th}$ day ($W_i$) is calculated as:

$$W_i = W_{i-1} + \varepsilon \cdot f_{PAR} f_E g(N) f_T(T_i) R_{pi}$$  \hspace{1cm} (3)

where $W_{i-1}$ is total crop DM on the previous day; $\varepsilon$ is the radiation use efficiency (g MJ$^{-1}$); $f_{PAR}$ is the fraction of intercepted radiation that depends on green leaf area index; $f_E$ is the ratio of actual to potential transpiration; $g(N)$ accounts for the effect of N status; $f_T(T_i)$ is a temperature function taken from Hansen et al. (1990; see eq. 4). A modification of this function could be used to simulate the impact of heat stress. $R_{pi}$ is the daily incident photosynthetic active radiation (MJ m$^{-2}$) set to 48% of global radiation.

$$f_T(T_i) = \begin{cases} 0 & T < T_{\alpha} \\ \frac{T - T_{\alpha}}{T_{\beta} - T_{\alpha}} & T_{\alpha} \leq T < T_{\beta} \\ 1 & T_{\beta} \leq T \end{cases}$$  \hspace{1cm} (4)

where $T_{\alpha}$ and $T_{\beta}$ are the temperatures thresholds for minimum and maximum dry matter production, respectively. The partitioning of $W_i$ in above-ground and below-ground DM declines linearly with time,
following the approach of the DAISY model (Hansen et al. 1990). The part of above-ground matter transferred to the storage organs is calculated according to Olesen et al. (2002).

**Root growth**

Development of the root system is a linear function of the accumulated temperature from crop emergence until a maximum root depth ($z_s$). The daily increase in root depth ($z_r$) is given by:

$$\Delta z_r = \begin{cases} a_r (T_{sz} - T_{bs}) & z_r < z_s \\ 0 & z_r \geq z_s \end{cases}$$  \hspace{1cm} (5)

where $a_r$ is set to 0.0025 m °C per day (Hansen et al. 1990); $T_{sz}$ is the daily mean soil temperature at depth $z_r$; $T_{bs}$ is the base temperature; and $z_s$ is the maximum root depth. Soil temperature is calculated with a heat flow equation based on the approach of Hansen et al. (1990).

**Green Area Index (GAI)**

A linear growth rate of GAI is simulated during the first 200 °C (base 0 °C) after emergence. Daily GAI expansion ($\Delta L_g$) is calculated by:

$$\Delta L_g = a_l D (T - T_b)$$  \hspace{1cm} (6)

where $D$ is plant density (m$^{-2}$); $T$ is mean daily air temperature (°C); $T_b$ is the base temperature; and $a_l$ is the expansion rate, which is set to 1.28 $10^{-5}$ m$^2$ °C$^{-1}$ (Porter 1984). Prior to anthesis, GAI expansion might be limited by phenological stage, dry matter, or nitrogen, according to:

$$\Delta L_g = \min(0.0092(T - T_b) + f_E f_P L_g, 0.0111 W - L_g, 0.4 U - L_g)$$  \hspace{1cm} (7)

where $f_E$ and $f_P$ are functions of actual transpiration and phenological stage, respectively; $W$ is the above-ground vegetative biomass; and $U$ is the actual crop N content.

GAI senescence is assumed to start at the two-leaf stage (computed from temperature sum after emergence) and is dependent on temperature and drought stress (described by the ratio of actual to potential transpiration ($E_{ta}/E_{tp}$)):

$$\Delta L_g = \frac{(T-6)}{a_s (1-b_s)} \left(1 - \frac{E_{at}}{E_{tp}} \right) L_{gx}$$  \hspace{1cm} (8)

where $L_{gx}$ (m$^2$ m$^{-2}$) is the maximum modeled GAI; $a_s$ is the duration of senescence equivalent to the period from anthesis to yellow ripeness; and $b_s$ is a factor that increases senescence under drought conditions.

**Soil N and C turnover**

Soil N and C dynamics influence the availability of soil N for uptake by the crop. The turnover of all pools follows first-order kinetics and is modified by temperature and soil water potential (Petersen et al. 2005). Three types of soil organic matter pools are considered in the model: added organic matter,
microbial biomass, and soil organic matter. The added organic matter is divided into the slowly (AOM1) and easily (AOM2) decomposable fractions. The decay of AOM1 and AOM2 pools is routed to the microbial biomass prior to the native organic matter (NOM). Partially decomposed materials (i.e. animal manure) have a fraction that goes directly to NOM. Mineralization and immobilization of N, as well as nitrification, are simulated. In this approach, C and N fluxes are calculated from all pools and N follows C stoichiometrically.

References


GLAM essential temperature routines

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Brief overview

The General Large Area Model (GLAM) for annual crops was designed to operate on spatial scales commensurate with those of global and regional climate models. GLAM was originally developed for groundnut in India (Challinor et al. 2004) and adapted for spring wheat in China by Li (2008).

GLAM determines the growth, development, and yield of annual crops by combining a soil water balance model with crop growth parameterizations. Between crop emergence and harvest, the daily increase in crop biomass is determined using a transpiration efficiency (TE) concept, whereby a crop specific TE (reduced under high vapor pressure deficit conditions and high temperatures) is used to convert crop transpiration to new biomass assimilated. Crop transpiration is determined from the potential evapotranspiration, as determined by the atmosphere, potentially extractable soil water, and the crop’s leaf area index (LAI). The length of the crop growing season (i.e. from emergence to harvest) is dependent on the accumulation of thermal time. Final yield is the product of biomass at the end of the growing season and harvest index. Harvest index increases at a prescribed rate during the later growth stages to represent partitioning of biomass to the harvested organs (e.g. grains). A yield gap parameter is used to reduce LAI from the physical value to an effective value, to account for mean effects of pests, diseases, and non-optimal management. It is calibrated to regional scale yield observations.

GLAM thermal time development (Challinor et al. 2004; Li 2008)

The simulation of developmental stages is controlled by the accumulated thermal time. Once the thermal time accumulation (tTT) reaches a specified thermal time for a given stage, the next developmental stage begins. Thermal time accumulation for each development stage is given by:

\[
t_{TT} = \int_{t_i}^{t_{i+1}} (T_{eff} - T_b)dt
\]

where \( t \) (days) is the time; \( T_b \) (°C) is the base temperature, below which crop development is zero; \( i \) is the number of the development stage; and \( t_{TT} \) (°Cd) is the thermal time. Thermal time is accumulated as the daily effective temperature (\( T_{eff} \)) exceeds the base temperature (\( T_b \)). The development stage \( i \) begins at time \( t_i \) and ends at time \( t_{i+1} \), as thermal time accumulation reaches the specified thermal duration.

\( T_{eff} \) (°C) is determined by the base \( T_b \) (°C), optimum \( T_o \) (°C), and maximum \( T_m \) (°C) temperatures. \( T \) (°C) is the daily mean temperature. We assume optimal development up to \( T_m \). This is different to Li (2008), who used a triangular function for calculating crop development:

\[
T_{eff} = \begin{cases} T & \text{for } T < T_o \text{ and } T \geq T_b \\ T_o & \text{for } T \geq T_o \text{ and } T \leq T_m \\ 0 & \text{for } T < T_b \text{ or } T > T_m \end{cases}
\]
For the developmental stages, the model uses cardinal temperature values according to Osborne et al. (2012):

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Sowing to Anthesis</th>
<th>Anthesis to Grain-filling</th>
<th>Grain-filling to End of Grain-filling (Physiological Maturity)</th>
<th>End of Grain-filling to Harvest Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_s) in °C</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(T_o) in °C</td>
<td>23</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>(T_m) in °C</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

(For the HSC AgMIP runs, the thermal time needed for each crop developmental stage was calibrated to the anthesis and physiological maturity date given for the HSC treatment 33)

**High temperature stress around flowering** (Osborne et al. 2012)

High temperature stress (HTS) at flowering was included by reducing the prescribed rate of harvest index increase by a reduction factor; calculated as the mean over the flowering growth stage of:

\[
1 - \left(\frac{T - T_{crit}}{T_{zero} - T_{crit}}\right)
\]

(3)

where \(T\) is the mean daily temperature; \(T_{crit}\) is the temperature above which harvest index is reduced; and \(T_{zero}\) is the temperature above which the seed set is entirely aborted. The values of \(T_{crit}\) and \(T_{zero}\) were set to 28°C and 36°C, respectively (Osborne et al. 2012). This HTS parameterization is a simplification of the original HTS parameterization (Challinor et al. 2005; Li 2008) in order to increase the speed of the simulations.

**Increased senescence**

Increased senescence was added according to Asseng et al. (2011). If daily \(T_{max}\) > 34°C, leaf senescence hastens according to a factor:

\[
F_{heat} = 4 - (1 - (T_{max} - 34)/2).
\]

(4)

**Vapor pressure deficit** (Challinor et al. 2004)

Vapor pressure deficit (VPD) is parameterized as:

\[
VPD = C_V [e_{sat}(T_{max}) - e_{sat}(T_{min})]
\]

(5)

where \(C_V\) is a constant (Tanner and Sinclair 1983). The saturation VPD at temperature \(T\), \(e_{sat}(T)\), is determined after Bolton (1980). VPD is used for calculations of potential evapotranspiration and above-ground biomass.

**Decrease in TE with high mean temperature** (Challinor et al. 2009)
$T_{ter1}$ and $T_{ter2}$ are temperature thresholds between which TE reduces linearly from its non-temperature-limited value, to zero. This therefore represents reduced photosynthesis with high temperatures. $T_{ter1}=25^\circ C$ and $T_{ter2}=30^\circ C$ are taken from Osborne et al. (2012).

References


Temperature driven processes in the crop module of the HERMES model

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The HERMES model (e.g. Kersebaum 2007, 2011) is an agro-ecosystem model that simulates soil-crop interactions, with an emphasis on water- and nitrogen-related processes. Many processes in HERMES are influenced by temperature, mostly in a non-linear way. Although soil processes also influence crop growth, the following text focuses only on the temperature-related processes within the crop module. The model follows a generic approach, defining crop specific parameters in external files; therefore a general formulation of processes is given here (though concrete functions are related to wheat).

Phenological development

Phenological development is described using the thermal summation approach. The effective temperature is limited by a minimum temperature, which is referred to as base temperature $T_b$. If applicable in a specific development phase $n$, the accumulation of thermal sum can be modified by factors accounting for day length and vernalization effects. Thermal sums, as well as requirements for day length and vernalization, have to be defined separately for each development stage:

$$DD_{n,t} = DD_{n,t-\Delta t} + (T_{av} - T_{bn}) \cdot b_S \cdot b_V \cdot b_D \cdot \Delta t \quad (1)$$

where

$$b_S = 1 + 0.2 \cdot (1 - \zeta_W)^2 \quad (2)$$

and

$$b_V = \left(\sum V_{act} - V_{bas}\right) / (V_{req,n} - V_{bas}) \quad (3)$$

where $DD_{n,t}$ is the actual temperature sum in developmental stage $n$; $DD_{n,t-\Delta t}$ is the temperature sum of the last time step (t-\Delta t) in developmental stage $n$; $T_{av}$ is the daily mean air temperature at 2 m above ground; $T_{bn}$ is the base temperature of developmental stage $n$; $b_S$ is the acceleration factor for water stress; $b_V$ is the vernalization factor; $b_D$ is the day length factor; and $\zeta_W$ is the drought stress factor.

The calculation of the vernalization factor uses the sum of $V_{act}$ as a fraction of each day, according to: dependence on the daily average temperature as shown in Fig. 1; the required vernalization days ($V_{req,n}$) in developmental stage $n$; and a number of base vernalization days $V_{bas}$ (9 days), which is $(V_{req,n} - 1)$, if $V_{req,n}$ is smaller than 9 days, or zero when $V_{req,n}$ is zero. No vernalization and day length requirements were set for the Maricopa variety.
Crop growth

Simulating crop growth follows a generic approach where the basic algorithms are based on the SUCROS model (van Keulen et al. 1982). Daily net dry matter production by photosynthesis and respiration is driven by radiation and temperature.

Gross CO₂ assimilation \( (A_g) \) is calculated by converting radiation or sunshine duration into fractions of clear and overcast sky to describe light interception, according to Goudriaan and van Laar (1978).

The plant-specific maximum CO₂ assimilation rate at light saturation \( A_{max} \) is a function of temperature, which is defined separately for C3 and C4 crops in HERMES. The dependency of \( A_{max} \) on temperature for C3 crops is shown in Figure 2A.

Fig. 2:  
A) Temperature dependence of maximum CO₂ assimilation rate \( (A_{max}) \) at light saturation for C3 crops. \( T_{min_{crop}} \) denotes the crop specific minimum temperature for growth (4 C° for wheat).

B) Temperature dependence of maintenance respiration factor \( k_{r_{sp}} \).
Growth respiration is calculated as 30% of gross assimilation, and crop maintenance respiration $R_m$ is determined as:

$$R_m = k_{esp} \cdot \sum (R_{org,i} \cdot W_{org,i})$$

(4)

where $W_{org,i}$ is the mass of each crop organ $i$; $R_{org,i}$ is the organ-specific maintenance respiration coefficient (day$^{-1}$), defined for a standard temperature of 25 °C; and $k_{esp}$ is the temperature scaling factor (Fig. 2B).

Atmospheric CO$_2$ concentration, denoted as [CO$_2$], has an impact on the crop’s photosynthesis rate and stomata resistance, which in turn influences transpiration (Nendel et al. 2009; Kersebaum and Nendel 2013). HERMES has the option of choosing between three different algorithms to consider the effect of [CO$_2$]. One option, based on Mitchell et al. (1995), is described in detail by Nendel (these proceedings) for the MONICA model. A second approach from Nonhebel (1996) was also integrated. However, for the MARICOPA simulations, a simpler third approach based on Hoffmann (1995) was used, which adjusted $A_{max}$ by the factor

$$K_{CO_2} = \frac{(C_a - \Gamma^*)/(k_1 + C_a - \Gamma^*)}{(C_{a0} - \Gamma^*)/(k_1 + C_{a0} - \Gamma^*)}$$

(5)

where $C_{a0}$ denotes the ambient [CO$_2$] (350 ppm) and $C_a$ the elevated [CO$_2$]. Furthermore:

$$k_1 = 220 + 0.158 \cdot l_g$$

(6)

and

$$* = 80 - 0.0036 \cdot l_g,$$

(7)

where $l_g$ is the global radiation.

The [CO$_2$] effect on transpiration was calculated using the Penman-Monteith formula, according to Allen et al. (1998), and using the stomata resistance calculation suggested by Yu et al. (2001), as:

$$r_s = \frac{C_s \left(1 + \frac{D}{D_0}\right)}{a \cdot A_g}$$

(8)

where $a$ is a constant; $A_g$ denotes the gross photosynthesis rate; $D/D_0$ describes the air water vapor deficit; and $C_s$ is the ambient CO$_2$ concentration at leaf level, which was set equal to $C_a$ in this case. $D_0$ and $a$ were used for parameter calibration using the data of the German FACE experiment (Weigel and Dämmgen 2000). Indirectly, temperature affects this equation through photosynthesis and vapor pressure deficit.
References


InfoCrop is a Decision Support System (DSS) based on a generic crop growth model and described in detail by Aggarwal et al. 2006. This DSS is designed to simulate the effects of weather, soil, agronomic management (including sowing time, nitrogen, residues, and irrigation), and major pests on crop growth and yield. The basic crop model has been written in Fortran Simulation Translator programming language (FST/FSE; Graduate school of Production Ecology, Wageningen, the Netherlands; Van Kraalingen 1995). In this model, the total crop growth period is divided into three phases: sowing to seedling emergence; seedling emergence to anthesis; and storage organ filling.

The model requires inputs on varietal coefficients relating to phenology, growth, and source-sink balance. The phase-wise phenology parameters are base temperature and thermal time requirements for three phenological phases, optimal and maximal temperatures, and sensitivity to photoperiod. Required growth parameters include radiation use efficiency (RUE), growth rates of leaf area and root, specific leaf area, light interception at maximum canopy size, etc. The necessary source-sink balance parameters are rate of grain fill, potential storage organ weight, N content of the storage organ, and sensitivity of the storage organ setting to low- and high temperatures. In most cases, the thermal times of three phenological phases, sensitivity to temperature and photoperiod, early vigor, index of storage organs formation, and the potential weight of the storage organs were sufficient to adequately characterize the varieties.

Crop management input data include time of planting, seed rate, depth of planting, amount, time and depth of placement of different organic matters and nitrogen, and amount, time, and type of irrigation, etc. The soil input data required are textural parameters, thickness (three user defined layers), bulk density, saturated hydraulic conductivity, soil organic carbon, pH, slope, soil water holding capacity, and permanent wilting point for each of the three soil layers. The model also requires daily weather data (minimum and maximum temperatures, rainfall, solar radiation, wind velocity, and vapor pressure), and it includes a provision for changing the atmospheric CO₂ concentrations. Initial soil water and nitrogen content data are required at the start of each simulation. The influence of climate change parameters (change in temperature and CO₂, and rainfall) are simulated by influencing the phenology, growth, and source–sink aspects of the crop in the following ways.

