Uncertainty of wheat water use: Simulated patterns and sensitivity to temperature and CO2

Davide Cammarano a,1,*, Reimund P. Rötter b, Senthold Asseng a, Frank Ewert c, Daniel Wallach d, Pierre Martre e,f,1, Jerry L. Hatfield g, James W. Jones a, Cynthia Rosenzweig h, Alex C. Ruane h, Kenneth J. Boote a, Peter J. Thorburn i, Kurt Christian Kersebaum j, Pramod K. Aggarwal k, Carlos Angulo c, Bruno Basso l, Patrick Bertuzzi m, Christian Biernath n, Nadine Brison o,p,3, Andrew J. Challinor q,r, Jordi Doltra r, Sebastian Gayler t, Richie Goldberg h, Lee Heng g, Josh E. Hooker v, w, Leslie A. Hunt x, Joachim Ingwersen y, Roberto C. Izaurralde z, A, Christoph Müller b, Soora Naresh Kumar c, Claas Nendel d, Garry O’Leary d, Jørgen E. Olesen e, Tom M. Osborne f, Eckart Priesack N, Dominique Ripoche l, Pasquale Steduto h, Claudio O. Stöckle I, Pierre Stratonovitch G, Thilo Streck y, Iwan Supit t, Fulu Tao b, k, Maria Travasso d, Katharina Waha b, 2, Jeffrey W. White m, Joost Wolf n

a Agricultural & Biological Engineering Department, University of Florida, Gainesville, FL 32611, United States
b Climate Impacts Group, Natural Resources Institute Finland (Luke), FI-00790 Helsink, Finland
c Institute of Crop Science and Resource Conservation (INRES), Universität Bonn, 53115, Germany
d National Institute for Agricultural Research (INRA), UMB124 Agrosystèmes et développement territorial, 31226 Castanet-Tolosan Cedex, France
e INRA, UMR1095 Genetics, Diversity and EcoPhysiology of Cereals (GDEC), F-63 100 Clermont-Ferrand, France
f Blaise Pascal University, UMR1095 GDEC, F-63 170 Aubièrè, France
g National Laboratory for Agriculture and Environment, Ames, IA 50011, United States
h National Aeronautics and Space Administration (NASA), Goddard Institute for Space Studies, New York, NY 10025, United States
i Commonwealth Scientific and Industrial Research Organization (CSIRO), Ecosystem Sciences, Dutton Park QLD 4102, Australia
j Institute of Landscape Systems Analysis, Leibniz Centre for Agricultural Landscape Research, 15374 Müncheberg, Germany
k Consultative Group on International Agricultural Research, Research Program on Climate Change, Agriculture and Food Security, International Water Management Institute, New Delhi, 110002, India
l Department of Geological Sciences and Kellogg Biological Station, Michigan State University, East Lansing, MI, United States
m National Institute for Agricultural Research (INRA), US1116 AgroClim, F-84 914 Avignon, France
n Institute of Soil Ecology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, D-85764, Germany
o National Institute for Agricultural Research (INRA), UMR0211 Agronormie, F-78750 Thiverval-Grignon, France
p AgriParisTech, UMR0211 Agronomie, F-78750 Thiverval-Grignon, France
q Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds LS297, United Kingdom
r CGIAR-ESP Program on Climate Change, Agriculture and Food Security, International Centre for Tropical Agriculture (CIAT), A.A. 6713, Cali, Colombia
s Cantabrian Agricultural Research and Training Centre (CIFA), 39600 Muriedas, Spain
t Water & Earth System Science Competence Cluster, c/o University of Tübingen, 72074 Tübingen, Germany
u International Atomic Energy Agency, 1400 Vienna, Austria
v School of Agriculture, Policy and Development, University of Reading, RG6 6AR, United Kingdom
w Joint Research Center, via Enrico Fermi, 2749 Ispra, 21027 Italy
x Department of Plant Agriculture, University of Guelph, Guelph, Ontario, N1G 2W1, Canada
y Institute of Soil Science and Land Evaluation, Universität Hohenheim, 70599 Stuttgart, Germany
z Dept. of Geographical Sciences, Univ. of Maryland, College Park, MD 20742, United States
A Texas A&M AgLife Research and Extension Center, Texas A&M Univ., Temple, TX 76502, United States
b Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany
c Centre for Environment Science and Climate Resilient Agriculture, Indian Agricultural Research Institute, New Delhi 110 012, India
d Landscape & Water Sciences, Department of Primary Industries, Horsham 3400, Australia, Australia
e Department of Agroecology, Aarhus University, 8630, Tjele, Denmark

* Corresponding author. Present Address: The James Hutton Institute, Invergowrie, Dundee, DD2 5DA, U.K.
E-mail addresses: Davide.Cammarano@hutton.ac.uk, davide.cammarano@ufl.edu, davide.cammarano@gmail.com (D. Cammarano).
1 Present address: INRA, Montpellier SupAgro, UMR759 Laboratoire d’EcoPhysiologie des Plantes sous Stress Environnementaux, F-34 060 Montpellier, France.
2 Present address: Commonwealth Scientific and Industrial Research Organization (CSIRO), Agriculture, 306 Carmody Road, 4067 St.Lucia, Australia.
3 Passed away in 2011 while this work was being carried out.

http://dx.doi.org/10.1016/j.fcr.2016.08.015
0378-4290© 2016 Elsevier B.V. All rights reserved.
Projected global warming and population growth will reduce future water availability for agriculture. Thus, it is essential to increase the efficiency in using water to ensure crop productivity. Quantifying crop water use (WUE; i.e. actual evapotranspiration) is a critical step towards this goal. Here, sixteen wheat simulation models were used to quantify sources of model uncertainty and to estimate the relative changes and variability between models for simulated WU, water use efficiency (WUE, WU per unit of grain dry mass produced), transpiration efficiency (T_eff, transpiration per kg of unit of grain yield dry mass produced), grain yield, crop transpiration and soil evaporation at increased temperatures and elevated atmospheric carbon dioxide concentrations ([CO_2]). The greatest uncertainty in simulating water use, potential evapotranspiration, crop transpiration and soil evaporation was due to differences in how crop transpiration was modelled and accounted for 50% of the total variability among models. The simulation results for the sensitivity to temperature indicated that crop WU will decline with increasing temperature due to reduced growing seasons. The uncertainties in simulated crop WU, and in particularly due to uncertainties in simulating crop transpiration, were greater under conditions of increased temperatures and with high temperatures in combination with elevated atmospheric [CO_2] concentrations. Hence the simulation of crop WU, and in particularly crop transpiration under higher temperature, needs to be improved and evaluated with field measurements before models can be used to simulate climate change impacts on future crop water demand.

© 2016 Elsevier B.V. All rights reserved.
bles are usually more accurate than any individual model (Asseng et al., 2013; Martre et al., 2015; Rötter et al., 2012). A further benefit of ensembles is that the variability among the simulations from an ensemble can be used to estimate the uncertainty range when using different CSMs.

In this paper we used simulations from a recent multi-model study (Asseng et al., 2013) that focused solely on wheat grain yield, to explore simulations of crop WUE, WUE, and T_eff and their variability and sensitivity to temperature and [CO2] changes.

The objectives of this study were to: i) quantify the contributions of sources of model uncertainty to calculations of crop transpiration, soil evaporation, and potential evapotranspiration; and to ii) estimate the relative changes, the patterns and the variability between models for the simulated WU, WUE, T_eff, yield, crop transpiration and soil evaporation at elevated temperatures and [CO2].

2. Materials and methods

2.1. Experimental sites

Experimental data from four locations with contrasting growing season rainfall and temperature were used which were described in details in Asseng et al. (2013). The locations were Wageningen – NL (Groot et al., 1991), Balcarce – AR (Travasso et al., 1995), New Delhi – IN (Naveen, 1986), and Wongan Hills – AU (Asseng et al., 1998). In particular, the experimental sites were defined in terms of yield and season length as long high yielding and long season in the NL, high/medium yielding and medium season in AR, irrigated and short season in IN, and low yielding, rainfed, short season in AU (Asseng et al., 2013). These locations were chosen to represent four different wheat mega-environments, a concept used by wheat breeders for testing cultivars (Monfreda et al., 2008) that accounts for about 80% of the wheat-growing area of the world (Additional details were provided in Tables S1 and S2).

The data were quality controlled and standardized using the AgMIP data protocols (Rosenzweig et al., 2011). The management information used at each site was obtained from the experimentalists. The crops were kept weed and disease-free. Daily weather data of solar radiation, maximum and minimum temperature and rainfall were recorded at weather stations on site, with the exception of IN, where solar radiation was obtained from the NASA POWER dataset (White et al., 2011b). At NL, the average daily wind speed at 2-m height was measured. At the three other locations daily wind speed was estimated using the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA) (Rienecker et al., 2011). At all locations dew-point temperature was estimated using MERRA. Atmospheric [CO2] was assumed to be at 360 ppm for all the locations, in line with measured atmospheric [CO2] for the mid-point (year 1995) of the baseline climate period 1980–2009.

Measured experimental field data used for this study were harvested grain dry matter yield (Y, t ha⁻¹), in-season measurements of total aboveground biomass (dry matter) (AGB; t ha⁻¹), leaf area index (LAI, m² m⁻²), water usage (WU, mm), and soil water content to maximum rooting depth (SWC, Vol%). For each location soil the soil layers were supplied to all modelling groups (Table S2). For each soil layer (i for up to n layers) and from the layer-specific SWC, the plant available soil water content to maximum rooting depth (PAW, mm) was calculated using the lower limit of water extraction for each soil layer (LL, Vol%) which is similar to the soil moisture content at wilting point, and the thickness of each soil layer (st, m) as follows:

\[
PAW = \sum_{i=1}^{n} s_{i} (SWC_{i} - LL_{i})
\]  (1)

At NL, the SWC was measured down to 1 m, so the SWC and PAW were calculated assuming that the soil between 1 m and maximum rooting depth of 2 m was similar to the 0.6–1 m layers. At AR, the SWC was measured down to 1.2 m and the maximum rooting depth was 1.3 m. While, in IN and AU the SWC was measured up to 1.5 m and 2.1 m, and the maximum rooting depth was 160 and 210, respectively.

Soil water balance (SWB) was calculated for each simulation run using the simulated drainage (mm), runoff (mm), crop transpira-

Fig. 1. Simulated potential reference evapotranspiration (ET0) and percentage of simulated water use variance. (a) Simulated seasonal ET0 for the 30-year baseline calculated from the average of those models using Penman-Monteith (PM, 7 models), Priestley-Taylor (PT, 6 models), and Penman (P, 3 models) equations. Different letters indicate significant differences at α = 0.05. (b–d) Simulated proportion of variance for water use explained by ET0 (light grey), crop transpiration (Ta, black), and soil evaporation (Es, white) for (b) the experimental year and the 30-year baseline, (c) average daily air temperature increases, and (d) increasing atmospheric CO2 concentrations.
tion (mm), soil evaporation (mm), and rainfall (mm) for NL, AR, AU, while for IN irrigation was also considered (mm). To calculate the ∆Soil Water Change (SWB) the following equation was used:

\[
SWB = \text{Rain} + \text{Irrigation} - \text{Drainage} - \text{Runoff} - \text{Transpiration} - \text{Evaporation}
\]  

(2)

2.2. Crop models

Based on a twenty-six member multi-model ensemble study conducted by Asseng et al. (2013), sixteen crop models which simulate crop transpiration (Ta) and soil evaporation (Es) as separate fluxes were selected for detailed analysis of water use simulations (for more detailed information on the simulated processes see Table S3). The models, which varied in complexity and functionalities, have all been described and used in modelling wheat crops. Additional details on modelling procedures were described in Asseng et al. (2013), for this study we used the models calibrated against phenology and yield. At the beginning of the study a questionnaire was sent to the modelers to provide information on which type of ET₀ was used in the crop models. Information on different implementations of the ET₀ calculation in the 16 wheat models using the Penman (P; Penman, 1948), Penman-Monteith (PM; Allen et al., 1998) or Priestley-Taylor (PT; Priestley and Taylor, 1972) equations (Table S3). Analysis of variance (ANOVA) for unbalanced designs was used to test the differences among the three ET₀ formulas at each location.

2.3. Data analysis

The partitioning of uncertainty of simulated WU was made to explore which component was responsible for most of the variability. WU can be expressed as follows, based on simulated cumulative ΣET₀, ΣTa and ΣEs:

\[
WU = \sum \frac{Es}{ET₀} + \sum \frac{Ta}{ET₀}
\]  

(3)

The variance is calculated as follows:

\[
\text{Var}(WU) = \text{Var}\left(\frac{\sum Ta}{\sum ET₀}\right) + E\left(\sum ET₀\right)^2 + \text{Var}\left(\frac{\sum Es}{\sum ET₀}\right) + E\left(\sum ET₀\right)^2 + \text{Var}\left(\sum ET₀\right)\]

(4)

where \(\sum Ta/\sum ET₀\) was transpiration as a fraction of evaporative demand and \(\sum Es/\sum ET₀\) was soil evaporation as a fraction of evaporative demand. A way of quantifying the contribution of
\[
\sum \frac{T_a}{\sum ETo}, \sum \frac{E_s}{\sum ETo}, \text{ and } \sum ETo \text{ to the overall uncertainty was through the first-order sensitivity coefficients (S1):}
\]

\[
S1(Ta) = Var\left(\sum \frac{Ta}{\sum ETo}\right) \times E\left(\sum ETo\right)^2
\]

\[
S1(Es) = Var\left(\sum \frac{E_s}{\sum ETo}\right) \times E\left(\sum ETo\right)^2
\]

\[
S1(ETo) = Var\left(\sum ETo\right) \times \left[E\left(\sum \frac{E_s}{\sum ETo} + \sum \frac{Ta}{\sum ETo}\right)\right]^2
\]

If there are no interactions among terms, S1(x) is the fraction of overall variance contributed by factor x and the sum of the S1 can be somewhat larger or smaller than 1, depending on whether there were positive or negative correlations between terms. The larger the values of S1(x), the greater the contribution of factor x to the overall variance. From the sum of the first-order sensitivity coefficients, we calculated the percentage contribution of each term.