Effects on phenology

The total development of a crop is calculated by integrating the temperature-driven developmental rates of the three phases described above. The rate of development from sowing to seedling emergence is dependent on thermal time and moderated by the available soil moisture. The seedling emergence to anthesis phase is divided into three major sub-phases, depending upon environmental factors. The rate of development is linearly related to the daily mean temperature, from base temperature to the
optimum temperature; the rate decreases above the optimum temperature, and if temperature goes below the base temperature or above the maximum temperature of growth, the rate of development becomes zero. This is modulated depending on the sensitivity of the crop/cultivar to the photoperiod, water- and nitrogen stress. In the case of rice, transplantation shock slows down the developmental rate. Similar to the vegetative development, the duration of storage organ filling phase is also dependent on crop/cultivar-specific thermal time and is modified by water and nitrogen stress.

**Effects on dry matter accumulation, partitioning**

Dry matter production is a function of RUE, photosynthetically active radiation, total leaf area index (LAI), and a crop/cultivar specific light interception coefficient. RUE is further modified to account for developmental stage, crop-specific response of photosynthesis to temperature, CO₂, water and nitrogen availability, and other biotic factors. The effect of temperature mimics a crop-specific decrease in photosynthesis due to adverse mean daytime temperature. The net dry matter available each day for crop growth is partitioned into roots, leaves, stems, and storage organs as a crop-specific function of developmental stage, which (as mentioned above) is a temperature-driven state variable.

Net leaf area growth rate is a function of initial specific leaf area, initial LAI, dry matter partitioning to the leaf, senescence, and net loss in leaf area due to stresses. When LAI is < 0.75 during the initial stages of development, there is a greater control of temperature over the formation of leaf area. The photosynthetic characteristics of the non-lamina green areas are assumed to be the same as those of leaves. Non-lamina green area senescence rate is accelerated by temperature. Simulation of leaf senescence is based on several empirical constants relating to shading, ageing, nitrogen remobilization, temperature, water stress, and death due to pests and diseases. Temperatures higher or lower than the optimum accelerate rate of senescence, depending upon the crop sensitivity to temperature.

**Influence on source-sink balance**

The number of spikelets formed is determined shortly before anthesis. In InfoCrop, the net growth during this period and a crop-specific factor relating storage organ to growth are utilized to calculate the increase in grain number. A percentage of grains formed could be lost due to pests or adverse temperatures. Adverse temperatures during the meiosis stage could also significantly increase sterility. In InfoCrop, a part of the storage organ becomes sterile if either the maximum or minimum temperatures of the day deviate from their respective threshold values during anthesis and a few days afterwards. This reduces the number of storage organs subsequently available for accumulating weight. The storage organs start filling up shortly after anthesis, with a rate dependent on temperature, potential filling rate, and the availability of dry matter. Growth of the storage organs is terminated on the attainment of potential weight, or due to non-availability of dry matter, and on fulfillment of the thermal time-dependent development stage.

**Evapotranspiration**

Potential evapotranspiration is estimated from radiation balance and air-drying power, and is influenced by temperature. The extent of evaporation and transpiration depends on canopy and soil characteristics and atmospheric evaporative demand.
**Frost damage**

Frost days were considered as any day when the minimum temperature fell below a crop-specific minimum temperature. Such frost, depending upon its duration, was assumed to affect leaf and non-leaf green area index in proportion to its sensitivity. Irrigation is known to partially alleviate frost damage. This has been mimicked in InfoCrop by reducing the damage due to frost in cases where the available water fraction in surface soil layer exceeds a certain level.

**Soil nitrogen and carbon dynamics**

InfoCrop simulates the processes of mineralization, immobilization, nitrification, denitrification, and urea hydrolysis. The effects of temperature, moisture, and pH (the most important abiotic factors affecting the N-transformation processes) in the soil are also accounted for. InfoCrop considers temperature separately, as this is the most dominating factor regulating biological activities. Temperature effects are also considered when simulating soil carbon dynamics such as mineralization, immobilization, and methane and CO₂ emissions.

**Models and application**

The InfoCrop model is well calibrated and validated for simulating the growth and yield of wheat and rice (Aggarwal et al. 2006), maize (Byjesh et al. 2010), sorghum (Srivastava et al. 2010), mustard (Bhoomiraj et al. 2010), potato (Singh et al. 2005), cotton (Hebbar et al. 2008), soybean and ground nut (Bhatia et al. under review), and coconut (Naresh Kumar et al. 2008) for the Indian region, and can be used for tropical conditions worldwide. This model is being applied in climate change impact assessments, deriving adaptation gains, crop yield forecasts, crop management, yield gap analysis, etc. Some of the immediately available recent references are provided below.

**References**


Naresh Kumar S. and Aggarwal, P.K. 2013. Climate change and coconut plantations in India: Impacts and potential adaptation gains. Agricultural Systems http://dx.doi.org/10.1016/j.agsy.2013.01.001


Phenological development

The simulated daily increase in temperature sum from emergence is based on a table, in which the increase is dependent on the average daily temperature. The actual increase in temperature sum can be calculated with or without a reduction for sub-optimal day length. The increase in the crop’s development stage is calculated as the increase in temperature sum, divided by the temperature sum requirements for the vegetative and the generative periods:

*------ Change in temperature sums from sowing/planting (P) and from emergence for crop development without and with day length effect

\[ DTSULP = \text{LIMIT}(0., \text{TEFFMX-} \text{TBASEM}, \text{TMPA-} \text{TBASEM}) \times \text{PUSHPL} \]

\[ \text{IF (.NOT. YCH)} \quad \text{PUSHEM} = \text{INSW(DAY - DAYEM, 0., 1.)} \]

\[ \text{IF (YCH)} \quad \text{PUSHEM} = \text{INSW}(365. + \text{DAY-} \text{DAYEM, 0., 1.)} \]

\[ \text{DTSU} = \text{MAX}(0., \text{LINT(DTSMIB, ILDTSM, TMPA)}) \]

\[ \text{DTSUM} = \text{DTSU} \times \text{PUSHEM} \]

\[ \text{DTSUML} = \text{DTSU} \times \text{PUSHEM} \times \text{RDAYL} \]

* Calculation of development stage

\[ \text{IF (DVS .LT. 1.0) THEN} \]

* effects of day length and temperature on development during vegetative phase

\[ \text{DVR} = \frac{\text{DTSUML}}{\text{TSUM1}} \]

ELSE

* development during generative phase

\[ \text{DVR} = \frac{\text{DTSUML}}{\text{TSUM2}} \]

END IF

Daily growth rate

Growth rate is determined by radiation use efficiency (RUE), light interception, and correction factors for non-optimal daytime temperature, low minimum temperature, and atmospheric CO₂ concentration:

*------ Radiation use efficiency as dependent on development stage (g DM MJ⁻¹)

\[ \text{RUE} = \text{LINT(RUETB, ILRUE, DVS)} \]

*------ Correction of radiation use efficiency for change in atmospheric CO₂ concentration (-)

\[ \text{RCO} = \text{LINT(COTB, ILCO, CO)} \]

*------ Reduction of radiation use efficiency for non-optimal day-time temperatures and for low minimum temperature

\[ \text{DTEMP} = \text{TMAX} - 0.25*(\text{TMAX-} \text{TMIN}) \]

\[ \text{RTMP} = \text{LINT(TMPTB, ILTMPF, DTEMP)} \times \text{LINT(TMNTB, ILTMNF, TMIN)} \]

*------ Correction of RUE for both non-optimal temperatures and atmospheric CO₂

\[ \text{RTMCO} = \text{RTMP} \times \text{RCO} \]
SUBROUTINE GROWTH(DAY, EMERG, PAR, KDIFF, NLUE, LAI, RUE, RTMCO, TRANRF, 
  $                                   FINT, FINTT, NNI, PARINT, GRT)
  IMPLICIT REAL (A-Z)
  LOGICAL EMERG
  SAVE

  TINY = 0.001
  IF (EMERG) THEN
    PARINT = PAR * (1. - EXP(-KDIFF*LAI))
  ELSE
    PARINT = 0.
  END IF

  * Fractional light interception for resp. PAR and total radiation [-]
  FINT = PARINT/PAR
  KGLOB = 0.75 * KDIFF
  FINTT = 1. - EXP(-KGLOB*LAI)

  * Nitrogen reduction factor (new relationship included for NREF)
  * NREF = EXP(-NLUE*(1.0-NNI))
  NREF = LIMIT(0., 1.0, 1.-NLUE*(1.0001-NNI)**2)

  * Growth rate GRT in kg DM ha-1 d-1 calculated from PARINT in
  * MJ PAR/m2 and RUE in g DM/ MJ PAR --> multiply with 10
  IF(TRANRF .LE. NREF) THEN
    * Water stress is more severe as compared to nitrogen stress
    GRT = 10*RTMCO * RUE * PARINT * TRANRF
  ELSE
    * Nitrogen stress is more severe as compared to water stress
    GRT = 10*RTMCO * RUE * PARINT * NREF
  ENDIF

  RETURN
END

Death rate of leaves

Relative death rate of leaves due to senescence increases with rising values for the average daily temperature:

* --------------------------------------------------------------------- *
* SUBROUTINE DEATHL                                                   *
* Purpose: To compute the relative death rate (d-1) of leaves due to age, *
* shading and drought and due to nitrogen stress and the death rate of leaves in total (kg ha-1 d-1) *
* --------------------------------------------------------------------- *
SUBROUTINE DEATHL(DAY, EMERG, DVS, DVSDLT, RDRTMP, RDRSHM, RDRRL, TRANRF, 
  $                                   LAI, LAICR, WLVG, RDRNS, NNI, SLA,
  $                                   RDRDV, RDRSH, RDR, DLV, DLVS, DLVNS, DLAIS, DLAINS, DLAI)
  IMPLICIT REAL (A-Z)
LOGICAL EMERG
SAVE

IF (DVS .LT. DVSDLT) THEN
    RDRDV = 0.
ELSE
    RDRDV = RDRTMP
ENDIF

RDRSH = MAX(0.,RDRSHM * (LAI-LAICR) / LAICR)
RDRDRY = (1. - TRANRF) * RDRL
RDR   = MAX(RDRDV, RDRSH, RDRDRY)

IF (EMERG .AND. NNI .LT. 1.) THEN
    DLVNS = WLVG * RDRNS * (1. - NNI)
    DLAINS = DLVNS * SLA
ELSE
    DLVNS = 0.
    DLAINS = 0.
ENDIF

IF (EMERG) THEN
    DLVS = WLVG * RDR
    DLAIS = LAI * RDR
ELSE
    DLVS = 0.
    DLAIS = 0.
END IF

DLV = DLVS + DLVNS
DLAI = DLAIS + DLAINS

RETURN
END

Initial increase in leaf area index (LAI)

Daily increase in LAI (m² leaf area m⁻² ground surface d⁻¹) becomes stronger during initial growth (i.e. development stage < 0.2), when the average daily temperature rises.
*---- Growth during juvenile stage:
  IF ((DVS .LT. 0.2).AND.(LAI .LT. 0.75))
  $ GLAI = (LAI * (EXP(RGRLAI * DTEFF * DELT) - 1.)/ DELT ) * TRANRF*
  $ EXP(-NLAI* (1.0 - NNI))

*---- Growth at day of seedling emergence:
  IF (LAI.EQ.0.)
  $ GLAI = LAII / DELT
  ENDIF

*---- Growth before seedling emergence:
  IF (.NOT. EMERG) GLAI = 0.
  RETURN
  END

Crop emergence

If crop growth simulations starts at sowing or planting, the simulated crop emergence occurs when the temperature sum requirement for emergence is fulfilled.

*------ Change in temperature sums from sowing/planting (P)
  DTSULP= LIMIT(0., TEFFMX-TBASEM, TMPA-TBASEM) * PUSHPL

----- Temperature sums (C.d) from sowing/planting (P)
  TSULP= INTGRL(TSULP, DTSULP, 1.)

IF (PL .AND. (TSULP .GE. TSUMEM) .AND. (.NOT. EMERG)) THEN
  IDEMERG= IDAY
  DAYEM= REAL(IDEMERG)
  EMERG= .TRUE.
ENDIF

Evaporative demand

Actual water losses by soil evaporation and crop transpiration are based on potential evapotranspiration calculations according to the Penman approach (Penman 1948, 1956; Frère and Popov 1979). This method consists mainly of two parts: a) net absorbed radiation, and b) evaporative demand of the atmosphere (e.g. EAC for crop). EAC is determined by both the vapor pressure deficit (SVAP – VAP) and the wind speed function, for which SVAP increases with rising temperature.

*---- Saturated vapour pressure according to equation of Goudriaan (1977)
  SVAP = 6.11*EXP(17.4*TMPA/(TMPA+239.))

*---- Measured vapour pressure should not be greater than saturated
* vapour pressure
  VAP = AMIN1(SVAP,VAP)
--- Evaporative demand of the atmosphere (mm d⁻¹)

\[
\begin{align*}
    EA &= 0.26 \times (SVAP - VAP) \times (0.5 + BU \times WIND) \\
    EAC &= 0.26 \times (SVAP - VAP) \times (1.0 + BU \times WIND)
\end{align*}
\]

*--- Penman formula (1948), and conversion to cm d⁻¹

\[
\begin{align*}
    E0 &= 0.1 \times \frac{\Delta \times (RNW/LHVAP) + \Gamma \times EA}{\Delta + \Gamma} \\
    ES0 &= 0.1 \times \frac{\Delta \times (RNS/LHVAP) + \Gamma \times EA}{\Delta + \Gamma} \\
    ET0 &= 0.1 \times \frac{\Delta \times (RNC/LHVAP) + \Gamma \times EAC}{\Delta + \Gamma}
\end{align*}
\]

References


Description of statistical wheat model

David B. Lobell

These statistical models were developed from the elite spring wheat yield trial (ESWYT) database of CIMMYT, as used by Gourdji et al. (2013). These trials were managed with irrigation and high nutrient inputs, and therefore the model is designed to predict yields only under these conditions.

The model takes the form:

$$\text{yield} = c_j + \gamma \times \text{year} + \beta \times W + \epsilon$$

(1)

where $c_j$ are country fixed effects; $\gamma$ is the overall time trend for ESWYT; $W$ are a set of environmental variables defined by growth stage; and $\beta$ are the coefficients for these variables. The environmental variables in $W$ include: air temperature (both linear and squared terms), diurnal temperature range (DTR), shortwave radiation, day length, vapor pressure deficit (VPD), and interaction terms between VPD and temperature (linear and quadratic). Vapor pressure deficit was calculated as the difference between saturation and actual vapor pressures, which were derived from daily minimum and maximum temperatures and relative humidity data.

Figure 1 summarizes the temperature response at different stages and humidity levels. Yields are strongly and negatively affected by warming in the grain filling, especially in humid locations due to higher canopy temperatures. Negative effects are also seen in the reproductive stages under both humid and arid conditions, likely due to an enhanced sensitivity to water stress during this period. Responses to warming during the vegetative stage are generally positive.

![Figure 2. Summary of yield responses to temperature for the regression model, calibrated to the ESWYT database. All responses are expressed as yields relative to 12 °C. Thicker segments are significantly different from 0 (p<0.05).](image)
Applying the model requires knowledge of the stage lengths, which are often not available. Therefore, a separate model is first applied to calculate stage length for a given sowing date. Heading date is first predicted using a model fit to trial data to the Gourdji et al. (2012) study; this model uses average day length and accumulated growing degree days (GDD) from sowing to 105 days afterwards as predictors:

\[
\text{Heading day} = 246.7 - 0.0389 \times \text{GDD}_{105} - 8.31 \times \text{(mean day length for 105 days after sowing)}
\]  \hspace{1cm} (2)

The reproductive stage is then defined as a window of 300 GDD before, to 100 GDD after, the heading date. Finally, the grain-filling period is defined as occurring from the end of the reproductive period until 1400 GDD later. All weather variables are then averaged within the three growth stages for use as predictors in the larger statistical model. When applied to the Hot Serial Cereals experiment, the country was set to Mexico and year was set to 2005, so that all variations in predicted values are due to the weather terms.

**References**

The essential temperature routines in LPJmL for wheat simulations

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Temperature directly influences crop growth by affecting phenology, photosynthesis, and autotrophic respiration (air and soil temperature). Crop growth is also affected indirectly by temperature effects on potential evapotranspiration.

Direct effects on crop growth

Phenology

Unless sowing dates are prescribed, temperature affects the start and length of the growing period, and thus productivity. Sowing dates are determined by temperature in regions with seasonal temperature variation, or with a combined seasonal variation in temperature and precipitation and a ‘cold’ season, i.e. at least one month where mean temperature is ≤ 10°C. In both these cases, sowing dates are modeled by calculating the average date over the previous 20 years, on which mean daily temperature falls below (‘winter’ types) or rises over (‘spring’ types) an empirically-determined, crop-specific threshold value (Table 1, Waha et al. 2012).