Water use efficiency (WUE) was calculated as:

\[
WUE = \frac{Y}{\Sigma WU}
\]

where \(Y\) is the simulated grain dry matter yield and \(\Sigma WU\) was the cumulative evapotranspiration calculated from sowing to harvest.

Transpiration efficiency (\(T_{eff}\)) on a grain yield basis was calculated following the definition of Angus and van Herwaarden (2001):

\[
T_{eff} = \frac{Y}{\sum Ta}
\]

where \(\sum Ta\) is the cumulative water transpired from sowing to harvest.

2.4. Sensitivity analysis

In addition to the simulations based on the measured experimental conditions, simulations were conducted using daily weather data for the period 1980–2010 for all the locations to create a baseline. A sensitivity analysis of the sixteen models to temperature and \([CO_2]\) was done using a partly-factorial design. Daily minimum and maximum temperature were increased by either 3 °C (+3C) or 6 °C (+6C) and \([CO_2]\) was increased in 90 ppm increments from a baseline to a maximum of 720 ppm. Wind speed and relative humidity were kept unchanged with the increased temperatures, so vapor pressure was re-calculated using the modified temperatures. In order to understand the effects of climate factors alone on crop responses, soil and crop management were kept the same for all the simulations except that dates of irrigation and fertilization were adapted to the changed phenology.
The relative changes in Y, WU, Ta, Es, WUE, and T_eff were calculated as:

\[ r_k = \frac{\bar{Y}_{\text{sensitivity, } k} - \bar{Y}_{\text{baseline, } k}}{\bar{Y}_{\text{baseline, } k}} \times 100 \]  

(10)

where \( r_k \) is the predicted relative change with respect to the 30-year baseline according to model \( k \), \( \bar{Y}_{\text{sensitivity, } k} \) is any of the above variables averaged over the 30 years of climate sensitivity according to model \( k \), and \( \bar{Y}_{\text{baseline, } k} \) are the variables averaged over the 30 years of baseline climate according to model \( k \).

More detailed analysis of the multi-model intercomparison in terms of decomposition of the mean square error and other statistical indicators can be found in [Martre et al. (2015)](#).

### 3. Results

#### 3.1. Decomposition of the variability

The simulated growing season \( E_T_0 \) using the three methods (PM, PT, and P) ranged from 786 mm for AU to 483 mm for the NL (Fig. 1a). Total season \( E_T_0 \) values calculated by the three methods differed at each location (\( P < 0.05 \); Fig. 1a).

When the uncertainty of simulated WU was partitioned between Ta, Es, and \( E_T_0 \), and following equations [2] to [6], the first-order sensitivity coefficient S1(Ta) contributed the most to the variability in WU among models (Fig. 1b–d). For the single year dataset the term S1(Ta) was 46% of the variability, S1(Es) was 30%, and \( (E_T_0) \) was 24% (Fig. 1b). For the simulations averaged over the 30-year baseline, S1(Ta), S1(Es), and S1(\( E_T_0 \)) were 51%, 28% and 21%, respectively (Fig. 1b). There was little change in the first order sensitivity coefficients as temperature increased. The S1(Ta), S1(Es), and S1(\( E_T_0 \)) values were 46, 37, and 18% at +3C and 50, 36 and 14% at +6C (Fig. 1c). Simulations with four [CO2] showed similar results with S1(Ta) ranging between 53 and 54% (Fig. 1d).

#### 3.2. Observed and simulated data

The daily patterns of growing season rainfall, observed and simulated PAW, \( E_T_0 \), LAI, Es, Ta, WU, and AGB are shown for NL, AR, IN, and AU in Figs. 2–5, respectively. The four wheat-growing locations differed in terms of the evaporative demand of the atmosphere, soil conditions, and the temporal variability of growing season rainfall and temperature (Figs. 2–5). For example, at AU rainfall occurred frequently throughout the season with occasional days of heavy rainfall in spring and summer (Fig. 5a). In contrast, there was no rainfall at the IN site (Fig. 4a). NL and AR had frequent heavy rainfall during the growing season (Figs. 2a and 3a). The in-season observed values for the plant available soil water, aboveground biomass, water use, and LAI were within the range of the simulations in NL, AR, and AU (Figs. 2, 3 and 5). There were some
discrepancies between observed and simulated values in IN for the LAI, PAW and WU (Fig. 4).

The end-of-season cumulative WU, WUE, Ta, Es, Teff, and Y for the single experimental year, and for the 30-year period from 1980 to 2009 are shown in Table 1. Simulated average values for WU was less variable than for WUE and Teff. The coefficient of variation (CV) across locations for the single experimental year varied between 14 and 23% for WU, and between 16 and 37% for WUE. Average CV of simulated values varied between 20 and 33% for Ta, between 34 and 73% for Es, and between 24 and 55% for Teff (Table 1).

3.3. Crop simulation models sensitivity to average daily air temperature and atmospheric CO2 concentration

The average simulated WU, Y, Ta, Es, WUE, and Teff decreased with increased temperature for all four locations (Fig. 6). However, the variability of the models increased as temperature increased for all the variables (Fig. 6). The models showed higher uncertainties for Australia, where except for the simulated WU which had little variability. In Australia simulated Teff varied between −100 and +100% when temperature was increased by +6°C (Fig. 6).

Simulated average WU, Ta, and Es decreased with increasing [CO2] while Y, WUE, and Teff increased with increasing [CO2] at all locations (Fig. 7). The simulated relative changes to [CO2] showed less variability than temperature. This outcome seemed to be consistent across the models, with the exception of few outliers. At 720 compared to 360 ppm [CO2] in the four locations, the overall simulated values changed by −4% for WU, +31% for Y, −2% for Ta, −9% for Es, +38% for WUE, and +34% for Teff (Fig. 7). Only the variability of WUE and Teff was higher at 720 ppm than at 360 ppm, ranging between 0 and 100% changes at 720 ppm (Fig. 7).

The respective effects of changing temperature and [CO2] interact in generating model outputs of the 16 crop models. For simulated WU, increasing [CO2] to 720 ppm does not offset its reduction caused by temperature increase (Fig. 8). The effects of [CO2] in compensating temperature-induced losses of WUE and Teff were larger than for simulated WU (Fig. 8). For example, with a 6°C increase, WUE increased if [CO2] was above 450 ppm in NL and IN, or above 550 ppm in AR and AU (Fig. 8).

Of particular interest is the variability in the direction of change in simulated responses to increased temperature or [CO2]. It was studied by counting how many models showed similar trend; for example how many models simulated a decrease in WU at +6°C, and how many simulated an increase in WU at +6°C. Overall, with a 6°C increase across the four locations, 94% of the models computed that WU decreased, 83% that Ta decreased, 52% that Es decreased, 78% that WUE decreased, and 63% that Teff decreased (Fig. 6). Modelling the effect of 720 ppm CO2, 69% of the models agreed that WU decreased, 97% that Y increased, 56% that Ta decreased, and 83%
Fig. 6. Effects of higher temperatures, respect to the 30 years historical data, on simulated water use related variables and grain yield. Boxplot of the relative change of multi-model simulations with increases in average daily air temperature of 3 °C and 6 °C for water use (WU), grain yield (Y), cumulative crop transpiration (Ta), cumulative soil evaporation (Es), water use efficiency (WUE), and transpiration efficiency (Teff), for experimental sites in the Netherlands (NL), Argentina (AR), India (IN), and Australia (AU). The percentage of individual models that predict the same trend is shown above each set of points.

Table 1
Average (AV), standard deviation (STD), and coefficient of variability (CV%) for the Netherlands (NL), Argentina (AR), India (IN), and Australia (AU) for seven parameters using the 16 crop simulation models.

| Variable | Unit                  | 1-Year          | Baseline (30-years)          |
|----------|-----------------------|------------------|------------------------------|
|          |                       | NL   | AR   | IN   | AU   | NL  | AR  | IN  | AU  |
| ETO      | (mm)                  | 548.8| 92.7 | 16.9 | 516.7| 590.1| 92.6| 15.7| 647.2| 68.4| 10.6|
| WU       | (mm)                  | 445.4| 100.3| 22.5 | 371.3| 301.9| 49.9| 13.9| 132.1| 43.8| 33.2|
| Ta       | (mm)                  | 143.7| 60.6 | 22.5 | 99.6 | 69.4 | 50.7| 17.1| 101.9| 39.8| 39.1|
| Es       | (mm)                  | 7.7  | 0.4  | 5.7  | 1.5  | 9.4  | 1.0 | 4.2 | 5.0  | 2.2  | 21.9 |
| WUE      | (kg ha⁻¹ mm⁻¹)        | 18.1 | 4.1  | 22.6 | 6.6  | 13.8 | 2.6 | 9.9 | 3.7  | 37.3 |      |
| Teff     | (kg ha⁻¹ mm⁻¹)        | 29.2 | 16   | 55   | 23.3 | 24   | 7.4 | 19.9 | 8.2  | 43.2 |      |
| ETO      | (mm)                  | 556.7| 88.3 | 15.9 | 539.6| 564.6| 10.3| 68.7| 12.2 | 692.7| 68.8| 9.9 |
| WU       | (mm)                  | 449.9| 99.3 | 22.1 | 365.9| 329.4| 52  | 15.8| 258.6| 49.7| 19.2|
| Ta       | (mm)                  | 297.9| 75.3 | 25.3 | 257  | 244.8| 62.9| 25.7| 154.4| 46.9| 30.4|
| Es       | (mm)                  | 152  | 56.9 | 37.5 | 109  | 84.7 | 46.7| 55.1| 104.2| 44.2| 42.4|
| Yield    | (t ha⁻¹)              | 7.4  | 0.9  | 12.3 | 5.5  | 0.4  | 8   | 0.6 | 12.2 | 2.8  | 21.4 |
| WUE      | (kg ha⁻¹ mm⁻¹)        | 17.3 | 4.9  | 22.1 | 15.6 | 15.4 | 1.8 | 11.6| 4.2  | 36.7 |      |
| Teff     | (kg ha⁻¹ mm⁻¹)        | 27.5 | 13.4 | 48.6 | 25.5 | 21.9 | 6.7 | 30.5| 20.4 | 10.1 | 49.3 |

a Potential evapotranspiration.
b Water use.
c Crop transpiration.
d Soil evaporation.
e Water use efficiency.
f Transpiration efficiency.
that $Es$ decreased. All models projected that WUE and $T_{eff}$ would increase (Fig. 7).

The calculated SWB using Eq. (2) showed that for both baseline and sensitivity to temperature and CO$_2$ the NL had a higher variability among the models with respect to the other locations (Fig. 9). The variability among the different components of Eq. (2) showed that transpiration ($Ta$) was the component having the higher variability followed by the drainage (Fig. 10). For example, in the NL the simulated transpiration varied between 100 and 500 mm for the baseline runs (No temperature changes) and drainage between 0 and 400 mm, for the upper and lower hinge representing the 25th and 75th percentile, respectively. At +6°C the variability of simulated crop transpiration among models ranged between 10 and 540 mm while simulated drainage ranged between 0 and 350 mm (Fig. 10a).

4. Discussion

In this study, most of the variability in simulated WU was due to model differences in $Ta/ET_o$ and $Es/ET_o$ rather than the choice of the $ET_o$ formula. This is true for the experimental years, the 30-year baseline and for the simulations with increased temperature or CO$_2$. While differences in the choice of the $ET_o$ formula have been shown to be important (Kingston et al., 2009; McAfee, 2013; McKenney and Rosenberg, 1993; Utset et al., 2004; Xu and Singh, 2002), studies focusing on the $ET_o$ formula have not analyzed how the partitioning of $ET_o$ between $Es$ and $Ta$ would influence the simulations of crop WU. Other studies have focused on the partitioning within the growing season of the $Es$ and $Ta$ only, showing that $Es$ can account for 20% to 40% of WU (Kool et al., 2014; French and Schultz, 1984).

Although the overall first order effect of $Ta/ET_o$ accounted for 51% of the total of first order effects on WU for both different temperature and CO$_2$ changes across the four locations, no experimental data were available to validate these aspects of the simulation. Differences among models in simulating rooting depth/distribution and soil water extraction by roots could be an important reason for differences in $Ta$ estimation (Wu and Kersebaum, 2008).

Understanding the partitioning of WU between crop transpiration and soil evaporation is critical because of its implications for agricultural, ecological, and hydrological studies. In addition, considering the variability in the simulation of PAW, and particularly of simulated LAI, the differences in $Ta/ET_o$ are not surprising because the water is transpired by crops through stomata that are on leaves.

Given the variability of the simulated SWB, and of the other components like drainage, further research into the reasons of variation of different sub-routines among models is necessary. The hardest part is to get detailed and accurate measurements of each sub-component in a single experiment.