In regions with temperature seasonality, the sowing month is the month in which mean monthly temperatures of the past ($\overline{T}_{m,j}$) exceed (or fall below) the temperature threshold. Winter wheat and winter rapeseed are sown in autumn, as both crops have to be exposed to vernalizing temperatures. Consequently, the mean monthly temperatures have to fall below the crop-specific temperature threshold (12 °C for wheat):

$$\overline{T}_{m,j} = \alpha \times T_{m,j} + (1-\alpha) \times \overline{T}_{m,j-1}$$ (1)

where $T_{m,j}$ is the mean temperature of month $m$ in year $j$; $\overline{T}_{m,j}$ is the exponential weighted moving average temperature of month $m$ in year $j$; and $\alpha$ is the coefficient representing the degree of weighting decrease (=1/20).

Daily average temperature data of the simulated year determine the specific date of sowing in the sowing month, in order to consider the climatic specificity of the simulated year (Waha et al. 2012).

Phenological development towards maturity is modeled using the heat unit theory (Boswell 1926), by accumulating daily mean temperatures above a crop-specific base temperature (Table 1, Bondeau et al. 2007) up to a maturity threshold. For winter varieties with vernalization requirements, phenological development is retarded until vernalization is completed. Vernalization requirements (0 to 60 days) and temperature threshold for vernalization for winter wheat and winter rapeseed (12°C) are described in
Bondeau et al. (2007) and van Bussel (2011, chapter 6). Increased temperatures lead to a shortened growing period and potentially decreased yields because crops reach maturity earlier in the year:

\[
PHU = \sum_{day=sowing}^{maturity} (T - T_b)
\]

where \(PHU\) is phenological heat units from sowing to maturity; \(T\) is daily mean temperature; and \(T_b\) is base temperature (0 °C for wheat). In winter varieties, increased temperatures can lead to unsuccessful vernalization and delayed phenological development.

**Autotrophic respiration**

Maintenance respiration is calculated based on C:N ratios, air and soil temperature for above and below ground tissues, respectively, tissue biomass, and phenology, as described in Sitch et al. (2003):

\[
g(T) = \exp\left[308.56\left(\frac{1}{56.02} - \frac{1}{T + 46.02}\right)\right]
\]

where \(g(T)\) is the response of the respiration rate to temperature and \(T\) the air or soil temperature in °C.

**Photosynthesis**

Temperature affects leaf development through photosynthesis (Bondeau et al. 2007). The crop-specific inhibition function \(t_{stress}\) describes the response of C3 and C4 plants to extreme temperatures, and later influences the response of photosynthesis to the photosynthetically active radiation absorbed and daily net photosynthesis (Haxeltine and Prentice 1996; Sitch 2000):

\[
t_{stress} = \left\{1 + \exp\left[T_1(T_2 - T)\right]\right\}^{-1} \times \left\{1 - 0.01\exp\left[T_3(T - T_4)\right]\right\}
\]

where the first term describes the photosynthetic response to low temperatures and the second term describes the photosynthetic response to high temperatures. \(T_1\) and \(T_4\) are the lower and upper limit for CO2 (\(T_1=0\) °C and \(T_4=40\) °C for wheat); and \(T_2\) and \(T_3\) are the lower and upper limit of temperature optimum for photosynthesis (\(T_2=12\) °C and \(T_3=17\) °C for wheat). Low productivity (net photosynthesis minus autotrophic respiration) can lead to reduced leaf growth, which affects crop productivity through reduced light interception.

**Indirect effects on crop growth**

**Potential Evapotranspiration**

Potential evapotranspiration is calculated as:

\[
PET = E_t \times \alpha
\]

where \(\alpha\) is the Priestley-Taylor coefficient (1.32; as in Gerten et al. 2004).
The daily equilibrium evapotranspiration rate \((E_q)\) is calculated as:

\[
E_q = \left[\Delta/(\Delta + \gamma)\right]R_n/L
\]  

(6)

where \(\Delta\) is the rate of increase of the saturation vapor pressure with temperature; \(\gamma\) is the psychrometer constant (\(\approx 65\) Pa/K); \(R_n\) is net radiation (net short-wave flux minus net long-wave flux) in J/m\(^2\)*d, calculated from latitude, day of the year, sunshine hours, and air temperature, following Prentice et al. (1993); and \(L\) is the latent heat of vaporization of water (\(\approx 2.5 * 10^6\) J/kg). Furthermore:

\[
R_n = R_s - R_l
\]  

(7)

where \(R_s\) is the net downward short-wave flux and \(R_l\) is the net upward long-wave flux, as calculated in Prentice et al. (1993, eq. 7-11).

\[
R_s = (c + dh_i)(1 - \beta)Q_0 \cos z
\]  

(8)

where \(c\) (\(=0.25\)) and \(d\) (\(=0.5\)) are empirical constants \((c + d = \) the clear-sky transmittivity) and \(\beta\) is the short-wave albedo.

\[
Q_0 = Q_{00} \left[1 + 2 \times 0.01675 \times \cos(360i/365)\right]
\]  

(9)

where \(Q_{00}\) is the solar constant (1360 Wm\(^{-2}\)), and

\[
\cos z = \sin l \times \sin \delta + \cos l \times \cos \delta \times \cosh
\]  

(10)

where \(l\) is latitude, \(h\) is the time of day in angular units from solar noon, and

\[
\delta = -23.4^\circ \times \cos \left[360(i+10)/365\right]
\]  

(11)

\[
R_l = \left[b + (1 - b) n_i \right] (A - T_c)
\]  

(12)

where \(b\) (\(=0.2\)) and \(A\) (\(=107\)) are empirical constants; \(T_c\) is the mean daily temperature in °C; \(n_i\) is the daily proportion of bright sunshine from monthly sunshine interpolated to quasi-daily values \((i=\) julian day). Temperature effects on the equilibrium evapotranspiration rate affect water stress (the ratio between \(E_q\) -based atmospheric water demand and plant water supply), and thus plant root growth (Waha et al. 2013), as well as soil moisture.
References


**MCWLA-Wheat model and its essential temperature routines**

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The MCWLA (Model to simulate the Crop-Weather relationship over a Large Area; Tao et al. 2009a, b) can be adapted to simulate the growth, development, and productivity of winter wheat; thus the MCWLA-Wheat crop model (Tao and Zhang 2013). Tao et al. (2009a, b) describe in detail the MCWLA model development, parameters optimization, and uncertainties analysis, but generally, MCWLA simulates crop growth and development in a daily time-step. It is designed to investigate the impacts of weather and climate variability (change) on crop growth, development, and productivity at a large scale.

MCWLA-Wheat is based on the MCWLA, but the phenological development module is revised to account for the effects of vernalization and photoperiod on winter wheat development rate. The leaf area index (LAI) development module is revised to fit the LAI development of winter wheat and the effects of high temperature stress at anthesis and grain-filling on grain yield are also parameterized. Specifically, for MCWLA-Wheat, after the planting date (pd), the thermal time (TDD) elapsed after a given development stage \(i\) is defined as:

\[
TDD_i = \sum_{t=pd}^{i} DTT
\]

where \(t\) is time and \(i\) is the developmental stage (0 = sowing to emergence; 1 = emergence to the start of floral initiation; 2 = the beginning to the end of floral initiation; 3 = the end of floral initiation to flowering; and 4 = flowering to maturity). Development stage \(i\) is completed after a specified TDD has elapsed, and harvest occurs at maturity. Daily thermal time \(DTT\) is calculated as:

\[
DTT = (T_{eff} - T_b) \times \text{[minimum (VF, DF)]}
\]

where \(T_{eff}\) is the daily effective temperature, calculated according to Tao et al. (2009a); \(T_b\) is the base temperature below which development ceases; VF (0-1) is a vernalization factor; and DF (0-1) is a day length/photoperiod factor.

In MCWLA-Wheat, the growth of crop leaf area is determined as follows:
where $D_{VR}$ is calculated as:

$$D_{VR} = DTT/(TDD_3 - TDD_0)$$  (7)

and $D_{Tr}$ is calculated as:

$$D_{Tr} = TDD_3/(TDD_3 - TDD_1)$$  (8)

$L_{Al\text{max}}$ is the maximum leaf area index ($L_{Al}$) of the crop (8.5 m$^2$ m$^{-2}$ in this study for winter wheat), and $\varphi$ is a parameter to modify the relative development rate of $L_{Al}$ between different development stages (0.3 in this study). The soil water stress factor $S$ is given by:

$$S = \frac{T_T}{T_{Tpot}}$$  (9)

$S$ begins to affect growth at values less than the critical threshold value $S_{cr}$. $T_T$ and $T_{Tpot}$ are the rates of transpiration and potential transpiration, respectively. $F$ is the flooding stress factor; its value increases by 1.0 when one flooding event occurs (defined as soil water being greater than capacity for three continuous days) between sowing and maturity. $F_{cr}$ is a parameter to adjust the damage extent of one flooding event (5 in this study). $L_{Adg}$ is the mean rate of $L_{Al}$ decrease after flowering to maturity (-0.05 m$^2$ m$^{-2}$ per day in this study). $Y_{gp}$ is the yield gap parameter, used to reduce $L_{Al}$ from the physical value to an effective value, which accounts for the mean effects of pests, diseases, and non-optimal management. $H_{sl}$ is a heat stress factor, describing the role of high temperature in hastening leaf senescence (Porter and Gawith 1999; Asseng et al. 2011; Lobell et al. 2012). According to Asseng et al. (2011), $H_{sl}$ is given by

$$H_{sl} = \begin{cases} 
4 - (1 - (T_{\text{max}} - 34)/2) & T_{\text{max}} > 34^\circ C \\
1 & T_{\text{max}} \leq 34^\circ C
\end{cases}$$  (10)
The daily rate of change of harvest index \((H_{id})\) is given by

\[
H_{id} = \begin{cases} 
0 & i \leq 3 \\
H_i \frac{DTT}{TDD_3 - DTT} H_{sf} H_{sg} & i > 3 
\end{cases}
\]  

(11)

where \(H_i\) is harvest index under optimal climate conditions and \(H_{sf}\) describes the impacts of high temperature stress during flowering on the rate of change of harvest index. In MCWLA-Wheat, \(H_{sf}\) is parameterized as by Li et al. (2010), who modified the parameterization proposed by Challinor et al. (2005) to simulate the effects of high temperature stress during flowering on wheat harvest index in China. \(H_{sg}\) describes the impacts of dry-hot wind on the rate of change of harvest index; this wind is a disaster for wheat during grain-filling period, when high temperature, low humidity, and strong winds together cause wheat to dry out, and consequently reduce grain weight and yield (China Meteorological Administration 2007). \(H_{sg}\) is given by:

\[
H_{sg} = 1 - \gamma
\]  

(12)

where \(\gamma\) was set at 0.15 once \(T_{max} \geq 35 ^\circ C\) and mean humidity \(\leq 30 \%\); 0.075 when \(32 ^\circ C \leq T_{max} < 35 ^\circ C\) and mean humidity \(\leq 35\%\); and 0.0 when \(T_{max} < 32 ^\circ C\), based on the documents on the disaster of dry-hot wind for wheat (China Meteorological Administration, 2007).

References


Temperature functions in the crop part of the MONICA model

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The MONICA model (Nendel et al. 2011) is an agro-ecosystem model emphasising soil and plant processes. Many of the processes considered in the model are linked in a regulating manner, and affected by temperature. This abstract summarises the most important temperature functions of the crop part of the MONICA’s crop part.

Ontogenesis

Plant development is simulated using the principle of heat summation. The effective temperature is limited by a minimum temperature, which is referred to as base temperature. A suitable level of soil moisture (at least 30% of available water, but less than would cause ponding at the soil surface) is required for seed emergence. If soil moisture is ideal, the temperature of the top soil layer can be used for heat summation as

\[
DD_{0,t} = DD_{0,t-1} + (T_{S10} - T_{B0}) \cdot \Delta t
\]

where \(DD_{0,t}\) is the actual temperature sum in developmental stage 0; \(DD_{0,t-1}\) is yesterday’s temperature sum in developmental stage 0; \(T_{S10}\) is the soil temperature at 0–10 cm depth; \(T_{B0}\) is the base temperature at developmental stage 0; and \(\Delta t\) is the time step. As soon as the crop-specific temperature sum for seed emergence is reached, the subsequent developmental stage is initiated. From this moment the daily mean air temperature, as opposed to soil temperature, is summed. Stress factors considering drought and N deficiency accelerate the summation, while vernalisation and day length factors decelerate it. Degree days are summed as

\[
DD_{n,t} = DD_{n,t-1} + (T_{av} - T_{Bn}) \cdot b_s \cdot b_v \cdot b_D \cdot \Delta t
\]

where

\[
b_s = \max(1 + (1 - \xi_w)^2, 1 + (1 - \xi_N)^2)
\]

and \(DD_{n,t}\) is the actual temperature sum in developmental stage \(n\); \(DD_{n,t-1}\) is yesterday’s temperature sum in developmental stage \(n\); \(T_{av}\) is the daily mean air temperature at 2m above ground; \(T_{Bn}\) is the base temperature developmental stage \(n\); \(bs\) is the environmental stress acceleration factor; \(b_v\) is the vernalisation factor; \(b_D\) is the day length factor; \(\xi_w\) is the drought stress factor; and \(\xi_N\) the stress factor for N deficiency.

Crop growth

The modelling of crop growth follows a generic approach used by SUCROS model (van Keulen et al. 1982). Daily net dry matter production by photosynthesis and respiration is driven by radiation and temperature. Gross CO₂ assimilation is calculated by estimating the sky cover duration. Atmospheric CO₂
concentration, or \([\text{CO}_2]\), has an impact on the crop’s photosynthesis rate and stomata resistance, which in turn influences transpiration (Nendel et al. 2009). Mitchell et al. (1995) presented a set of algorithms for calculating maximum rate of photosynthesis, based on the ideas of Farquhar and von Caemmerer (1982) and Long (1991)

\[
A = \frac{(C_i - \Gamma^*) \cdot V_{c_{\max}}}{C_i + K_c \cdot \left(1 + \frac{O_i}{K_o}\right)}
\]  

(4)

where \(A\) is the \(\text{CO}_2\) assimilation rate; \(C_i\) is the inter-cellular \(\text{CO}_2\) concentration; \(^*\) is the compensation point of photosynthesis, related to \(C_i\) in the absence of dark respiration; \(O_i\) is the inter-cellular \(\text{O}_2\) concentration; \(V_{c_{\max}}\) is the maximum saturated Rubisco carboxylation rate; and \(K_c\) and \(K_o\) are the Michaelis-Menten constants for \(\text{CO}_2\) and \(\text{O}_2\), respectively. Temperature dependencies of \(C_a\) \(O_i\) \(K_c\) \(K_o\) and \(V_{c_{\max}}\) and its parameters were described by Long (1991). Accordingly, \(C_i\) is calculated from atmospheric \(\text{CO}_2\) concentration \(C_a\) as

\[
C_i = C_a \cdot 0.7 \cdot \left(1.674 - 6.1294 \times 10^{-2} \cdot T_{av} + 1.1688 \times 10^{-3} \cdot T_{av}^2 - 8.8741 \times 10^{-7} \cdot T_{av}^3\right) / 0.73547
\]

(5)

and \(O_i\) is calculated as

\[
O_i = 210 + \left(0.047 - 1.3087 \times 10^{-4} \cdot T_{av} + 2.5603 \times 10^{-6} \cdot T_{av}^2 - 2.1441 \times 10^{-8} \cdot T_{av}^3\right) / 2.6934 \times 10^{-2}
\]

(6)

The algorithm used for light intensities below saturation, presented by Mitchell et al. (1995), is not applied in the model. Instead, \(A_{\max}\) is adapted to light interception according to Goudriaan and van Laar (1978). Mitchell et al. (1995) proposed the following algorithm for the transition between photosynthetic quantum use efficiency and light-saturated photosynthesis:

\[
\epsilon_L = \frac{0.37 \cdot (C_i - \Gamma^*)}{4.5 \cdot C_i + 10.5 \cdot \Gamma^*}.
\]

(7)

where \(\epsilon_L\) is the radiation use efficiency of \(\text{CO}_2\) assimilation. The compensation point of photosynthesis is obtained from

\[
\Gamma^* = \frac{0.5 \cdot 0.21 \cdot V_{c_{\max}} \cdot O_i}{V_{c_{\max}} \cdot K_o}
\]

(8)

where

\[
V_{c_{\max}} = 98 \cdot \frac{A_{\max}}{34.668} \cdot k(T)_{V_{c_{\max}}}
\]

(9)

and \(A_{\max}\) denotes the plant-specific maximum \(\text{CO}_2\) assimilation rate and \(k(T)_{V_{c_{\max}}}\) is the temperature function for \(V_{c_{\max}}\) (Figure 1).
For crops with C₄ metabolism, we assume no direct impact of atmospheric CO₂ concentration on photosynthesis. The crop-specific maximum CO₂ assimilation rate is merely modified by a simple temperature function (Figure 2).