The large variability between models indicates that there are major differences in the way the processes that affect water use are modeled. Differences among models in simulating soil water
Fig. 8. Interaction patterns between temperature and atmospheric CO₂ concentration on simulated water use related variables and grain yield. Relative change in (a, f, k, and p) water use (WU), (b, g, l, and q) grain yield (Y), (c, h, m, and r) cumulative crop transpiration (Ta), (d, i, n, and s) water use efficiency (WUE), and (e, j, o, and t) transpiration efficiency (Teff) simulations for experimental sites in (a–e) the Netherlands, (f–j) Argentina, (k–o) India, and Australia (p–t) with increases in average daily air temperature versus atmospheric CO₂ concentration.

extraction by roots could be an important reason for differences in Ta estimation (Wu and Kersebaum, 2008). Variability in the simulation of PAW and LAI would have a direct effect on the differences in Ta/ET₀. Since PAW was among the given soil parameters, causes are primarily related to differences in the models’ crop interfaces to soil (roots) and atmosphere (LAI).

Models have been tested against the same limited set of CO₂ response data, which are from open-top chamber or Free Air Carbon dioxide Enrichment Experiments (FACE) data. Models also typically include many processes that respond to temperature, while the response to CO₂ is often lumped at a higher level of integration as discussed in details by Kersebaum and Nendel (2014). Some models used an empirical relationship between CO₂ and radiation use efficiency while other models used the CO₂ dependency of the photosynthesis light response curve (Tubiello and Ewert, 2002) or directly simulated stomatal conductance and rubisco-kinetics based photosynthesis.

However, there is no clear relationship between model results and model’s structure because models are complex and many elements of structure interact with each other (Basso et al., 2014; Li et al., 2015; Martre et al., 2015). Further research into the sources of variation of different sub-routines among models is necessary.

Increased [CO₂] in field crops has led to decreases in WU of 3–8%, and an increase in Y of 8–31% (Hatfield et al., 2011; Kimball et al., 2002; Long et al., 2006; Manderscheid and Weigel, 2007; Tao and Zhang, 2013). The variability in the experimental results depends on crop management, CO₂ concentrations used in the experiments, the type of experiment (e.g. open-top chambers or field experiments), and the different scaling methods used to compare a crop response to CO₂ concentrations across different experiments (Long, 2012). A meta-analysis of wheat studies found that increasing [CO₂] from 400 to 800 ppm increases WUE by between 5% and 38% (Hatfield et al., 2011; Kimball et al., 2002; Long et al., 2006; Manderscheid and Weigel, 2007; Tao and Zhang, 2013; Wang et al., 2013). The
Fig. 9. Boxplots of the simulated Soil Water Balance (SWB) calculated using Eq. (2) for the Netherlands (NL), Argentina (AR), India (IN), and Australia (AU); (a) Effect of temperature on each of the model simulation of the baseline 30-years period (Base), the increases in average daily air temperature of 3 °C (T3) and 6 °C (T6); (b) for the increases in atmospheric CO₂ concentrations.

Fig. 10. Boxplots of the simulated components of the Soil Water Balance (SWB) calculated using Eq. (2). Simulated Drainage (Drain), Runoff (Runoff), crop transpiration (Ta), and soil evaporation (Es) are shown for the Netherlands (NL), Argentina (AR), India (IN), and Australia (AU); (a) Effect of temperature on each of the model simulation of the baseline 30-years period (Base), the increases in average daily air temperature of 3 °C (T3) and 6 °C (T6); (b) for the increases in atmospheric CO₂ concentrations.

results of this study regarding the simulated response at the four locations for WU, Y, and WUE to [CO₂] was in line with these studies. This concordance contrasts with claims that on average models overestimate [CO₂] effects (Ewert et al., 2007; Long et al., 2006; Tubiello et al., 2007).

Another important outcome of our study is to have traced the average pattern of WU, WUE, and T_{eff} change with temperature and [CO₂] increases. Despite variability, the majority of models had the same direction of change in Y, WU, WUE, and T_{eff} in the sensitivity to temperature and [CO₂]. This allowed us to draw conclusions about general crop responses when temperature and [CO₂] both change. The interaction between increase in temperature and increase in [CO₂] showed that, depending on the location, Y, WUE, and T_{eff} reductions due to temperature can be largely offset by increasing [CO₂]. The response of WUE to temperature is of particular interest
since this response may be driving yield changes in many regions with limited rainfall and water for irrigation (Pirttiöja et al., 2015).

The changes in temperature used in this study (+3 °C and +6 °C) caused more model output variability than the changes in atmospheric [CO2] (from 360 ppm to 720 ppm at 90 ppm intervals). But, the crop models’ agreement related to the magnitude of changes is variable-specific. For example, crop models showed good agreement in terms of relative change of simulated Y under temperature and elevated [CO2] changes, WU showed good agreement under temperature changes and lower agreement under [CO2], while WUE, and T_eff showed less agreement under temperature changes and higher agreement under elevated [CO2] (Figs. 6 and 7).

5. Conclusion

The largest uncertainty in simulated crop WU among CSMSs is due to differences in how models simulate crop transpiration. The simulated response to increased temperature caused a decline in WU. The sixteen models showed greatest uncertainty of simulated WUE, and T_eff at increased temperatures and with interactions between temperature and [CO2]. To improve the simulated impacts of climate on crop water dynamics, crop transpiration in CSMSs needs to be improved with detailed experimental data.

Acknowledgments

We thank the anonymous referees for the valuable comments and suggestions that helped improve the manuscript. S.G. was supported by a grant from the Ministry of Science, Research and Arts of Baden-Württemberg (AZ Zu 33-721.3-2) and the Helmholtz Center for Environmental Research, Leipzig (UFZ); R.P., T.P. and F.T. were supported by funds from the European FACCE MACSUR project through the Finnish Ministry of Agriculture and Forestry; P.M., P.B., N.D. and D.R. were supported by INRA Environment and Agronomy Division and by the funding within the framework of JPI FACCE MACSUR project through the INRA Metaprogram on the Adaptation of Agriculture and Forests to Climate Change; K.C.K. and C.N. received support from the German Federal Office for Agriculture and Food with FACCE MACSUR (2812ERA147) and from COST ES106; C.M. acknowledges financial support from the KULUNDA project (011L909SL) and the FACCE MACSUR project (031A103B) funded through the German Federal Ministry of Education and Research (BMBF); C.O.S. was supported by the project of Regional Approaches to Climate Change for Pacific Northwest Agriculture (REACH-PNA) funded through award #2011-68002-30191 from the National Institute for Food and Agriculture. This work has been carried out under the framework of the Agricultural Model Intercomparison and Improvement Project (AgMIP).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jfr.2016.08.015.