Maintenance respiration is calculated for the daylight period (photoperiod) and darkness using AGROSIM algorithms (Mirschel and Wenkel 2007):

\[
M_{\text{photo}} = \sum (W_i \cdot m_i) \cdot 2^{a(T_{\text{photo}} - b)} \cdot (2 - L_N)
\]  

(10)

\[
M_{\text{dark}} = \sum (W_i \cdot m_i) \cdot 2^{a(T_{\text{dark}} - b)} \cdot L_N
\]  

(11)

where

\[
L_N = 2 - \left( \frac{L_P}{12} \right)
\]  

(12)
and

\[ T_{\text{photo}} = T_{\text{max}} - \left( \frac{T_{\text{max}} - T_{\text{min}}}{4} \right) \]  

(13)

\[ T_{\text{dark}} = T_{\text{min}} + \left( \frac{T_{\text{max}} - T_{\text{min}}}{4} \right) \]  

(14)

where \( M_{\text{photo}} \) and \( M_{\text{dark}} \) are maintenance respiration during the photoperiod and darkness, respectively. \( W_i \) is the dry mass of organ \( i \); \( m_i \) is the specific maintenance respiration of organ \( i \); \( L_N \) is the normalised day length; \( L_P \) is the photoactive day length; and \( T_{\text{photo}} \) and \( T_{\text{dark}} \) are the mean temperatures during the photoperiod and dark period, respectively. \( T_{\text{max}} \) is the daily maximum and \( T_{\text{min}} \) the daily minimum air temperatures. Growth respiration is calculated accordingly.

Assimilates produced in the photosynthesis module are distributed to single plant organs. The partitioning coefficients are taken from a matrix, which includes the development stages of the crop. Daily partitioning is calculated using linear regression between the elements of the matrix and the relative crop development.

**Heat stress**

Heat stress affects the production of ovules during bloom, and is defined in this model as heat that exceeds a plant-specific threshold during the photoperiod. According to Challinor et al. (2005), during a defined plant-specific phase of increased sensitivity, extreme temperatures affect the crop according to

\[ F_H = 1 - \left( \frac{T_{\text{photo}} - T_{\text{critH}}}{T_{\text{limH}} - T_{\text{critH}}} \right) \cdot r_F \]  

(15)

where \( F_H \) is the heat impact on ovules; \( T_{\text{critH}} \) is the critical temperature for initiation of heat stress effects; \( T_{\text{limH}} \) is the maximum temperature above which heat stress effects are not further aggravated; and \( r_F \) is the daily flower emergence rate during bloom, which is calculated, following an idea of Moriondo et al. (2011), as

\[ r_F = p_{F,d} - p_{F,d-1} \]  

(16)

where \( p_{F,d} \) denotes the fraction of flowers that opened today and \( p_{F,d-1} \) the fraction of flowers that opened the day before. The fraction of open flowers \( p_F \) is calculated as

\[ p_F = \frac{1}{1 + \left( \frac{1}{0.015} \right) e^{-1.4D_{BF}}} \]  

(17)

where \( D_{BF} \) denotes the number of days after begin of bloom. The reduction factor \( \xi_{\text{H}} \) is then derived from the smallest value of \( F_H \) during the sensitive phase

\[ \xi_{\text{H}} = \min(F_{H1}, \ldots, F_{Hn}) \]  

(18)
where $F_{H1}$ and $F_{Hn}$ are the levels of heat impact on the first day and last days of the sensitive phase, respectively. Heat stress reduces the assimilate flow to the storage organ

$$W_i = A_g \cdot a_s \cdot \zeta_H$$  \hspace{1cm} (19)

where $W_i$ is the biomass of the storage organ; $A_g$ is the gross CO$_2$ assimilation; and $a_s$ is the assimilate partitioning coefficient for the storage organ.

An offspring of the SUCROS model, MONICA follows a generic approach that describes features of different crops only by using different sets of parameters. The described temperature functions are therefore valid for all crops that MONICA simulates.

References


Thermal dependence of plant growth in four crop models embedded in the Expert-N model system

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The Expert-N model system (Priesack and Bauer 2003; Priesack 2006; Priesack et al. 2006; Priesack and Gayler 2009) is a modular, mechanistic ecosystem model that simulates matter and energy fluxes in the soil-plant-atmosphere continuum at field scale. In the AgMIP simulation study, we compared the simulation results of four different crop growth sub models, i.e. SPASS (Wang 1997, 1998, 2000), SUCROS (van Keulen and Seligman 1987; Goudriaan and van Laar 1994; van Laar et al. 1997), CERES (Ritchie et al. 1987; Ritchie and Godwin 2013), and GECROS (Yin and van Laar 2005). These models differ in the functions representing crop development and crop growth, but are based on the same functions for the simulation of soil water flow, soil solute transport, soil C- and N-turnover, and soil heat transfer.

All four plant growth models consider air temperature as a driving factor of plant development and growth. However, the extent of this differs between modeling approaches and will be described here. For the well documented models CERES (v2.0) and GECROS (v1.0), we will not explicitly present equations but will instead refer to the original literature.

Crop growth model SPASS

Temperature functions with an optimum

The usual temperature function applied in the SPASS model has the following general mathematical form, which needs optimal temperature as an input parameter, besides a minimal and a maximal temperature \((0 \leq T_{\text{min}} < T_{\text{opt}} < T_{\text{max}})\):

\[
f_T(T, T_{\text{min}}, T_{\text{opt}}, T_{\text{max}}) = \frac{2(T - T_{\text{min}})^{\alpha}(T_{\text{opt}} - T_{\text{min}})^{\alpha} - (T - T_{\text{min}})^{2\alpha}}{(T_{\text{opt}} - T_{\text{min}})^{2\alpha}},
\]

where the exponent \(\alpha\) depends on the input temperatures, and can be calculated by using the condition \(f_T(T_{\text{max}}, T_{\text{min}}, T_{\text{opt}}, T_{\text{max}}) = 0)\):

\[
\alpha = \log(2)/\log[(T_{\text{max}} - T_{\text{min}})/(T_{\text{opt}} - T_{\text{min}})]
\]

After emergence, when the value of the development stage \(s_{\text{dev}} \geq 0\) is positive, development is simulated based on daily development rates \(\mu_{\text{dev},v}\) and \(\mu_{\text{dev},g}\) for the vegetative and the generative (or reproductive) phase of development:
\[
\mu_{dev,v}^{day} = \mu_{dev,v}^{max} f_v(T) f_V f_P \\
\mu_{dev,r}^{max} \text{ maximal vegetative development rate } [d^{-1}] \\
f_v(T) \text{ temperature factor of the vegetative phase } [1], \text{ see eq. (7)} \\
f_V \text{ impact factor of vernalisation } [1] \\
f_P \text{ impact factor of photo period } [1] \\
\mu_{dev,r}^{max} \text{ maximal generative (or reproductive) development rate } [d^{-1}] \\
f_r(T) \text{ temperature factor of the generative phase } [1]
\]

From these rates the actual value \( s_{dev} [1] \) of the development stage is calculated (e.g. for \( n \) days after emergence with \( \Delta t^{day} = 1 \) d):

\[
s_{dev} = \int_{t_2}^t \mu_{dev}^{day} dT = \sum_{d_i = d_e}^{d_n} \mu_{dev}^{day} \Delta t^{day}
\]

\[t \quad \text{actual time } [d] \quad t_2 \quad \text{time of emergence } [d] \quad \tau \quad \text{variable of time integration } [d] \quad d_c \quad \text{day number till emergence } [d] \quad d_n \quad \text{day number till } n \text{ days after emergence } [d] \]

where \( \mu_{dev}^{day} [d^{-1}] \) is composed of the development rates of both phases:

\[
\mu_{dev}^{day} = \begin{cases} \\
\mu_{dev,v}^{day} & \text{for } 0 \leq s_{dev} < 1 \\
\mu_{dev,r}^{day} & \text{for } 1 \leq s_{dev} < 2 
\end{cases}
\]

Both for the vegetative and the generative phase in SPASS, the temperature impact factor is given by a temperature function with optimal temperature after equation (1), for which (corresponding to the development phase) each case requires input values for a minimal, optimal, and maximal temperature:

\[
f_v(T) = f_r(T, T_{min,v}, T_{opt,v}, T_{max,v}) \quad f_r(T) = f_r(T, T_{min,r}, T_{opt,r}, T_{max,r})
\]
Vernalization

The daily vernalization rate $\mu_{vn}^{\text{day}} [d^{-1}]$ is dependent on the daily average air temperature $T_{\text{day}} [\degree C]$; again by applying equation (4) with $\Delta t^{\text{day}} = 1$ $\degree$:

$$\mu_{vn}^{\text{day}} = f_T(T_{\text{day}}, T_{\text{min, vn}}, T_{\text{opt, vn}}, T_{\text{max, vn}})/\Delta t^{\text{day}},$$

(8)

from which the number of vernalization days $n_{vd}$ until the $n$-th day after germination can be given:

$$n_{vd} = \int_{t_1}^{t_n} \mu_{vn}^{\text{day}} d\tau = \sum_{d=d_g}^{d_n} \mu_{vn}^{\text{day}} \Delta t^{\text{day}}$$

(9)

$t_1$ time of germination [d] $t_n$ end of $n$-th day after germination [d] $\mu_{vn}^{\text{day}}$ daily vernalisation rate [d$^{-1}$] $\tau$ integration variable [d] of time $d_g$ first day after germination [d] $d_n$ $n$-th day after germination [d]

From the vernalization impact factor $f_V [1]$ the development rate is then estimated by:

$$f_V = \min\{1; \max(0; (n_{vd} - n_{vbd})/(n_{vsd} - n_{vbd}))\}$$

(10)

$n_{vbd}$ minimal no. of vernalisation days [1] $n_{vsd}$ saturation no. of vernalisation days [1]

Leaf photosynthesis

The gross leaf photosynthesis $P_g [kg CO_2 ha^{-1} d^{-1}]$ also depends on temperature via the gross photosynthesis rate at light saturation $P_g m [kg CO_2 ha^{-1} d^{-1}]$:

$$P_{gl} = P_{gm} [1 - \exp(-\epsilon_{PAR} \phi_{PAR} P_{gm}^{-1})]$$

(11)

$P_{gl}$ gross leaf photosynthesis rate [kg CO$_2$ ha$^{-1}$ d$^{-1}$] $P_{gm}$ gross leaf photosynthesis rate at light saturation [kg CO$_2$ ha$^{-1}$ d$^{-1}$] $\epsilon_{PAR}$ light use efficiency [kg CO$_2$ (MJ)$^{-1}$] $\phi_{PAR}$ absorbed photosynthetic active radiation [MJ ha$^{-1}$ d$^{-1}$]

$$P_{gm} = P_{\text{max, 340}} f_{CO_{2, p}} f_{N, p} f_{T, p}$$

(12)

$P_{gm}$ gross leaf photosynthesis rate at light saturation [kg CO$_2$ ha$^{-1}$ d$^{-1}$] $P_{\text{max, 340}}$ maximal gross leaf photosynthesis rate [kg CO$_2$ ha$^{-1}$ d$^{-1}$] at 340 vppm CO$_2$ vppm volume parts per million $f_{CO_{2, p}}$ CO$_2$-reduction factor of photosynthesis [1] $f_{N, p}$ leaf-N reduction factor of photosynthesis [1] $f_{T, p}$ temperature reduction factor of photosynthesis [1]
The reduction factor of temperature of photosynthesis $f_{T,p}$ [1] is determined by three cardinal temperatures ($T_{\text{min},p}, T_{\text{opt},p}, T_{\text{max},p}$) of photosynthesis and again, using equation (1):

$$f_{T,p} = f_T(T_{\text{day}}, T_{\text{min},p}, T_{\text{opt},p}, T_{\text{max},p})$$ (13)

- $f_{T,p}$: temperature reduction factor of photosynthesis [1]
- $T_{\text{day}}$: average daily air temperature [°C]
- $T_{\text{min},p}$: minimal temperature of photosynthesis [°C]
- $T_{\text{opt},p}$: optimal temperature of photosynthesis [°C]
- $T_{\text{max},p}$: maximal temperature of photosynthesis [°C]

**Leaf photo respiration**

For $C_3$ plants, photo respiration is described by introducing the CO$_2$-compensation point $\Gamma_f [\text{ppm}]$, which increases exponentially with temperature:

$$\epsilon_{\text{PAR}} = \epsilon_0 (C_a - \Gamma_f)/(C_a + 2 \Gamma_f)$$ (14)

$$\Gamma_f = \Gamma_{f0} Q_{10}^{(T_{\text{act}} - T_{\text{ref}})/10}$$ (15)

- $\epsilon_{\text{PAR}}$: light use efficiency kgCO$_2$ MJ$^{-1}$
- $\epsilon_0$: maximal light use efficiency kgCO$_2$ MJ$^{-1}$ at low light conditions, low temperature and low atmospheric CO$_2$ concentration
- $C_a$: atmospheric CO$_2$ concentration in surrounding air [ppm]
- $\Gamma_f$: CO$_2$ compensation point [ppm] at actual surrounding air temperature $T_{\text{act}}$
- $\Gamma_{f0}$: CO$_2$ compensation point [ppm] at reference temperature $T_{\text{ref}}$
- $Q_{10}$: $Q_{10}$-value [1] (= 2.0)
- $T_{\text{ref}}$: reference temperature (= 20 °C)
- $T_{\text{act}}$: actual air temperature [°C]

**Maintenance respiration**

Maintenance respiration of the plant is modeled by considering the maintenance respiration of the different organs and of the metabolic activity. Maintenance respiration is directly proportional to living biomass and increases with air temperature:
\[
\sigma_{mnt, lvs} = B_{liv,lvs} \sigma_{0, lvs} f_T(T_{day}) f_{nc,lv} 0.75
\]  
(16)

\[
\sigma_{mnt, stm} = B_{liv,stm} \sigma_{0, stm} f_T(T_{day}) f_{nc,stm}
\]  
(17)

\[
\sigma_{mnt, sto} = B_{liv,sto} (1 - f_{rev,sto}) \sigma_{0, sto} f_T(T_{day}) f_{nc,sto}
\]  
(18)

\[
\sigma_{mnt, rts} = B_{liv,rts} \sigma_{0, rts} f_T(T_{day}) f_{nc,rts}
\]  
(19)

\[
\sigma_{mnt, mtb} = 0.1 \ P_{g, crp}^{day}
\]  
(20)

\[\sigma_{mnt, plo}\] maintenance respiration \([kgCO_2 \ \text{ha}^{-1} \ \text{d}^{-1}]\) of plant organs \(plo = lvs, \ \text{stm}, \ \text{sto}, \ \text{rts}\)

\[B_{liv, plo}\] living biomass \([kg]\) (dry matter) of plant organ \(plo\)

\[\sigma_{0, mnt, plo}\] maintenance respiration \([kgCO_2 \ \text{kg}^{-1} \ \text{ha}^{-1} \ \text{d}^{-1}]\) of the plant organ \(plo\) at reference air temperature \(T_{ref}\)

\[f_T(T_{day}) = Q_{10}^{(T_{act} - T_{ref})/10}\]  
with \(Q_{10} = 2.0\)

\[f_{nc, plo}\] fraction of material in storage organs without maintenance requirements \([1]\)

\[f_{nc, plo}\] impact factor of N-content of plant organ \(plo\)

\[\sigma_{mnt, mtb}\] maintenance respiration \([kgCO_2 \ \text{ha}^{-1} \ \text{d}^{-1}]\) of metabolic activity

\[P_{g, crp}^{day}\] daily gross crop photosynthesis \([kgCO_2 \ \text{ha}^{-1}]\)

**Biomass growth**

In the SPASS model, biomass growth rates are considered to depend only indirectly on temperature. Exceptions are the corn filling rate, leaf appearance rate, and root elongation rate. In the case of wheat and barley, we determine, additionally to the daily growth rate of storage organs \(\mu_{B, sto}^{day} \ [kg \ \text{ha}^{-1} \ \text{d}^{-1}]\),

a daily grain filling rate \(\mu_{B, grn}^{day} \ [kg \ \text{ha}^{-1} \ \text{d}^{-1}]\), which describes the growth of the grains:

\[
\mu_{B, grn}^{day} = \min[\mu_{B, sto}^{day}, \mu_{B, grn, max} \ n_{grn} n_{plt} \ \xi_{B, sto} \ f_Tgf(T_{day})]
\]  
(21)

\(\mu_{B, grn, max}\) maximal daily grain filling rate per grain \([mg \ \text{d}^{-1}]\) (input parameter)

\(\xi_{B, sto}\) transformation efficiency of storage organs \([kg TM \ \text{kg}^{-1} CH_2O]\)

\(f_Tgf(T_{day}) = f_T(T_{day}, T_{min, grf}, T_{opt, grf}, T_{max, grf})\) by application of equation (1) with

\(T_{day}\) average daily air temperature \([^\circ C]\)

\(T_{min, grf}\) min. temp. of grain filling \([^\circ C]\)

\(T_{opt, grf}\) opt. temp. of grain filling \([^\circ C]\)

\(T_{max, grf}\) max. temp. of grain filling \([^\circ C]\)

\(n_{grn}\) number of grains per plant \([1]\)

\(n_{plt}\) number of plants per hectare \([\text{ha}^{-1}]\)
Canopy formation

To simulate the development and growth of leaves, their number has to first be calculated. This is achieved by use of process models to describe the initiation of leaf primordia and the leaf appearance rate. Given the maximal daily rate of leaf primordia initiation, \[ \mu_{lvs,ini,max}^{day} \] [d\(^{-1}\)], the actual daily rate of leaf primordia initiation \[ \mu_{lvs,ini}^{day} \] [d\(^{-1}\)] results from:

\[ \mu_{lvs,ini}^{day} = \mu_{lvs,ini,max}^{day} f_T(T_{day}, T_{min,v}, T_{opt,lvs}, T_{max,v}) f_P(h_{php}) \] (22)

\[ \mu_{lvs,ini}^{day} \] actual daily leaf primordia initiation rate [d\(^{-1}\)]
\[ \mu_{lvs,ini,max}^{day} \] maximal daily leaf primordia initiation rate [d\(^{-1}\)] (input parameter)
\[ f_T \] impact factor of temperature by application of equation (1) with
\[ T_{day} \] average daily air temperature [\(^\circ\)C]
\[ T_{min,v} \] min. temp. of veg. phase [\(^\circ\)C]
\[ T_{opt,lvs} \] opt. temp. of leaf growth [\(^\circ\)C]
\[ T_{max,v} \] max. temp. of veg. phase [\(^\circ\)C]
\[ f_P \] impact factor of photo period [1]
\[ h_{php} \] photo period [d]

Similarly the maximal daily leaf appearance rate, \[ \mu_{lvs,app,max}^{day} \] [d\(^{-1}\)], serves to calculate the emergence of the leaf ligulum by the actual daily leaf appearance rate \[ \mu_{lvs,app}^{day} \] [d\(^{-1}\)] in dependence of temperature and photo period:

\[ \mu_{lvs,app}^{day} = \mu_{lvs,app,max}^{day} f_T(T_{day}, T_{min,v}, T_{opt,lvs}, T_{max,v}) f(h_{php}) \] (23)

From this result, the total number of leaves (or total number of primordia) \[ n_{lvs,prm} \] [1] at floral initiation \[ t_1 = d_{fi} \] [d], which have appeared since plant emergence \[ t_1 = d_{em} \] [d]:

\[ n_{lvs,prm} = \int_{t_0}^{t_1} \mu_{lvs,ini}^{day}(\tau) d\tau = \sum_{d=d_{em}}^{d=d_{fi}} \mu_{lvs,ini}^{day} \] (24)

and similarly the total number of emerged leaves \[ n_{lvs,fi} \] [1] at floral initiation \[ t_1 = d_{fi} \] [d]:

\[ n_{lvs,fi} = \int_{t_0}^{t_1} \mu_{lvs,app}^{day}(\tau) d\tau = \sum_{d=d_{em}}^{d=d_{fi}} \mu_{lvs,app}^{day} \] (25)

Root growth

Based on a plant specific maximal daily root elongation rate to determine rooted depth and vertical root extension, the following daily root extension rate is estimated, which depends on soil temperature and soil water content:
\[
\mu^\text{day}_{\text{ext,rts}} = \mu^\text{max}_{\text{ext,rts}} f_T,\text{rts} f_{\theta,\text{rts}}
\]  

\( \mu^\text{day}_{\text{ext,rts}} \) daily vertical root elongation rate \([\text{mm d}^{-1}]\)  
\( \mu^\text{max}_{\text{ext,rts}} \) maximal daily vertical root elongation rate \([\text{mm d}^{-1}]\)  
\( f_{\theta,\text{rts}} \) stress factor of water shortage \([1]\)  
\( f_T,\text{rts}(T_z) = f_T(T_z, T_{\text{min,rts}}, T_{\text{opt,rts}}, T_{\text{max,rts}}) \) impact factor of temperature on root growth  
\( T_z \) soil temperature at depth \( z \) \([\text{°C}]\)  
\( T_{\text{min,rts}} \) min. temp. of root growth \([\text{°C}]\)  
\( T_{\text{opt,rts}} \) opt. temp. of root growth \([\text{°C}]\)  
\( T_{\text{max,rts}} \) max. temp. of root growth \([\text{°C}]\)  

**Crop growth model SUCROS**

**Thermal Time**

Development stages are assumed to be directly proportional to thermal time \( t_T \) \([\text{°C d}]\), which is cumulatively given by the sum of effective temperatures:

\[
t_T = \sum_{i=t_1}^{t_n} \max\{0 ; (T_{a,i} - T_b)\} \Delta t^\text{day}
\]  

\( t_1 \) day of emergence of cultivated crop \([\text{d}]\)  
\( t_n \) actual day \([\text{d}]\)  
\( T_{a,i} \) average daily air temperature at day \( i \) \([\text{°C}]\)  
\( T_b \) base temperature \([\text{°C}]\)  
\( \Delta t^\text{day} \) time step of the length of a day \([\text{d}]\)  

**Development Stages**

In the SUCROS model, three different development stages are discerned: The stage between seed germination and field emergence; the stage from field emergence until flowering (vegetative phase); and the stage from flowering to maturity. The stages are indicated by a numerical value \( s_{\text{dev}} \) \([1]\):

\[
s_{\text{dev}} = \begin{cases} 
0 & \text{at seed emergence} \\
1 & \text{at flowering} \\
2 & \text{at maturity Reife}
\end{cases}
\]  

The actual development stage then results by a normalization of the actual thermal time \( t_T \) corresponding to the development phase:

\[
s_{\text{dev}} = \begin{cases} 
\frac{t_T}{t_T,\text{veg,1}} & \text{for the vegetative phase} \\
1 + \frac{t_T}{t_T,\text{veg,2}} & \text{for the generative phase}
\end{cases}
\]
by using the critical thermal times $t_{{T_{,crit,1}}}$ [$^\circ C$ $d$] and $t_{{T_{,crit,2}}}$ [$^\circ C$ $d$] (input data) that describe the thermal times needed to either fulfill the vegetative or the generative phase.

**Development Rates**

The corresponding daily development rate $\mu_{{dev}}$ [d$^{-1}$] is due to:

$$\frac{ds_{{dev}}}{dt} \approx \frac{ds_{{dev}}}{\Delta t} = \frac{\Delta t}{\Delta t} = \max\{0; T - T_b\} , \quad i = 1, 2$$

(30)

defined in dependence of the development phase (vegetative $i = 1$ or generative $i = 2$) by:

$$\mu_{{dev}}^{day} = \begin{cases} (T - T_b)/t_{{T_{,crit,i}}} & \text{for } T > T_b \\ 0 & \text{for } T \leq T_b \end{cases}$$

(31)

**Leaf Photosynthesis**

The gross leaf photosynthesis rate depends on temperature through the gross leaf photosynthesis at light saturation:

$$P_{{gl}} = P_{{gm}} [1 - \exp(- \epsilon_{PAR} \phi_{PAR} P_{{gm}}^{-1})]$$

(32)

$P_{{gl}}$ gross leaf photosynthesis [kg CO$_2$ ha$^{-1}$ d$^{-1}$]

$P_{{gm}}$ gross leaf photosynthesis at light saturation [kg CO$_2$ ha$^{-1}$ d$^{-1}$]

$\epsilon_{PAR}$ light use efficiency [kg CO$_2$ (MJ)$^{-1}$]

$\phi_{PAR}$ absorbed photosynthetic active radiation [MJ ha$^{-1}$d$^{-1}$]

In contrast to the version of the light saturation curve in the SPASS model, the gross leaf photosynthesis rate at light saturation $P_{{gms}}$ in the SUCROS model is simulated as independent of the atmospheric CO$_2$ concentration, but is impacted by senescence. Therefore effects of temperature, leaf N-content, and development stage are considered:

$$P_{{gm}} = P_{{max}} f_{d_{p,i}(s_{{dev}})} f_{T,p} \min\{f_{\theta,p}; f_{N,p}\}$$

(33)

$P_{{gm}}$ gross leaf photosynthesis at light saturation [kg CO$_2$ ha$^{-1}$ d$^{-1}$]

$P_{{max}}$ maximal gross leaf photosynthesis rate [kg CO$_2$ ha$^{-1}$ d$^{-1}$]

$f_{d_{p,i}(s_{{dev}})}$ senescence reduction factor [1]

$f_{N,p}$ leaf-N reduction factor [1]

$f_{T,p}$ temperature factor [1]

$f_{\theta,p}$ water stress factor [1]

where the senescence reduction factor can be defined by tables of values and prescribed by input data specific for crop and variety.
The temperature factor \( f_{T,p} \) is given by interpolation of tabular values depending on crop and variety (input data):
\[
f_{T,p} = f_{T,p,\beta}(T_{\text{day}})
\] (34)

This temperature function is given by tabular values, which can represent measured data. For \( n \) data \( \mathbf{d}_i = (x_i, y_i)_{1 \leq i \leq n} \), a function is defined by:
\[
y = f_{\mathbf{d}_i}(x) = \begin{cases} y_1 & \text{für } x \leq x_1 \\ y_i + (x - x_i) \frac{y_{i+1} - y_i}{x_{i+1} - x_i} & \text{für } x_i < x \leq x_{i+1} \\ y_n & \text{für } x_n \leq x
\end{cases}
\] (35)

which interpolates the prescribed values.

Thus, for corresponding data \( \mathbf{d}_i = (T_i, y_i)_{1 \leq i \leq n} \), representing temperatures \((T_i)_{1 \leq i \leq n} \,[^\circ C]\), we can define and prescribe a temperature function \( f_{T,\mathbf{d}_i}(T) \) using measured data.

**Leaf area growth**

The daily leaf growth rate \( \mu_{\text{day},\text{gr}} \) of green leaf area during the juvenile development phase also depends on the daily average air temperature \( T_{\text{day}} \,[^\circ C] \):
\[
\mu_{\text{day},\text{gr}} = \mu_{\text{LA}} \max\{0 ; T_{\text{day}} - T_{\text{ref}}\}
\] (36)

where, depending on the species and variety of the cultivated crop, the specific leaf area growth \( \mu_{\text{LA}} \,[^\circ C^{-1} \, \text{d}^{-1}] \) and the corresponding reference temperature \( T_{\text{ref}} \,[^\circ C] \) are given input parameters.

During later development phases the daily growth of green leaf area is determined by the corresponding growth rate \( \mu_{\text{day},\text{gr}} \,[^\circ C^{-1} \, \text{d}^{-1}] \), which is now assumed to be directly proportional to the daily leaf biomass growth rate \( \mu_{\text{day},\text{B,gr}} \,[\text{kg} \, \text{ha}^{-1} \, \text{d}^{-2}] \), with a proportionality constant given by the specific leaf area \( s_{\text{LA}} \,[\text{kg} \, \text{ha}^{-1}] \) (per leaf dry matter) of the crop species:
\[
\mu_{\text{day},\text{gr}} = s_{\text{LA}} \mu_{\text{day},\text{B,gr}}
\] (37)

During senescence, the leaf area death rate results from the composition of the leaf area death rate due to senescence \( \sigma_{\text{day},\text{sns}} \,[^\circ C^{-1} \, \text{d}^{-1}] \) and the leaf area death rate due to shading \( \sigma_{\text{day},\text{shd}} \,[^\circ C^{-1} \, \text{d}^{-1}] \):
\[
\sigma_{\text{LA}} = \min\{\sigma_{\text{day},\text{sns}} ; \sigma_{\text{day},\text{shd}}\}
\] (38)
where the death rate due to senescence additionally depends on the average air temperature $T_{\text{day}} \, ^{\circ}C$ and the development phase $s_{\text{dev}} \, [1]$, which is prescribed by tabular input values and corresponding interpolation for both dependencies:

$$d_{LA,sns}^{\text{day}} = f_{d_{LA,i}}(s_{\text{dev}}) \cdot f_{d_{LA,j}}(T_{\text{day}}) \tag{39}$$

**Root growth**

Starting with an assumed rooting depth of 35 mm at crop emergence, the growth of root length is simulated by applying the daily depth extension $\mu_{\text{ext,rts}}^{\text{day}} \, [\text{mm} \cdot \text{d}^{-1}]$ of the roots:

$$\mu_{\text{ext,rts}}^{\text{day}} = \min\{18; \mu_{\text{ext,rts}}^{\text{max}} \cdot f_{T,\text{rts}}\} \tag{40}$$

- $\mu_{\text{ext,rts}}^{\text{day}}$: daily root depth extension rate $[\text{mm} \cdot \text{d}^{-1}]$
- $\mu_{\text{ext,rts}}^{\text{max}}$: maximal daily root depth extension rate $= 2.2 \, \text{mm} \cdot \text{d}^{-1} \cdot ^{\circ}C^{-1}$
- $f_{T,\text{rts}}$: temperature function of root depth extension $[^{\circ}C]$

Thereby the temperature function $f_{T,\text{rts}} \, [^{\circ}C]$ of root depth extension is calculated as the arithmetic mean of minimal and maximal daily air temperature, which in case of negative temperatures during the vegetation period is further corrected.

**Crop growth model CERES**

In CERES models, plant development depends on the thermal time experienced by a plant, thus determining nine subsequent plant development stages that affect plant growth. The daily development rate between a base air temperature ($T_b=0.0 \, ^{\circ}C$) and maximum air temperature ($T_m=26.0 \, ^{\circ}C$) is directly proportional to the daily mean air temperature $T_a$ (Priesack 2006; eq. 683). More so than in the other three models presented here, the nine development stages have a strong impact on plant growth routines. The development stage determines the ratio of leaf area to leaf biomass (Priesack 2006; eq. 709). The phyllochron and the thermal time then define the leaf area growth rate (Priesack 2006; eqs. 710, 732), the number of leaves (Priesack 2006; eq. 731), the stem, leaf, and root growth rates (Priesack 2006; eqs. 717-721, 741, 744), and growth of tillers (Priesack 2006; eqs. 738, 740, 743, 745). In the case of root growth, not only the biomass growth rates but also the computation of the root length growth rate is affected by air temperature (Priesack 2006; eq. 750). Temperature also determines a factor that reduces the photosynthetic rate (Priesack 2006; eqs. 706, 707, 723) and the senescence of leaves (Priesack 2006; p.196 and eqs. 733, 734, 735).

**Crop growth model GECROS**

In GECROS, phenological development depends on cumulative thermal day units that determine the development rates and hence the development stage of the plant. A temperature response function for phenological development can be described by genotype specific or measured minimum, optimum, and
maximum temperatures (Yin and van Laar 2005; eq. 50 and p. 47). A time course of daily air temperatures is computed from minimum and maximum temperature data using a sine function, with an assumed maximum at 2 pm, following Matthews and Hunt (1994; see also, Yin and van Laar 2005; eq. H3). The development stage determines the sink strength of plant organs and thus assimilate partitioning, accumulation, and re-allocation. It controls the leaf area development, leaf senescence, the determination of grain number, and 1000-grain weights, and is involved in the estimation of the nitrogen demand of the plant (Yin and van Laar 2005; p. 100-102, 111).

In GECROS, the estimation of photosynthetic rates and dark respiration is based on the biochemical photosynthesis model by Farquhar et al. (1980), with extensions by Yin et al. (2004). Following a two-leaf approach, leaf temperatures are estimated for sunlit and shaded leaves, taking into account the respective transpiration rates (De Pury and Farquhar 1997; Wang and Leuning 1998). The leaf transpiration rates depend on the temperature gradient between the leaf and air (Yin and van Laar 2005; eqs. 2, 6). Leaf temperatures also affect the stomatal conductance to estimate the diffusion of CO₂ from the external air to the reactive sites in the cells (Yin and van Laar 2005; eq. 4 and p.121). The Michaelis-Menten constants of CO₂ and O₂, as well as the CO₂ compensation point in the absence of dark respiration, carboxylation rates, electron transport, and the rate of leaf dark respiration, are temperature dependent (Yin and van Laar 2005; p.123-124). The dependence of the kinetic properties of Rubisco and capacity of electron transport on leaf temperatures is given by eqs. A4a-A4c and A5 in Yin and van Laar (2005).

References


Temperature functions of the OLEARY and CONNOR wheat crop model

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Introduction

Temperature controls many aspects of simulating crop growth and yield, either by directly affecting the crop or by influencing the crop through various soil processes. This summary deals with only those functions that directly affect the crop through air temperature. The effect of air temperature is the first and most important component to get right because of its strong dominating influence on crop development. Development is important because it drives many other secondary processes such as growth and senescence, and biomass partitioning to leaves, stems, roots, and grains etc.

Phenological development

Table 1 shows the salient temperature functions used to predict five phenological stages in the OLEARY and CONNOR wheat crop model (O’Leary et al. 1985; O’Leary and Connor 1996). An important feature of the phenological model is the simulation of some phenostages, independent of the previous stage and over a longer period. This helps to reduce compounding errors from earlier stages such as emergence, stem extension, or booting.