References

Alcamo, J., Floske, M., Marker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climate changes. Hydrol. Sci. J. 52 (2), 247–275.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage. FAO, via Terme di Caraccila, Rome, paper 56.
Angulo, C., et al., 2013. Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe. Agric. Forest Meteorol. 170, 32–46.
Angus, J.F., van Herwaarden, A.F., 2001. Increasing water use and water use efficiency in dryland wheat. Agron. J. 93 (2), 290–298.
Asseng, S., et al., 1998. Performance of the APSIM-wheat model in western Australia. Field Crops Res. 52 (2), 163–179.
Asseng, S., et al., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3 (9), 827–832.
Bassu, S., et al., 2014. How do various maize crop models vary in their responses to climate change factors? Global Change Biol. 20 (7), 2301–2320.
Blum, A., 2005. Drought resistance, water-use efficiency, and yield potential – are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56 (11), 1159–1168.
Challinor, A.J., et al., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 (4), 287–291.
Condon, A.G., Richards, R.A., Rebetezka, G.J., Farquhar, G.D., 2002. Improving the intrinsic water-use efficiency of crop yield. Crop Sci. 42 (1), 122–131.
Condon, A., Richards, R., Rebetezka, G., Farquhar, G., 2004. Breeding for high water-use efficiency. J. Exp. Bot. 55 (407), 2447–2460.
Dixon, J., Braun, H.J., Crouch, J., 2009. Overview: transitioning wheat research to serve the future needs of the developing world. In: Dixon, J., Braun, H.J., Kosina, P., Crouch, J. (Eds.), Wheat Facts and Futures. CIMMYT, Mexico, D.F., p. 2009.
Elliott, J., et al., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. U. S. A. 111 (9), 3239–3244.
Ewert, F., Porter, J.R., Rounsevill, M.D.A., 2007. Crop models, CO2, and climate change. Science 315 (5811), 459.
Foley, J.A., et al., 2011. Solutions for a cultivated planet. Nature 478, 337–342.
French, R.J., Shultz, J.E., 1984. Water use efficiency of wheat in a Mediterranean-type environment. I. the relationship between yield, water use and climate. Aust. J. Agric. Res. 35, 743–764.
Godfray, H.C.J., et al., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818.
Groot, J.R., De Willigen, P., Verberne, E.L.J., 1991. Nitrogen turnover in the soil-crop system. Developments in Plant and Soil Sciences, 44. Kluwer Academic Publisher.
Hatfield, J.L., et al., 2011. Climate impacts on agriculture: implications for crop production. Agron. J. 103 (2), 351–370.
Hollis, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93 (2), 281–289.
Kersebaum, K.C., Nendel, C., 2014. Site-specific impacts of climate change on wheat production across regions of Germany using different CO2 response functions. Eur. J. Agron. 52, 22–32.
Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO2-enrichment. Adv. Agron. 77, 293–368.
Kingston, D.G., Todd, M.C., Taylor, R.G., Thompson, J.R., Arnell, N.W., 2009. Uncertainty in the estimation of potential evapotranspiration under climate change. Geophys. Res. Lett. 36.
Knox, J., Hess, T., Daccache, A., Wheeler, T., 2012. Climate change impacts on crop productivity in Africa and South Asia. Environ. Res. Lett. 7 (3).
Kool, D., et al., 2014. A review of approaches for evapotranspiration partitioning. Agric. Forest Meteorol. 184, 56–70.
Li, T., et al., 2015. Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. Global Change Biol. 21 (3), 1328–1341.
Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J., Orr, D.R., 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO2 concentrations. Science 312 (5782), 1918–1921.
Long, S.P., 2012. Virtual Special Issue on food security – greater than anticipated impacts of near-term global atmospheric change on rice and wheat. Global Change Biol. 18 (5), 1480–1490.
Müller, C., Robertson, R.D., 2014. Projecting future crop productivity for global economic modeling. Agric. Econ. 45 (1), 37–50.
Manderscheid, R., Weigel, H.J., 2007. Drought stress effects on wheat are mitigated by atmospheric CO2 enrichment. Agron. Sustain. Dev. 27 (2), 79–87.
Martre, P., et al., 2015. Multimodel ensembles of wheat growth: many models are better than one. Global Change Biol. 21 (2), 911–925.
McAfee, S.A., 2013. Methodological differences in projected potential evapotranspiration. Clim. Change 120 (4), 915–930.
McKenney, M.S., Rosenberg, N.J., 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. Agric. Forest Meteorol. 64 (1–2), 81–110.
Mearns, L.O., Rosenzweig, C., Goldberg, R., 1997. Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. Clim. Change 35 (4), 367–396.
Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22 (1).
Naveen, N., 1986. Evaluation of Soil Water Status, Plant Growth and Canopy Environment in Relation to Variable Water Supply to Wheat. Indian Agricultural Research Institute, New Delhi, India.
Osborne, T., Rose, G., Wheeler, T., 2013. Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. Agric. Forest Meteorol. 170, 183–194.
Passioura, J.B., Angus, J.F., 2010. Improving productivity of crops in water-limited environments. Adv. Agron. 106, 37–75.
Passioura, J.B., 2006. Increasing crop productivity when water is scarce – from breeding to field management. Agric. Water Manage. 80 (1–3), 176–196.
Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond. Ser. A 193 (1032), 120.
### SUPPLEMENTAL INFORMATION

**Table S1.** Field experiments, crop management and climate characteristics of the four sites where models were calibrated modified after Asseng et al. (2013).

| Location | Wageningen | Balcarce | New Delhi | Wongan Hills |
|----------|------------|----------|-----------|--------------|
| Country  | The Netherlands | Argentina | India | Australia |
| Latitude | 51.97 | -37.5 | 28.38 | -30.89 |
| Longitude | 5.63 | 58.3 | 77.12 | 116.72 |
| Environment | High-yielding long-season | High/medium-yielding medium-season | Irrigated short-season | Low-yielding rain-fed short-season |
| Soil type | Silty clay loam | Clay loam | Sandy loam | Loamy sand |
| Maximum root depth (cm) | 200 | 130 | 160 | 210 |
| Plant available soil water content (mm to maximum rooting depth) | 354 | 205 | 121 | 125 |

**Crop management**

| Cultivar | Arminda | Oasis | HD 2009 |
|----------|---------|-------|---------|
| Sowing date (day of year) | 294 | 223 | 328 | 164 |
| Total applied N fertilizer (kg N ha\(^{-1}\)) | 160 | 120 | 120 | 50 |
| Total irrigation (mm) | 0 | 0 | 383 | 0 |

**Phenology**

| Anthesis (day of year) | 178 | 328 | 49 | 275 |
| Maturity (day of year) | 213 | 363 | 93 | 321 |
| Growing Season Length (days) | 284 | 140 | 130 | 157 |

**Environmental Characteristics**

| Experimental year | 1982/1983 | 1992 | 1984/1985 | 1984 |
| Mean growing season air temperature (°C) | 8.8 | 13.7 | 17.3 | 14.0 |
| Mean growing season rainfall (mm) | 595 | 336 | 0 | 164 |

**30 years average**

| Mean growing season air temperature (°C) | 8.5 | 12.0 | 18.9 | 16.2 |
| Mean growing season rainfall (mm) | 716 | 395 | 84 | 246 |

*aGeographical degrees and minutes – the latter expressed in decimals; the minus sign before latitude and longitude indicates South of equator and West of Greenwich (0) meridian.*
Table S2. Soil depth, hydraulic limits, bulk density, organic carbon, and soil pH provided to the modelling group for each site.