Table 1. Phenological stages and decimal code (DC) simulated in the OLEARY and CONNOR wheat crop model (O’Leary et al. 1985; O’Leary and Connor 1996), for an example cultivar Yecora Rojo, developed from the AgMIP wheat single crop data set (low), showing the thermal (TT, day-degree) and photothermal (PTT, day-degree-hour) time needed to reach each stage. For booting and anthesis stages, photothermal time is used with lower temperature (Tb) and photoperiod thresholds (Pb). No upper limits are applied to temperature or photoperiod in the simulation of phenostage.

| Stage       | Stage          | Lower Tb | Lower Pb | TT  | PTT   | Notes                                                                 |
|-------------|----------------|----------|----------|-----|-------|                                                                      |
| Emergence   | Sowing to EM   | 3        |          | 100 |       | With depth correction other than 3 cm sowing depth                  |
| Stem extension | Sowing to SE | 4        |          | 350 |       |                                                                      |
| Booting     | SE to BO       | 4        | 0        | 550 |       |                                                                      |
| Anthesis    | Sowing to AN   | 2        | -10      | 2370|       | Negative threshold provides algebraic insensitivity to photoperiod |
| Maturity    | AN to MA       | 8        |          | 465 |       |                                                                      |
**Biomass accumulation**

The accumulation of biomass is driven primarily by transpiration and transpiration efficiency (TE, kg/ha/mm), which is modified by temperature (Tf) and nitrogen (Nf) functions, via radiation use efficiency (RUE, g/MJ). These are defined as:

\[
\text{TEmax} = \frac{58}{\text{VPD}}
\]  
\[
\text{RUE} = \{(\text{TEmax} \times \text{PT}) / (\text{IPAR} \times 10)\} \times \text{Tf} \times \text{Nf}
\]  
\[
\text{TE} = \text{Minimum}\{10 \times \text{RUE} \times \text{IPAR} / \text{PT}, 200\}
\]

where TEmax is the atmospheric derived TE; VPD is the daily vapour pressure deficit (kPa); PT is the potential transpiration (mm); IPAR is the intercepted photosynthetic active radiation (MJ/m²). Mean daily temperature reduces RUE and TE linearly below 10°C from unity to zero at 0°C and above 25°C to 35°C, respectively, after Keulen and Seligman (1987).

**Biomass partitioning to root**

Partitioning to roots is determined by a function of daily air temperature, which provides a minimal root:shoot ratio at the optimum temperature of 20°C (Friend 1966; Davidson 1969; O'Leary et al. 1985). The calculation sequence is defined as:

\[
\text{SR} = 10.0 \times \text{EXP}(-1.02314**\text{AT})*(((293.15 -\text{AT})/\text{AT})**2))
\]  
\[
\text{IF}(\text{SR} < 0.5) \text{ SR} = 0.5
\]  
\[
\text{RSA} = 1.0 / \text{SR}
\]  
\[
\text{IF}(\text{DAY} = \text{EMERGE}) \text{ RSA} = 2.0
\]  
\[
\text{RAL} = 1.0 / (1.0 + 1.0 / \text{RSA})
\]

where SR is the shoot:root ratio; AT is the absolute mean daily air temperature (°K); RSA is the root:shoot ratio; DAY is day of year; EMERGE is day of year the crop emerged; and RAL is the daily allocation ratio of assimilated biomass to root. This code applies an asymmetric temperature function that partitions carbohydrate to roots at both cold and hot temperatures, with the greatest effect applied at hot temperatures. This has provided higher root-shoot ratios when crops were grown in hotter conditions from late sowing in southern Australia.

**Biomass partitioning to grain**

Temperature controls the partitioning of biomass to grain in two ways. Firstly, by increasing the relative grain growth rate initially at 0.3 g/g/day at 16°C with a Q10 of 2 (Vos et al. 1982); and during the linear growth period of 2.8 mg/grain/day at 16°C with a Q10 of 1.5 (Vos et al. 1982). Secondly, the timing of transferring pre-anthesis carbohydrate reserves to grain, like phenology, is driven by thermal time after
anthesis. No lower or upper limits apply to these temperature functions, apart from the lower limit applied to thermal time after anthesis (e.g. Tb = 8°C, Table 1).

**Biomass senescence**

Senescence of above ground and root biomass occurs in stages as the crop develops. For above ground biomass, it commences at a fixed rate from stem extension (0.003 g/g/day); increasing to 0.008 g/g/day at booting. From anthesis, the senescence rate increases from 0.01 to 0.15 g/g/day by maturity, defined by thermal time after anthesis, and increases up to 0.5 g/g/day under severe water stress. For root biomass, the rate of senescence is set to 50% of the shoot biomass.

**References**


Temperature functions in the SALUS wheat model

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The SALUS model (www.salusmodel.net; Basso et al. 2010, 2011; Basso and Ritchie 2012; Dzotsi et al. 2013) has two models for wheat: a simplified one and a complex one developed from the CERES Wheat model (Ritchie and Otter 1984). For the simple crop model, daily thermal time (DTT) is generally calculated as the average temperature for the day, minus a crop specific base temperature of 0°C. This is modified when daily temperatures are outside the range of the base temperature or an optimum development temperature. The equation and logic is:

\[
DTT = \frac{\min \left( T_{opt \text{ dev}}, \max \left( T_{base \text{ dev}}, T_{\min} \right) \right) + \min \left( T_{opt \text{ dev}}, \max \left( T_{base \text{ dev}}, T_{\max} \right) \right)}{2} - T_{\text{base dev}}
\]  

(1)

where \( T_{\text{opt dev}} \) is the optimal temperature for thermal time accumulation and \( T_{\text{base dev}} \) is the temperature that corresponds to no thermal time accumulation for that particular crop.

The calculated DTT is used to simulate leaf area index (LAI) for the day, using a predetermined curve for that crop; similar to that used in ALMANIC, EPIC. The LAI is then used with radiation use efficiency (RUE), light interception, and a temperature factor, to determine the accumulation of biomass. The cumulative DTT required from emergence to maturity is an input; thus each DTT value, when divided by maturity thermal time (TT), is the fraction of the season represented by DTT. Higher temperatures cause the crop to mature quicker, usually causing a decrease in accumulated biomass. The DTT is summed to calculate cumulative TT using in the following equations:

\[
LAI_{\text{rel}} = \frac{TT_{\text{rel}}}{(TT_{\text{rel}} + e^{C_1-C_2TT_{\text{rel}}})}
\]  

(2)

\[
LAI = LAI_{\text{yest}} + (LAI_{\text{rel}} - LAI_{\text{rel,yest}})LAI_{\text{max}} \min \left( F_{\text{drought}}, F_{\text{heat}}, F_{\text{cold}}, F_N, F_P \right)
\]  

(3)

where \( TT_{\text{rel}} \) is the ratio of current thermal time to thermal time to maturity; \( LAI_{\text{max}} \) is the potential LAI value; and \( C_1 \) and \( C_2 \) are constants. The LAI value is reduced by drought, heat, cold, nitrogen, and phosphorus stress as expressed by the various factors (\( F_\ldots \)) listed in equation 3.

The complex model uses the same DTT as in the simple model to simulate the rate of leaf appearance and leaf area per plant until the final leaf, and then the time for various phases thereafter. Leaf appearance rate is also related to photoperiod, as documented in Jame et al. 1998.

\[
dLea f Eq = \frac{F_{\text{photoperiod}}^{\text{DTT}}}{\text{Phyllochron}}
\]  

(4)

The variable Phyllochron is the cumulative TT required to grow one new leaf in a particular plant after being modified by photoperiod.
Other factors are influenced by temperature through a lookup table in the complex model. A relative importance fraction is generated between 0 and 1 for these factors, as a multiplier for potential rates of processes, and is interpolated from a general type flexible linear template, as shown in Figure 1 where four cardinal temperatures are defined. As an example, the factor for daily biomass modification uses values of 0, 15, 26, and 38 for the four critical temperature variables. Other factors calculated in a similar way with different critical temperatures are vernalization effectiveness, heat stress, cold hardening, winter kill, and grain filling rate.

![Figure 1. Relative importance factor for cardinal temperature](image)

For the complex model, leaf area expansion ($\text{LAExp}$) is calculated as a ratio of new leaf mass ($\text{dLeaf}$) to specific leaf weight ($W_{sl}$), which allows plants to grow thinner leaves under stress ($F_{str}$). Leaf senescence is calculated based on stage specific factors:

$$\text{LAExp} = \frac{\text{dLeaf}}{W_{sl}} \min (1, 1.15 F_{str})$$  \hspace{1cm} (5)

$$\text{LAI} = \text{LAI}_{\text{yest}} + 0.0001P_{\text{pop}} \text{LAExp} - \text{LAI}_{\text{senec}}$$  \hspace{1cm} (6)

Daily leaf growth per plant is calculated from a tabular value in a species file that increases as leaf number increases.

The winter kill routine has been modified from CERES to include genotype differences in winter wheat varieties with various sensitivities to winter kill. Fowler et al. (1999) reported these genotype differences and provided a model framework for calculating the winter kill thresholds. The concept of a low temperature causing 50% death, termed $LT_{50}$, is calculated each day during periods of cold temperature. Winter kill routines can prove to be valuable for climate change considerations; where global warming should make more areas available for winter wheat production, given its general superiority to spring wheat in quality and yield.
References


Temperature routines in SIMPLACE<LINTUL2-CC-HEAT>

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General overview

SIMPLACE (Scientific Impact assessment and Modeling PLatform for Advanced Crop and Ecosystem management) is a modeling framework based on the concept of encapsulating the solution of a modeling problem in discrete, replaceable, and interchangeable software units, called SimComponents or sub-models (Enders et al. 2010). A specific combination of sub-models within the framework is called a model solution (Gaiser et al. 2013). The crop models LINTUL2 (van Oijen and Leffelaar 2008) and LINTULCC (van Oijen and Ewert 1999) have been modified with respect to heat stress and phenology and implemented into the SIMPLACE framework.

Temperature data handling

Daily mean temperature $T_{mean}$ (°C) is calculated as the average of daily maximum temperature $T_{max}$ (°C) and daily minimum temperature $T_{min}$ (°C), which are provided as inputs. Daily effective temperature $T_e$ (°C) is calculated as the difference between $T_{mean}$ and base temperature $T_{base}$. For the AgMIP wheat pilot, $T_{base}$ was set to 1°C for the phase between emergence and anthesis, while $T_{base}$ was 9 °C between anthesis and maturity (Porter and Gawith 1999).

Impact of temperature on crop phenology

In SIMPLACE<LINTUL2-CC-HEAT>, crop development rate is relative to the daily increment of photothermal time, $\Delta PVTT$ (°C d), for the period between emergence and anthesis, or to the daily increment of thermal time $\Delta TT$ (°C d) for the period between anthesis and maturity. $\Delta PVTT$ is calculated by correcting $\Delta TT$ by factors describing the response of the cultivar to photoperiod and vernalization; the latter was switched off in this study. For daily mean temperatures between base temperature $T_{base}$ and an optimum temperature ($T_{opt,d}$) of 32 °C, $\Delta TT$ is equal to daily effective temperature $T_e$ (Equation 1). When $T_{mean}$ is higher than 32 °C, $\Delta TT$ is linearly reduced to 0 °C d at an upper temperature threshold ($T_{upper}$) of 40 °C (Equation 1). $\Delta TT$ is 0 °C d when $T_{mean}$ is lower than $T_{base}$ or higher than $T_{upper}$ (Equation 1). Thresholds for $T_{opt}$ and $T_{upper}$ were defined according to McMaster et al. (2008).

$$\Delta TT = \left\{ \begin{array}{ll} T_e & \text{if } T_{base} \leq T_{mean} \leq T_{opt} \\ \frac{(T_{upper} - T_{mean})(T_{opt,d} - T_{base})}{T_{upper} - T_{opt,d}} & \text{if } T_{opt} < T_{mean} \leq T_{upper} \\ 0 & \text{else} \end{array} \right. \quad (1)$$
Impact of temperature on leaf development

Impact of temperature on leaf growth

The daily increment of the leaf area index $\Delta LAI$ (-) during the juvenile stage is driven mainly by the daily effective temperature $T_e$ and by the ratio between transpiration $TRAN$ (mm d$^{-1}$) and potential transpiration $PTRAN$ (mm d$^{-1}$). The juvenile stage is defined as the phase in which leaf area index $LAI$ is less than 0.7, and $PVTT$ is less than 30% of the photo-vernal thermal time required until anthesis $PVTT_{anthesis}$. Leaf area expansion for the rest of the growth period is calculated based on specific leaf area $SLA$ and daily growth rate of leaf dry matter $GLV$ (g m$^{-2}$ d$^{-1}$; Equation 2). Relative growth rate of $LAI$ during exponential growth $RGRL$ and $SLA$ were constants set to 0.009 (°C d$^{-1}$) and 0.022 m$^2$ g$^{-1}$.

$\Delta LAI = \begin{cases} 
LAI(\exp(RGRL \times T_e) - 1) \frac{TRAN}{PTRAN} & \text{if } \frac{PVTT}{PVTT_{anthesis}} < 0.3 \text{ AND } LAI < 0.75 \\
SLA \times GLV & \text{else} 
\end{cases}$

(2)

Impact of temperature on leaf aging

Relative death rate of leaves due to ageing $RDRDV$ (d$^{-1}$) is 0.03 d$^{-1}$ when $T_{mean}$ is lower than 10 °C; 0.04 d$^{-1}$ at a $T_{mean}$ of 15 °C; and 0.09 d$^{-1}$ when $T_{mean}$ is higher than 30 °C. Between these lower, central, and upper values, $RDRDV$ is calculated by linear interpolation. The process is restricted to the development phase after anthesis.

Impact of temperature on evapotranspiration

Reference crop evapotranspiration $ET_0$ (mm d$^{-1}$) is calculated based on the Penman equation (Penman 1963; van Oijen and Leffelaar 2008). Daily mean temperature is required to compute saturation vapor pressure $e_s$ (kPa) and the change of saturation vapor pressure $\Delta$ (kPa °C$^{-1}$), as defined by:

$ET_0 = 0.408 \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} 2.63(1 + 0.54u_2)(e_s - e_a)$

(3)

$\Delta = 4158.6 \frac{e_s}{(T_{mean} + 239)^2}$

(4)

$e_s = 0.611 \exp \left( \frac{17.4T_{mean}}{T_{mean} + 239} \right)$

(5)

where $\gamma$ is the psychrometric constant (kPa °C$^{-1}$); $R_n$ the net radiation absorption rate (J m$^{-2}$ d$^{-1}$); $u_2$ the wind speed measured at 2 m above ground (m s$^{-1}$); and $e_a$ the actual vapour pressure (kPa).

Effects of high temperatures on yield

The impact of heat stress on crop yield is simulated based on the modified GAEZ model approach (Teixeira et al., 2013). It is assumed that crops are only sensitive to heat stress during the period around
anthesis (15 days before and after anthesis); known as the thermal-sensitive period. In this period, we calculated a daily heat stress intensity $f_{HSd}$ (-) (Equation 6) and then averaged this to derive a yield reduction factor $f_{HS}$ for the thermal-sensitive period (Equation 7). Crop yield $Y$ (Mg ha$^{-1}$) is then adjusted for heat stress around anthesis by reducing grain yield relative to the yield reduction factor $f_{HS}$ (Equation 8). In SIMPLACE<LINTUL2-CC-HEAT> heat stress occurs when daily maximum temperature $T_{max}$ exceeds a critical temperature threshold $T_{crit}$ set to 27 °C; maximum impact occurs when $T_{max}$ exceeds an upper temperature threshold $T_{lim}$ of 40 °C (Equation 6). While the original GAEZ model used daytime temperature to compute the yield reduction, we used daily maximum temperature because we found that the result was a better match for experimental data from Germany.

$$f_{HSd} = \begin{cases} 0 & \text{if } T_{max} < T_{crit} \\ \frac{T_{max} - T_{crit}}{T_{lim} - T_{crit}} & \text{if } T_{crit} \leq T_{max} \leq T_{lim} \\ 1 & \text{else} \end{cases}$$  \hspace{1cm} (6)$$

$$f_{HS} = \frac{\sum f_{HSd}}{TSP} \hspace{1cm} (7)$$

$$Y_{adj} = (1 - f_{HS})Y \hspace{1cm} (8)$$

where $TSP$ is the length of the thermal sensitive period (15 days before anthesis to 15 days after anthesis = 31 days); and $Y_{adj}$ the grain yield adjusted for the impact of heat stress around anthesis (Mg ha$^{-1}$).

References


Temperature responses in the wheat simulation model *SiriusQuality*

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The *SiriusQuality* wheat simulation model (Martre et al. 2006) originated from Sirius V99 (Jamieson et al. 1998b; Jamieson and Semenov 2000). However, Sirius V99 considers the canopy as homogeneous, with three main compartments, i.e. leaf, stem (true stem + leaf sheaths), and grain, whereas *SiriusQuality* calculates daily changes in individual organ size (leaf laminae, light exposed and shaded leaf sheath surface area, and internode length) of each phytomer, and their C and N mass. The main responses to temperature in *SiriusQuality* V2.0 are described below.