| Location       | Depth (cm) | LL (cm³ cm⁻³) | DUL (cm³ cm⁻³) | SAT (cm³ cm⁻³) | BD (g cm⁻³) | OC (%) | pH |
|----------------|------------|---------------|----------------|----------------|-------------|--------|----|
| the Netherlands| 5          | 0.18          | 0.39           | 0.49           | 1.35        | 2.80   | 6  |
|                | 10         | 0.18          | 0.39           | 0.49           | 1.35        | 2.80   | 6  |
|                | 20         | 0.18          | 0.39           | 0.49           | 1.35        | 2.80   | 6  |
|                | 30         | 0.18          | 0.39           | 0.49           | 1.35        | 2.80   | 6  |
|                | 40         | 0.18          | 0.37           | 0.49           | 1.35        | 1.40   | 6  |
|                | 60         | 0.20          | 0.37           | 0.49           | 1.35        | 1.40   | 6  |
|                | 80         | 0.20          | 0.37           | 0.49           | 1.35        | 1.20   | 6  |
|                | 100        | 0.20          | 0.37           | 0.49           | 1.35        | 1.20   | 6  |
|                | 130        | 0.20          | 0.37           | 0.49           | 1.35        | 1.00   | 6  |
|                | 200        | 0.20          | 0.37           | 0.49           | 1.35        | 1.00   | 6  |
| Argentina      | 5          | 0.16          | 0.38           | 0.47           | 1.05        | 3.15   | 6.2|
|                | 20         | 0.17          | 0.35           | 0.45           | 1.10        | 3.30   | 5.9|
|                | 40         | 0.18          | 0.36           | 0.43           | 1.15        | 1.20   | 6.0|
|                | 60         | 0.18          | 0.38           | 0.48           | 1.30        | 0.70   | 6.4|
|                | 80         | 0.26          | 0.40           | 0.49           | 1.35        | 0.30   | 6.6|
|                | 100        | 0.14          | 0.30           | 0.40           | 1.30        | 0.10   | 6.5|
|                | 120        | 0.14          | 0.30           | 0.40           | 1.30        | 0.10   | 6.5|
|                | 150        | 0.12          | 0.19           | 0.37           | 1.55        | 0.19   | 8.5|
|                | 180        | 0.12          | 0.19           | 0.37           | 1.58        | 0.19   | 8.6|
| India          | 15         | 0.11          | 0.17           | 0.37           | 1.56        | 0.45   | 7.9|
|                | 30         | 0.11          | 0.17           | 0.37           | 1.59        | 0.35   | 8.0|
|                | 60         | 0.11          | 0.18           | 0.37           | 1.50        | 0.31   | 8.0|
|                | 90         | 0.11          | 0.18           | 0.37           | 1.50        | 0.20   | 8.2|
|                | 120        | 0.12          | 0.19           | 0.37           | 1.55        | 0.19   | 8.5|
|                | 150        | 0.12          | 0.19           | 0.37           | 1.54        | 0.19   | 8.6|
|                | 180        | 0.12          | 0.19           | 0.37           | 1.58        | 0.19   | 8.6|
| Australia      | 5          | 0.07          | 0.13           | 0.35           | 1.31        | 1.23   | 4.70|
|                | 10         | 0.07          | 0.13           | 0.35           | 1.31        | 0.43   | 5.10|
|                | 20         | 0.08          | 0.14           | 0.35           | 1.45        | 0.37   | 5.10|
|                | 30         | 0.09          | 0.14           | 0.35           | 1.48        | 0.26   | 6.00|
|                | 40         | 0.09          | 0.15           | 0.35           | 1.51        | 0.24   | 6.00|
|                | 50         | 0.09          | 0.15           | 0.35           | 1.53        | 0.21   | 6.00|
|                | 70         | 0.09          | 0.15           | 0.35           | 1.50        | 0.20   | 6.00|
|                | 90         | 0.10          | 0.16           | 0.35           | 1.50        | 0.19   | 6.00|
|                | 120        | 0.10          | 0.16           | 0.35           | 1.50        | 0.18   | 6.00|
|                | 150        | 0.11          | 0.18           | 0.35           | 1.50        | 0.18   | 6.00|
|                | 180        | 0.12          | 0.18           | 0.35           | 1.50        | 0.18   | 6.00|
|                | 210        | 0.13          | 0.18           | 0.35           | 1.50        | 0.17   | 6.00|
Table S3. Modeling approaches of 26 wheat simulation models used in this study, modified after Asseng et al. (2013).