**Soil and canopy temperatures**

Near soil surface (0-2 cm) and canopy temperatures are calculated based on the surface energy balance (Jamieson et al. 1995a). Near soil surface (0-2 cm) temperature is calculated based on statistical fits of soil temperature data to estimates of the soil surface energy balance. Daily maximum soil temperature ($T_{\text{soil,max}}$, °C) is calculated from the available energy at the soil surface (avEN, MJ m$^{-2}$ d$^{-1}$) and daily maximum air temperature ($T_{\text{air,max}}$, °C), following Jamieson et al. (1995a), modified to allow for reduction of soil-air temperature difference at low temperatures (Jamieson et al. 1998a):

\[
T_{\text{soil,max}} = \begin{cases} 
T_{\text{air,max}} + 11.2 \left(1 - e^{-0.07(\text{avEN} - 5.5)}\right) - 0.5 \frac{T_{\text{air,min}} + T_{\text{air,max}}}{2} + 4, & \text{if } \frac{T_{\text{air,min}} + T_{\text{air,max}}}{2} < 8^\circ\text{C} \\
T_{\text{air,max}} + 11.2 \left(1 - e^{-0.07(\text{avEN} - 5.5)}\right), & \text{if } \frac{T_{\text{air,min}} + T_{\text{air,max}}}{2} \geq 8^\circ\text{C}
\end{cases}
\]

where

\[
\text{avEN} = \lambda \left( e^{(-K_L \text{LAI})} R_n - E_{\text{soil}} \right)
\]

and $R_n$ is the net radiation at the top of the canopy in equivalent evaporation (kg m$^{-2}$ day$^{-1}$); $K_L$ is the light extinction coefficient (m$^2$ m$^{-2}$); LAI is leaf area index (m$^2$ m$^{-2}$); $\lambda$ is the latent heat of vaporization of water (2.454 MJ kg$^{-1}$); and $E_{\text{soil}}$ (kg m$^{-2}$ day$^{-1}$) is soil evaporation, calculated following Tanner and Jury (1976), as modified by Jamieson et al. (1995b). $R_n$ is calculated from the global daily radiation ($R_g$, MJ m$^{-2}$ d$^{-1}$) as:

\[
R_n = \left( -0.1 + 0.241 R_g \right) / \lambda
\]
Daily minimum soil temperature \( T_{S,\text{min}}, \degree C \) is calculated from the minimum daily air temperature \( T_{A,\text{min}}, \degree C \) of the current day \( d \) and the deep soil temperature \( T_{S,\text{deep}}, \degree C \), calculated in a 10-day period:

\[
T_{S,\text{min}}(d) = \frac{T_{\text{air,min}}(d) + T_{\text{deep}}(d-1)}{2}
\]  

(4)

where

\[
T_{\text{deep}}(d-1) = \left( 9T_{\text{deep}}(d-2) + \frac{T_{S,\text{min}}(d-1) + T_{S,\text{max}}(d-1)}{2} \right) / 10
\]  

(5)

Canopy temperature \( T_{\text{can}}, \degree C \) is calculated from the crop energy balance, assuming a neutral wind profile:

\[
H = R_n - G - E_t = \frac{\rho C_p g_a}{86.4 \times 10^3 \lambda} (T_{\text{can}} - T_{\text{air}})
\]

(6)

where \( H \) (kg m\(^{-2}\) d\(^{-1}\)) is the sensible heat flux in equivalent evaporation; \( G \) (kg m\(^{-2}\) day\(^{-1}\)) is the soil heat flux in equivalent evaporation, given as \( \text{avEN}/\lambda \); \( E \) (kg m\(^{-2}\) d\(^{-1}\)) is the evapotranspiration, calculated as the sum of transpiration \( E_t \) (kg m\(^{-2}\) d\(^{-1}\)), calculated following Ritchie (1972), and \( E_{\text{soil}} \); \( \rho \) (1.225 kg m\(^{-3}\)) is the density of air; \( C_p \) (1.01 \( \times \) \( \times \) 10\(^{-3}\) MJ kg\(^{-1}\) K\(^{-1}\)) is the heat capacity of air at constant pressure; and \( g_a \) (m s\(^{-1}\)) is the boundary layer conductance for heat, given by Monteith (1973):

\[
g_a = \frac{k^2 \max(u_z, u_{z,\text{min}})}{\left( \ln\left( \frac{z - z_d}{z_m} \right) \right)^2}
\]

(7)

where \( k \) (0.41, dimensionless) is von Kármán’s constant; \( z \) (m) is the height at which air temperature and wind speed \( u_z \) (m s\(^{-1}\)) are measured (assumed to be equal to 2 m); \( z_m \) (m) is the momentum roughness length; and \( z_d \) (m) is the zero-plan displacement. The latter two parameters have been empirically determined as 0.13\( h \) and 0.63\( h \), respectively (Monteith, 1973), where \( h \) (m) is the canopy height, calculated as described in Lawless et al. (2005). A minimum wind speed \( u_{z,\text{min}} \) of 1.16 m s\(^{-1}\) (100 km d\(^{-1}\)) is assumed, to allow for buoyancy effects at low wind speed.

Rearranging Eqs. (6) and (7) gives the following equation for \( T_{\text{can}} \):

\[
T_{\text{can}} = T_{\text{air}} + \left( \frac{1 - e^{-K_{\text{LAI}}}}{\rho C_p g_a / 86.4 \times 10^3 \lambda} \right) R_n + E_{\text{soil}} - E_t
\]

(8)
Where daily wind speed is not available, a default value of 2.78 m s⁻¹ (240 km d⁻¹) is used, yielding a boundary layer conductance of 0.084 m s⁻¹.

**Thermal time**

Following the ARCWHEAT1 approach (Weir et al. 1984), daily integral of thermal time (\( T_\text{r}, \ ^\circ \text{Cd} \)) is calculated as the sum of eight contributions each day of a cosinusoidal variation between maximum and minimum temperatures (either air, soil, or canopy temperatures, depending on the development stage and process):

\[
T_\text{r} = \frac{1}{8} \sum_{r=1}^{8} (T_h - T_b)
\]  

where

\[
T_h(r) = T_{\text{min}} + f_r (T_{\text{max}} - T_{\text{min}})
\]

and

\[
f_r = \frac{1}{2} \left( 1 + \cos \frac{90}{8} (2r-1) \right)
\]

\( T_b (\ ^\circ \text{C} ) \) is the base temperature fixed at 0°C and \( T_h (\ ^\circ \text{C} ) \) is the calculated three hour temperature contribution to estimated daily mean temperature and \( f_r \) is the fraction that each 3 hour period during the day contributes to the thermal time for that day. Negative contributions of \( T_h \) are treated as zero.

In contrast with ARCWHEAT1, no optimum and maximum threshold temperatures are defined, so that \( T_\text{r} \) increases linearly with daily \( T_h \).

**Soil N mineralization**

It is assumed that mineralization of organic soil N (\( N_O, \ \text{g N m}^{-2} \)) takes place in the top 40 cm of the soil and that \( N_O \) is distributed equally in each 5 cm layer of the top soil. Daily \( N_O \) mineralization (\( N_m, \ \text{g N m}^{-2} \)) is distributed between available and unavailable soil water buckets in proportion with their water content, with temperature (\( F_T, \ \text{dimensionless} \)) and moisture (\( F_\theta, \ \text{dimensionless} \)) effects:

\[
N_m = K_0 F_T F_\theta N_O
\]

where

\[
F_\theta = \begin{cases} 
\theta / \theta_{FC}, & \theta \leq \theta_{FC} \\
\max \left( 0, 1 - \left( \theta - \theta_{FC} \right) / \left( \theta_s - \theta_{FC} \right) \right), & \theta > \theta_{FC}
\end{cases}
\]
\[ F_T = \max \left( 0, \ e^{0.57 - 0.024T_m + 0.002T_m^2} - e^{0.57 - 0.042T_m - 0.0051T_m^2} \right) \] (14)

\[ T_m = 0.66 + 0.93T_{\text{air,weekly}} \] (15)

\( \theta \) (mm) is the actual soil water content; \( \theta_{\text{FC}} \) (mm) is the soil water content at field capacity; \( \theta_s \) is the soil water content at saturation (mm); \( K_0 \) is the soil N mineralization rate constant (d\(^{-1}\)); \( T_m \) (°C) is the top soil temperature correction; and \( T_{\text{air,weekly}} \) (°C) is the weakly mean daily air temperature.

**Phenology**

*Rate of leaf appearance*

Leaf appearance rate is proportional to the temperature of the apex, which is calculated from simulated apex temperature (assumed to be similar to \( T_{\text{soil}} \) until Haun stage 4, and thereafter similar to \( T_{\text{can}} \)).

Many studies have shown that phyllochron depends on the sowing date, and several authors have discussed putative physiological causes of these variations (Slafer and Rawson 1997; McMaster et al. 2003), while others have shown that most of the observed variations in phyllochron are due to apex-air temperature differences (Vinocur and Ritchie 2001; Jamieson et al. 2008). In *SiriusQuality*, as a surrogate for the apex-air temperature correction, for a winter sowing (day of the year 1 to 90 for the northern hemisphere), the phyllochron decreases linearly with the sowing date and is minimum until mid-July for the northern hemisphere (day of the year 200):

\[ P_{SD} = \begin{cases} P \times (1 - R_p \min (SD, SD_{W/S})), & 1 \leq SD < SD_{S/A} \\ P, & SD \geq SD_{S/A} \end{cases} \] (16)

where SD is the sowing date in day of the year; \( P \) (°C leaf\(^{-1}\)) is a varietal parameter defining the phyllochron for autumn sowing; \( R_p \) (set at 0.003) is the rate of decrease of \( P_{SD} \) for winter sowing; and \( SD_{W/S} \) and \( SD_{S/A} \) are the sowing dates for which \( P_{SD} \) is minimum and maximum, respectively.

*Rate of vernalization*

The phenology routine in *SiriusQuality* was taken from Sirius V96 (Jamieson et al. 1998b) and modified as described here and elsewhere (e.g. He et al. 2012). The daily rate of vernalization (\( V_{\text{rate}}, \ d^{-1} \)) increases at a constant rate (\( V_{\text{AI}}, \ d^{-1} \cdot \text{°C}^{-1} \)) with daily mean apex temperature, from its value (\( V_{\text{BEE}}, \ d^{-1} \)) at the minimum vernalizing temperature (\( T_{\text{min}}^{\text{ver}}, \text{°C} \)) to a maximum for an intermediate temperature (\( T_{\text{int}}^{\text{ver}}, \text{°C} \)). Above \( T_{\text{int}}^{\text{ver}}, \ V_{\text{rate}} \) reduces to zero at the maximum vernalizing temperature (\( T_{\text{max}}^{\text{ver}}, \text{°C} \)). Previous work indicates that the vernalization requirement of some winter wheat genotypes can be eliminated, or greatly reduced, by a prolonged exposure to short photoperiods (Dubcovsky et al. 2006; Evans 1987); a process referred in the literature as short day vernalization. The vernalizing effect of short days was
introduced in *SiriusQuality* V2.0 to improve the simulation of anthesis date in the hot-serial-cereal experiment (White et al. 2011).

The photoperiodic effect on vernalization rate is likely to involve a quantitative interaction with temperature, rather than a complete replacement of the vernalization requirement (Brooking and Jamieson 2002; Allard et al. 2012;). It is modeled following the *Sirius* vernalization framework, with the assumption that the effectiveness of short days decreases progressively as photoperiods increase from $DL_{min}^\text{ver}$ (set at 8 h) to $DL_{max}^\text{ver}$ (set at 15 h):

$$
V_{rate} = \begin{cases}
    \text{VAI} \times T_i + \text{VBEE}, & T_{\text{min}}^\text{ver} \leq T_i \leq T_{\text{int}}^\text{ver} \\
    \text{max} \left( 0, \left( \text{VAI} \times T_{\text{int}}^\text{ver} + \text{VBEE} \right) \times \left( 1 + \frac{T_{\text{ver}}^\text{int} - T_i}{T_{\text{max}}^\text{ver} - T_{\text{ver}}^\text{int}} \times \frac{\text{DL}_{\text{eff}}^\text{ver} - \text{DL}_{\text{min}}^\text{ver}}{\text{DL}_{\text{max}}^\text{ver} - \text{DL}_{\text{min}}^\text{ver}} \right) \right), & T_{\text{int}}^\text{ver} < T_i \leq T_{\text{max}}^\text{ver}
\end{cases}
$$

where

$$DL_{\text{eff}}^\text{ver} = \text{max} \left( DL_{\text{min}}^\text{ver}, \text{min} \left( DL_{\text{max}}^\text{ver}, DL \right) \right)$$

**Light use efficiency**

Light use efficiency (LUE, g MJ⁻¹) for each leaf layer is calculated as a function of the average daily canopy temperature ($T_{\text{can,mean}}$, °C), the air CO₂ concentration (Jamieson et al. 2000), the ratio of diffuse to global solar radiation, the specific leaf nitrogen mass (Sinclair and Amir 1992), and the water deficit; assuming an additive effect of these factors (Jamieson et al. 1998b). The response function of LUE to temperature ($F_T$) uses the equation proposed by Yan and Hunt (1999):

$$
F_T = \begin{cases}
0, & T_{\text{can,mean}} < 0 \\
\left( \frac{T_{\text{max}} - T_{\text{can,mean}}}{T_{\text{max}} - T_{\text{opt}}} \right) \left( \frac{T_{\text{can,mean}}}{T_{\text{opt}}} \right)^\frac{T_{\text{can,mean}} - T_{\text{opt}}}{T_{\text{opt}} - T_{\text{max}}}, & 0 \leq T_{\text{can,mean}} \leq T_{\text{max}} \\
0, & T_{\text{can,mean}} > T_{\text{max}}
\end{cases}
$$

where $T_{\text{max}}$ (set at 50°C) is the daily average temperature, at which $F_T$ equals 0, and $T_{\text{opt}}$ (set at 18 °C) is the optimum temperature at which $F_T$ equals 1.
References

Temperature effects in the STICS model: Theoretical basis and essential routines for annual crops

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Introduction

STICS is a daily time step crop model (Brisson et al. 2008) developed since 1996 at INRA (France), in collaboration with other research and professional institutes. The STICS model has been widely used to assess impacts of climate change and adaptation of different crops (Brisson and Levrault 2010). Most recently, the STICS group is taking part in the international AgMIP project (Rosenzweig et al. 2012); an effort to improve crop model responses to climate factors and to produce enhanced assessments of the effects of global climate change. This paper aims to present the essential temperature routines of the STICS model so that they can be compared with the different approaches used by other crop models.

Growing degree days based on crop temperature

Temperature is used in crop models as the driving variable of the phenological time, in accordance with the long-accepted concept of growing degree days (Bonhomme et al. 1994). Studies (e.g. Ong 1983) have shown that it is better not to use air temperature, but rather a temperature closer to the plant (soil or organ) to explain the phasic chronology. In particular, this can be explained by the acceleration of the cycle in case of drought (Seghieri et al. 1995). Consequently, STICS adopted the idea of linking phenological time to the crop temperature.

Crop temperature (TCULT) is assumed to be the arithmetic mean of the maximum crop temperature (TCULTMAX) and the minimum crop temperature (TCULTMIN). The empirical method to calculate the maximum crop temperature is based on a relationship between midday surface temperature and daily evaporation (Seguin and Itier 1983):

\[
TCULTMAX(i) = TMAX(i) + \left(\frac{RNET(i)}{2.46} - ET(i) - 1.27\right) \cdot \frac{1.68}{\ln \left(\frac{1}{Z0(i)}\right)}
\]

(1)

\[Z0(i) = 0.13 \cdot HAUTEUR(i) \quad \text{and if} \quad Z0(i) \leq 0.001, \quad Z0(i) = 0.001\]

where \(RNET\) is the net daily radiation (MJ m\(^{-2}\)); \(ET\) the daily evapotranspiration (mm); \(TMAX\) is the maximum air temperature; and \(HAUTEUR\) is the canopy height. TCULTMAX cannot be lower than TMAX. TCULTMIN is equal to TMIN.

Crop development

Development driven by crop temperature may be slowed by sub-optimal photoperiod conditions, by non-compliance with vernalization requirements, or by the effect of water or nitrogen stress. The effect of temperature, achieved at a daily time step, increases linearly between the TDMIN and TDMAX thresholds, and decreases linearly between the TDMAX and TCXSTOP thresholds, as illustrated in Figure
1. It is not easy to alter the TMAX and TCXSTOP parameters because they correspond to occasional thermal conditions. Nevertheless, including this decrease in developmental and leaf growth, in agreement with experiments in hot conditions, is worthwhile for using the model in future climate conditions (Brisson et al. 2008).

Leaf dynamics

Many models, such as CERES (Ritchie and Otter 1985), have a marked preference for “leaf to leaf” simulation. However, Milroy and Goyne (1995) quoted several studies showing that simulating leaf area index (LAI) directly on a canopy scale gives as good results as a “leaf to leaf” model. Chapman et al. (1993) worked on a canopy scale and they suggested splitting the evolution of LAI into two curves. The first one represents the growth (always a logistic curve) and the other curve is the senescence (logistic or exponential). In STICS, leaf area growth is driven by phasic development, temperature, and stresses. An empirical plant density-dependent function represents inter-plant competition. For determinate plants, a maximal expansion rate threshold is calculated to avoid unrealistic leaf expansion.

The calculation of leaf growth rate (DELTAI in m² m⁻² d⁻¹) is shown in Eq. 2. The first calculation of the LAI growth rate (DELTAI_dev in m² plant⁻¹ degree-day⁻¹) describes a logistic curve, related to the phenological stages. This value is then multiplied by the effective crop temperature (DELTAI_T in degree-days), the plant density combined with a density factor, supposed to stand for the inter-plant competition characteristic for the variety (DELTAI_dens in plant m²⁻¹), and the water and nitrogen stress indices (DELTAI_stress).

\[
DELTAI_1 (t) = DELTAI_{dev} (t) \cdot DELTAI_T (t) \cdot DELTAI_{dens} \cdot DELTAI_{stress} (t)
\]  \hspace{1cm} (2)

The phasic development function is comparable to that of the PUTU model (Singels and Jagger 1991). The thermal function relies on crop temperature and cardinal temperatures. The density function (DELTAI_dens) is active only if LAI and plant density are greater than given thresholds, over which leaf area
per plant decreases exponentially. Senescence concerns both LAI and dry matter and is driven by the concept of leaf lifespan, which is shortened by temperature, nitrogen and water stresses.

**Biomass growth and yield**

Stresses linked to temperatures that are too high or too low (without attaining frost thresholds) are included in the temperature effect functions. The smooth shape of the radiation use efficiency dependency on crop temperature (Fig. 1) is quite classical (Ritchie and Otter 1985) and comes from the combined responses of photosynthesis and respiration to temperature. Yet the cardinal temperature values are highly dependent on the time step used; in our case, daily average crop temperatures. As far as yield is concerned, the number of grains is fixed during a phase of variable duration, which precedes the onset of filling. This duration can be shortened by high temperatures. The quantity of dry matter accumulated in grains is calculating by applying a progressive “harvest index” to the dry weight of plant. In this case, the temperature response in the model is a yes/no type, using the maximum and minimum crop temperatures for the stop filling at high and low temperatures, respectively.

**Frost**

The frost stress indices correspond to frost damage (1 = no frost; 0 = lethal frost) and the response to temperature, as well as the damage, varies as a function of the developmental stage. Each response is defined by four parameters. TDEBGELp (temperature at the beginning of frost action) and TLETALEp (lethal temperature) are independent of the developmental stage; whereas TGEL10p (temperature corresponding to 10% frost damage) and TGEL90p (temperature corresponding to 90% frost damage) are stage-dependent.

**References**


WheatGrow: A simulation model for predicting growth and productivity in wheat

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WheatGrow is a model developed since 1994 by the National Engineering and Technology Center for Information Agriculture, Nanjing Agricultural University. It runs at a daily time step, simulating wheat growth and development under potential production, and water- and nitrogen-limited scenarios. The model includes sub-models of phenological development, photosynthesis and biomass accumulation, biomass partitioning and organ formation, grain yield and quality formation, water and nitrogen balance. The structure of WheatGrow is outlined in Fig.1:

![Figure 1. Structural framework of WheatGrow](image)

**Phenological development**

The phenology of wheat was quantified by physiological development time (PDT: the development time accumulated under an optimum environment) (Cao and Moss 1997; Yan et al. 2000). PDT is a state variable with a value of 0 at emergence, 16.1 at jointing, 21.4 at booting, 26.8 at heading, 31.0 at flowering, 39.0 at grain filling, and 56.0 at maturity (Yan 1999). The interaction of daily thermal effectiveness (DTE), relative photoperiod effectiveness (RPE), intrinsic earliness (IE), and filling duration factor (FDF) determines the daily physiological effectiveness. These daily values of effectiveness were summed to obtain PDT. Five specific genetic parameters were used to adjust the genotypic differences in wheat development. These parameters were thermal sensitivity (TS), photoperiod sensitivity (PS), IE,
FDF, and physiological vernalization time (PVT). In the reproductive period, the primary process of phenological development in wheat is plant senescence. According to Lobell et al. (2012), senescence in wheat is determined by the normal temperature (and therefore a normal senescence process) and extreme high temperature (accelerated plant senescence). Daily thermal effectiveness (DTE) was therefore calculated under the normal temperature (NTE) and the extreme high temperature effectiveness (HTE) in this sub-model.

**Photosynthesis and biomass accumulation**

Gaussian integration was used to calculate daily canopy photosynthesis by integrating the instantaneous photosynthetic rate over the day and leaf area index. This model also considered actual CO₂ assimilation rate, which was influenced by CO₂ concentration, physiological age, average temperature, and N nutrient and water stress. Daily total dry matter was calculated from daily total gross assimilation of canopy and respiration consumption. Respiration was expressed as a daily loss of total dry matter. Maintenance and growth respiration were also calculated.

**Biomass partitioning and organ formation**

A partitioning index was used to simulate time-course dynamics of dry matter distribution among different organs during development. The shoot and root partitioning indices were defined as a fraction of dry weight in plant biomass. For green leaves, stems and ears are as the proportion of their dry weights in shoot. Partitioning index changed with PDT. Since water deficit affects biomass allocation, a water deficit factor was used to adjust shoot and root dry matter portioning, with daily biomass allocated to green leaves adjusted by both the water deficit factor and nitrogen nutrition index.

**Grain yield and quality formation**

The biomass allocation to spikes was affected by high and low temperatures. The proportion of grain weight in panicles was set as 80% in the model. The average moisture content of wheat grains is about 12.5%, so this was used as a default value to calculate final wheat yield. If the actual grain moisture content is not 12.5%, the simulated grain yield should be adjusted. Wheat grain quality, including the formation of starch and protein (i.e. the primary components of the wheat grain), depends on the processes of carbon and nitrogen assimilation during pre-anthesis, and translocation during post-anthesis. Grain starch and protein accumulation are affected by temperature, nitrogen, and water in this sub-model. Algorithms for starch and protein accumulation in the wheat grain were developed on the basis of non-structural carbohydrate formation, nitrogen uptake, and carbon and nitrogen flow dynamics in the plant, which were driven by PDT.

**Water and nitrogen balance**

The water balance sub-model was developed according to the soil water budget method, following the CERES-Wheat (Ritchie and Otter 1985) and MACROS models (Penning et al. 1989). The processes of water interception by crops, irrigation, rainfall, surface drainage/runoff, field evaporation and transpiration, and root water uptake were included. The drought stress factor was based on the critical
soil water content, which is the point of limited soil water availability. The waterlogging stress factor was quantified by integrating soil water content, waterlogging duration, and plant sensitivity at different growth stages. In the nitrogen balance sub-model, critical plant nitrogen content, nitrogen uptake, and allocation were quantified to describe the relationship between soil-N supply, plant uptake, dry matter production, and N accumulation in the grains.

References


Temperature routines in WOFOST

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The WOFOST model

The WOFOST (WOrld FOod STudies) model (Boogaard et al. 1998; Supit et al. 1994) was originally developed in the late 1980s as part of an interdisciplinary study on world food production potentials for annual crops. It was one of the crop growth models developed in Wageningen by the school of C.T. de Wit (Bouman et al. 1996), all of which are characterised by the hierarchical distinction between potential and water- and/or nutrient- limited production and share similar crop growth submodels, with light interception and CO2 assimilation as growth driving processes, and crop phenological development as a growth controlling process. WOFOST is the simplest of the group, as it was developed primarily for practical applications, which aim to keep input requirements as low as possible. The model dynamically describes phenological development, growth, and yield formation of a crop from emergence till maturity (at a daily time step), on the basis of crop genetic characteristics, management practices, and environmental conditions. In the model, crop yields can be calculated for three different production situations: potential, water-limited, and nutrient-limited (van Ittersum et al. 2003). For more background information, see www.wofost.wur.nl.

Temperature routines

The temperature inputs required by WOFOST are daily minimum and maximum air temperature [°C], as available from meteorological stations. The model then internally calculates the mean daily temperature as an arithmetic mean of these two figures. The following description of temperature routines is based on Supit et al. 1994.

Temperature effects on phenology

In WOFOST, the phenological development stage is calculated as a function of ambient air temperature, with an option for modification by day length. The development stage is expressed in a dimensionless variable: 0 denotes seedling emergence; 1 signifies full flowering; and physiological maturity gives a value of 2. The phenological stage is reached when the effective daily temperature sum reaches the pre-defined threshold; this is dependent on daily temperature, and is specified, allowing for non-linearity (lower and upper threshold values and optimum ranges; Fig. 1).

![Figure 1. Effective temperature from sowing to emergence (from Supit et al. 1994).](image)
**Temperature effects on photosynthesis**

Gross assimilation depends on the development stage, temperature, and transpiration rate. Maximum leaf CO₂ assimilation rate \( A_{m} \) has to be corrected for sub-optimal average daytime temperatures (Fig. 2). The correction factor is determined by daytime temperature and is crop specific.

At night assimilates, produced during daytime, are transformed into structural biomass. This process is hampered by low temperature. If low temperatures prevail for several days, assimilates accumulate in the plant and the assimilation rate diminishes and ultimately halts. In WOFOST, this temperature effect is accounted for by introducing a correction factor, which should be multiplied by \( A_{m} \). This correction factor is a function of low minimum temperature and is crop specific.

**Temperature effects on respiration**

The maintenance respiration rate depends on the amount of dry matter in various organs, the relative maintenance rate per organ, and temperature. Higher temperatures accelerate turnover rates in plant tissue and thus increase maintenance costs. Therefore, a variable \( Q_{10} \) is introduced, which is defined as the relative increase of the respiration rate per 10°C temperature increase. \( Q_{10} \) should be provided by the user. Maintenance respiration rate, at a certain temperature, can be calculated by:

\[
R_{m,T} = R_{m,25} \cdot Q_{10} \frac{T - T_r}{10}
\]

where
- \( R_{m,T} \): Maintenance respiration rate at temperature T [kg ha⁻¹ d⁻¹]
- \( R_{m,25} \): Maintenance respiration rate at reference temperature of 25°C [kg ha⁻¹ d⁻¹]
- \( Q_{10} \): Relative increase of the respiration rate per 10°C temperature increase [-]
- \( T \): Average daily temperature [°C]
- \( T_r \): Reference temperature [=25°C in the model] [°C]

For tropical species, the reference temperature may be up to 10°C higher than for species from temperate climates. The maintenance requirements of a crop are likely to be adapted to the higher growth temperatures. However, in WOFOST, the reference temperature is fixed at 25°C for all crops.
Temperature effects on leaf area dynamics

WOFOST assumes that the exponential growth rate of leaf area index is valid until the source-limited increase of leaf area index equals the exponential growth rate. Leaf area index growth rate per time step in the early, exponential growth stage can be calculated as:

\[ L_{\text{exp}, t} = \frac{LAI_t \cdot RL \cdot T_e}{T_{\text{b,age}}} \]  

(2)

where \( L_{\text{exp}, t} \) : LAI growth rate at time step \( t \) during exponential growth stage \([\text{ha ha}^{-1} \text{ d}^{-1}]\)

RL : Maximum relative increase of leaf area index \([\text{°C}^{-1} \text{ d}^{-1}]\)

\( T_e \) : Daily effective temperature \([\text{°C}]\)

Physiologic ageing

The life span of a leaf (physiological aging), and subsequent death, is crop specific, and defined as the maximum number of days a leaf can live at a constant temperature of 35°C. The physiologic ageing factor per time step can be calculated as:

\[ f_{\text{rai}} = \frac{T - T_{b,\text{age}}}{35 - T_{b,\text{age}}} \]  

(3)

where \( f_{\text{rai}} \) : Physiologic ageing factor for leaf age increase \([-]\)

\( T \) : Daily (average) temperature \([\text{°C}]\)

\( T_{b,\text{age}} \) : Lower threshold temperature for physiologic ageing \([\text{°C}]\)

The lower threshold temperature for physiologic ageing \( T_{b,\text{age}} \) is crop specific and should be provided by the user.

Temperature effects on evapotranspiration

WOFOST applies Penman formula:

\[ ETO = WR_{\text{ne}} + (1 - W)EA \]  

(4)

where \( ETO \) : Evapo(transpiration) \([\text{mm d}^{-1}]\)

\( W \) : Temperature related weighing factor \([-]\)

\( R_{\text{na}} \) : Net absorbed radiation in equivalent evaporation \([\text{mm d}^{-1}]\)

\( EA \) : Evaporative demand in equivalent evaporation \([\text{mm d}^{-1}]\)
to calculate the potential evapotranspiration. That involves a temperature related weighting factor \((W)\) which is calculated as

\[
    W = \frac{\Delta}{(\Delta + \gamma)}
\]  

(5)

where

- \(\Delta\): Slope of the saturation vapour pressure curve [hPa °C\(^{-1}\)]
- \(\gamma\): Psychrometric constant [hPa °C\(^{-1}\)]

where

\[
    \Delta = \frac{238.102 \cdot 17.32491 \cdot e_s}{(T + 238.102)^2}
\]

(6)

where

- \(D\): Slope of the saturation vapour pressure curve [hPa °C\(^{-1}\)]
- \(e_s\): Saturated vapour pressure [hPa]
- \(T\): Air temperature [°C]

References


Next steps for AgMIP-Wheat: The international heat stress genotype experiment

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Since the 3rd Annual Global Workshop of the Agricultural Model Intercomparison and Improvement Project (AgMIP) in October 2012, the AgMIP-Wheat team has focused on simulating the Hot Serial Cereal (HSC) experiment (Kimball et al. and Wall et al., these proceedings). This exercise has been enlightening and fruitful. We anticipate that further analyses of these results, based on the documentation of temperature algorithms presented in these proceedings, will further enlighten our understanding of how best to model the response of wheat to high temperatures. We propose to build on this experience as we move forward. Whereas the HSC experiment simulations involved very detailed data at a single location, as a next step, we suggest simulating wheat growth under a range of temperatures at multiple locations around the world.

The International Heat Stress Genotype Experiment (IHSGE) was a four-year collaboration between CIMMYT and key national agricultural research system partners to identify important physiological traits that have value as predictors of yield at high temperatures (Reynolds et al. 1994). Experiment locations were selected based on a classification of:

- Hot dry
- Hot humid
- Very hot dry
- Very hot humid

“Hot” and “very hot” locations were defined as having mean temperatures above 17.5 °C and 22.5 °C, respectively, during the coolest month of the wheat growing cycle. “Dry” and “humid” locations were defined as having mean vapor pressure deficits above and below 10 mb, respectively, during the wheat growing cycle. Throughout the experiment, a total of 12 locations were used. At two locations, normal and late sowing dates were used to provide contrasting temperature regimes at the same location. Sixteen genotypes were selected to represent a range from heat-tolerant to heat-susceptible. Variables measured in the experiment included:

- Plant count after emergence
- Biomass and ground cover at the 5-leaf stage
- Biomass at median 50% anthesis
- Days to 50% anthesis
- Days to physiological maturity
- Plant height
- Biomass, grain yield, spikes m⁻², grains spike⁻¹, and thousand grain weight at maturity
From the 12 original locations, we selected seven, between 27°N and 23°S, to represent the range of temperatures. All seven locations have at least two years of data, and two of the seven locations also include late sowing dates to provide contrasting temperatures at the same location. Average growing season temperatures ranged between 17.9-26.3 °C across all locations, sowing dates, and years. Minimum temperatures ranged from 5.8-19.1 °C during vegetative growth, from 9.5-17.0 °C during early reproductive growth, and from 10.8-19.8 °C during grain filling (Fig. 1). Maximum temperatures showed an even greater spread, with ranges of 20.8-37.5 °C during vegetative growth, 21.0-36.5 °C during early reproductive growth, and 23.5-37.3 °C during grain filling (Fig. 2). In addition, we selected two genotypes (Bacanora 88 and Nesser) from the original 16, which have contrasting sensitivity to high temperature, but both of which have low sensitivity to photoperiod.

We suggest that the IHSGE dataset represents a unique opportunity for the AgMIP-Wheat team to test wheat models across a range of locations and temperature conditions with comparison to relatively detailed physiological data. As such, we propose that the next steps for AgMIP-Wheat include the simulation of this dataset for the identified locations and genotypes.

![Figure 1. Minimum wheat growing-season temperatures (T_{min}) for three phenological stages at seven locations (Aswan, Egypt; Ciudad Obregon, Mexico; Dharwar, India; Dinajpur, Bangladesh; Londrina, Brazil; Tlaltizapan, Mexico; and Wad Medani, Sudan).](image)
Figure 2. Maximum wheat growing-season temperatures ($T_{\text{max}}$) for three phenological stages at seven locations (Aswan, Egypt; Ciudad Obregón, Mexico; Dharwar, India; Dinajpur, Bangladesh; Londrina, Brazil; Tlaltizapan, Mexico; and Wad Medani, Sudan).

References