| Model                  | Leaf area light interception | Light utilization | Yield formation | Phenology | Root distribution over depth | Environmental constraints involved | Type of water stress | Type of heat stress | Water dynamics | Evapotranspiration | Soil C/N: model | Process modified by elevated CO₂ | No. cultivar parameters | Climate input variables | Model relative | Model type |
|------------------------|------------------------------|-------------------|-----------------|------------|-----------------------------|----------------------------------|----------------------|-------------------|----------------|----------------------|----------------|-------------------------------|------------------------|------------------------|----------------|-----------|
| APSIM-Nwheat           | S                            | RUE               | Prt             | T/DL/V     | EXP W/N/A                   | S V C PT                         | CN/P(3)/B           | RUE/TE            | 7               | R/Tx/Tn/Rd/Rh            | C              | P                             |                        |                        |                |           |
| APSIM-wheat            | S                            | RUE               | Prt/Gn/B        | T/DL/V/O   | O W/N/A                     | E - C/R PT/PM                    | CN/P(3)/B           | RUE/TE            | 7               | R/Tx/Tn/Rd/e/W          | C              | P                             |                        |                        |                |           |
| AquaCrop               | S                            | TE                | HI/B            | T/DL/V/O   | EXP W/N/H                   | E/S V/R C FAO PM TM              | none                | TE/RUE            | 2               | R/Tx/ETo               | none           | P                             |                        |                        |                |           |
| CropSyst               | S                            | TE/RUE            | HI/B            | T/DL/V     | EXP W/N/H                   | E R C/R PM PM                   | N/P(4)               | TE/RUE            | 16              | R/Tx/Tn/Rd/Rh/W         | none           | P                             |                        |                        |                |           |
| DSSAT-CROP5IM          | S                            | RUE               | Prt             | T/DL/V     | EXP W/N                     | E/S - C PT CN/P(4)B            | RUE/TE              | 7               | R/Tx/Tn/Rd/Rh/W         | C              | P                             |                        |                        |                |           |
| EPIC wheat             | S                            | RUE               | HI              | T/V        | EXP W/N/H                   | E V C P/PM/P/PM/PM             | N/P(5)/B             | RUE/TE/GY         | 16              | R/Tx/Tn/Rd/Rh/W         | E              | P                             |                        |                        |                |           |
| Expert-N – CERES       | S                            | RUE               | B/Gn            | T/DL/V     | EXP W/N                     | E/S - R PT CN/P(3)/B           | RUE                  | 7               | R/Tx/Tn/Rd/Rh/W         | C              | P                             |                        |                        |                |           |
| Expert-N – GECROS      | D                            | P-R/TE           | Gp/Prt          | T/DL/V     | EXP W/N                     | E/S - R PM CN/P(3)/B           | RUE/TE              | 10              | R/Tx/Tn/Rd/Rh/W         | S              | P                             |                        |                        |                |           |
| Expert-N – SPASS       | D                            | P-R              | Gp/Prt          | T/DL/V     | EXP W/N                     | E/S - R PM CN/P(3)/B           | RUE                  | 5               | R/Tx/Tn/Rd/Rh/W         | C/S             | P                             |                        |                        |                |           |
| Expert-N – SUCROS      | D                            | P-R              | Prt             | T           | EXP W/N                     | E/S - R PM CN/P(3)/B           | RUE                  | 2               | R/Tx/Tn/Rd/Rh/W         | S              | P                             |                        |                        |                |           |
| FASSET                 | D                            | RUE               | HI/B            | T/DL       | EXP W/N                     | E/S - C MAK CN/P(6)/B          | RUE                  | 14              | R/Tx/Tn/Rd               | none           | P                             |                        |                        |                |           |
| GLAM-Wheat             | S                            | RUE/TE           | B/HI            | T/DL/V     | EXP W/H                     | E R C PT none                  | RUE/TE              | 22              | R/Tx/Tn/Td/Ta/e          | none           | G                             |                        |                        |                |           |
| HERMES                 | D                            | P-R              | Prt             | T/DL/V/O   | EXP W/N/A                   | E/S - C PM/PM/PM/PM            | N/P(2)               | RUE/F             | 6               | R/Tx/Tn/Rd/e/Rh/W        | S/C             | P                             |                        |                        |                |           |
| InfoCrop               | D                            | RUE               | Prt/Gn          | T/DL       | EXP W/N/H                   | E V/R C PM/PM/PM/PM            | CN/P(2)/B            | RUE/TE            | 10              | R/Tx/Tn/Rd/Rh/W/E        | S              | P                             |                        |                        |                |           |
| LINTUL-4               | D                            | RUE               | Prt/B           | T/DL       | LIN W/N/A                   | E - C P N/P(0)/L               | RUE/TE              | 4               | R/Tx/Tn/Rd/e/W          | L              | P                             |                        |                        |                |           |
| LINTUL -FAST           | D                            | RUE               | Prt             | T/DL/V     | EXP W                       | E C P CN/P(3)                 | RUE/TE              | 4               | R/Tx/Tn/Rd/RH           | L              | P                             |                        |                        |                |           |
| LPJmL                  | S                            | P-R              | HL_mws/B        | T/V        | EXP W                        | E - C PT none                 | F                     | 3               | R/Ta/Rd/CI             | E              | G                             |                        |                        |                |           |
| MCWLA-Wheat            | S                            | P-R              | HI/B            | T/DL/V     | EXP W/T/H                    | E V/R R PM none               | F                     | 7               | R/Tx/Tn/Rd/e/W          | none           | G                             |                        |                        |                |           |
| Model                  | T | RUE | Prt | T/DL/V/O | EXP | W/N/A/H | E | V | C | PM | CN/P(6)/B | F | 15 | R/Tx/Tn/Rd/RH/W | S/C | P     |
|-----------------------|---|-----|-----|----------|-----|---------|---|---|---|----|-----------|---|----|------------------|-----|-------|
| MONICA                | S | RUE | Prt | T/DL/V/O | EXP | W/N/A/H | E | V | C | PM | CN/P(6)/B | F | 15 | R/Tx/Tn/Rd/RH/W | S/C | P     |
| O’Leary-model         | S | TE  | GnPrt | T/DL/V/O | SIG | W/N/H   | E/S| V | C | P  | N/P(3)/B | TE | 18 | R/Tx/Tn/Rd/RH/W | none | P     |
| Table A2. Continued  |   |     |      |          |     |         |    |    |    |    |           |    |    |                  |     |       |
| SALUS                 | S | RUE | Prt/Hi | T/DL/V | EXP | W/N/H   | E | V | C | PT | CN/P(3)/B | RUE | 18 | R/Tx/Tn/Rd         | C   | P     |
| Sirius                | D | RUE | B/Prt | T/DL/V | EXP | W/N     | E | - | C | P/PT| N/P(2)    | RUE | 14 | R/Tx/Tn/Rd/e/W     | P   |       |
| SiriusQuality         | D | RUE | B/Prt | T/DL/V | EXP | W/N     | S | - | C | P/PT| N/P(2)    | RUE | 14 | R/Tx/Tn/Rd/e/W     | I   | P     |
| STICS                 | D | RUE | Gn/B  | T/DL/V/O | SIG | W/N/H   | E/S| V/R| C | P/PT/SW| N/P(3)/B  | RUE/TE | 15 | R/Tx/Tn/Rd/e/W     | C   | P     |
| WOFOST                | D | P-R | Prt/B | T/DL | LIN  | W/N'    | E/S| - | C | P   | P(1)      | RUE/TE | 3  | R/Tx/Tn/Rd/e/W     | S   | G     |

* S, simple approach (e.g. LAI); D, detailed approach (e.g. canopy layers).
* RUE, radiation use efficiency approach; P-R, gross photosynthesis – respiration; TE, transpiration efficiency biomass growth.
* HI, fixed harvest index; B, total (above-ground) biomass; Gn, number of grains; Prt, partitioning during reproductive stages; HI_mw, harvest index modified by water stress.
* T, temperature; DL, photoperiod (day length); V, vernalization; O, other water/nutrient stress effects considered.
* LIN, linear, EXP, exponential, SIG, sigmoidal, Call, carbon allocation; O, other approaches.
* W, water limitation; N, nitrogen limitation; A, aeration deficit stress; H, heat stress.
* E, actual to potential evapotranspiration ratio; S, soil available water in root zone.
* V, vegetative organ (source); R, reproductive organ (sink).
* C, capacity approach; R, Richards approach.
* P, Penman; PM, Penman-Monteith; PT, Priestley –Taylor; TW, Turc-Wendling; MAK, Makkink; HAR, Hargreaves; SW, Shuttleworth and Wallace (resistive model), ("bold" indicates approached used during the study).
* CN, CN model; N, N model; P(x), x number of organic matter pools; B, microbial biomass pool.
* RUE, radiation use efficiency; TE, transpiration efficiency; GY, grain yield; CLN, critical leaf N concentration; F, Farquhar model.
* Cl, cloudiness; R, rainfall; Tx, maximum daily temperature; Tn, minimum daily temperature; Ta, average daily temperature; Td, dew point temperature; Rd, radiation; e, vapor pressure; RH, relative humidity; W, wind speed.
* C, CERES; L, LINTUL; E, EPIC; S, SUCROS; I, Sirius.
* P, point model; G, global or regional model (regarding the main purpose of model).
* nitrogen-limited yields can be calculated for given soil nitrogen supply and N fertilizer applied, but model has no N simulation routines.