Paper:
Asseng, S, Ewert, F, Rosenzweig, C, Jones, JW, Hatfield, JL, Ruane, AC, Boote, KJ, Thorburn, PJ, Rötter, RP, Cammarano, D, Brisson, N, Basso, B, Martre, P, Aggarwal, PK, Angulo, C, Bertuzzi, P, Biernath, C, Challinor, AJ, Doltra, J, Gayler, S, Goldberg, R, Grant, R, Heng, L, Hooker, J, Hunt, LA, Ingwersen, J, Izaurralde, RC, Kersebaum, KC, Müller, C, Naresh Kumar, S, Nendel, C, O'Leary, G, Olesen, JE, Osborne, TM, Palosuo, T, Priesack, E, Ripoche, D, Semenov, MA, Shcherbak, I, Steduto, P, Stöckle, C, Stratonovitch, P, Streck, T, Supit, I, Tao, F, Travasso, M, Waha, K, Wallach, D, White, JW, Williams, JR and Wolf, J (2013) *Uncertainty in simulating wheat yields under climate change.* Nature Climate Change, 3 (9). 827 - 832.

http://dx.doi.org/10.1038/nclimate1916

2013-4-24

Quantifying uncertainties in simulating wheat yields under climate change

S. Asseng[1], F. Ewert[2], C. Rosenzweig[3], J.W. Jones[1], J.L. Hatfield[4], A. Ruane[3], K.J. Boote[5], P. Thorburn[6], R.P. Rötter[7], D. Cammarano[1], N. Brisson[8,9,#], B. Basso[10], P. Martre[11,12], P.K. Aggarwal[13], C. Angulo[2], P. Bertuzzi[14], C. Biernath[15], A.J. Challinor[16,40], J. Doltra[17], S. Gayler[18], R. Goldberg[3], R. Grant[19], L. Heng[20], J. Hooker[21], L.A. Hunt[22], J. Ingwersen[23], R.C. Izaurralde[24], K.C. Kersebaum[25], C. Müller[26], S. Naresh Kumar[27], C. Nendel[25], G. O'Leary[28], J.E. Olesen[29], T. M. Osborne[30], T. Palosuo[7], E. Priesack[15], D. Ripoche[14], M.A. Semenov[31], I. Shcherbak[10], P. Steduto[32], C. Stöckle[33], P. Stratonovitch[31], T. Streck[23], I. Supit[34], F. Tao[35], M. Travasso[36], K. Waha[26], D. Wallach[37], J.W. White[38], J.R. Williams[39] and J. Wolf[34]

[1]Agricultural & Biological Engineering Department, University of Florida, Gainesville, FL 32611, USA, email: sasseng@ufl.edu & jimj@ufl.edu & davide.cammarano@ufl.edu,
[2] Institute of Crop Science and Resource Conservation INRES, University of Bonn, 53115, Germany, email: fewert@uni-bonn.de & klav@uni-bonn.de,
[3]NASA Goddard Institute for Space Studies, New York, NY 10025, email: cynthia.rosenzweig@nasa.gov, alexander.c.ruane@nasa.gov, ccrag1@yahoo.com
[4]National Laboratory for Agriculture and Environment, Ames, IA 50011, email: jerry.hatfield@ars.usda.gov,
[5]Department of Agronomy, University of Florida, Gainesville, FL 32611-0500, USA, email: kjboote@ufl.edu,
[6]CSIRO Ecosystem Sciences, Dutton Park QLD 4102, Australia, email: peter.thorburn@csiro.au,
[7]Plant Production Research, MTT Agrifood Research Finland, FI-50100 Mikkeli, Finland, email: reimund.rotter@mtt.fi & taru.palosuo@mtt.fi,
[8]INRA, UMR0211 Agronomie, F- 78 750 Thiverval-Grignon, France,
[9]AgroParisTech, UMR0211 Agronomie, F- 78 750 Thiverval-Grignon, France,
[10]Department of Geological Sciences and W.K. Kellogg Biological Station, Michigan State University East Lansing, Michigan 48823, USA, email: basso@msu.edu, shcherba@mail.msu.edu
[11]INRA, UMR1095 Genetic, Diversity and Ecophysiology of Cererals (GDEC), F-63 100 Clermont-Ferrand, France, email: pierre.marte@clermont.inra.fr,
[12]Blaise Pascal University, UMR1095 GDEC, F-63 170 Aubière, France,
[13]CCAFS, IWMI, NASC Complex, DPS Marg, New Delhi 12, India, email: pkaggarwal.iari@gmail.com,
[14]INRA, US1116 AgroClim, F- 84 914 Avignon, France, email: dominique.ripoche@avignon.inra.fr & patrick.bertuzzi@avignon.inra.fr,
[15]Institute of Soil Ecology, Helmholtz Zentrum München - German Research Center for Environmental Health, Neuherberg, D-85764, Germany, email: priesack@helmholtz-muenchen.de & christian.biernath@helmholtz-muenchen.de,
[16]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds LS29JT, UK, CGIAR-ESSP Program on Climate Change, Agriculture and Food Security, International Centre for Tropical Agriculture (CIAT), A.A. 6713, Cali, Colombia, email: a.j.challinor@leeds.ac.uk,
[17]Agricultural Research and Training Centre (CIFA), Cantabria Government, 39600 Muriedas, Spain, email: jordidoltra@cifacantabria.org,

[18]WESS-Water & Earth System Science Competence Cluster, University of Tübingen, 727074 Tübingen, Germany, email: Sebastian.gayler@uni-tuebingen.de,
[19]Department of Renewable Resources, University of Alberta, Edmonton, AB, Canada T6G 2E3, email: Robert.Grant@ales.ualberta.ca,
[20]IAEA, Vienna, Austria, email: L.Heng@iaea.org,
[21]Agriculture Department, University of Reading, Reading, RG66AR, UK, email: j.hooker@reading.ac.uk,
[22]Department of Plant Agriculture, University of Guelph, Guelph, Ontario, Canada, N1G 2W1, email: thunt@uoguelph.ca,
[23]Institute of Soil Science and Land Evaluation, Universität Hohenheim, 70599 Stuttgart, email: joachim.ingwersen@uni-hohenheim.de & tstreck@uni-hohenheim.de,
[24]Joint Global Change Research Institute, College Park, MD 20740, USA, email: cesar.izaurralde@pnnl.gov,
[25]Institute of Landscape Systems Analysis, Leibniz Centre for Agricultural Landscape Research, 15374 Müncheberg, Germany, email:ckersebaum@zalf.de & nendel@zalf.de,
[26]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany, email: christoph.mueller@pik-potsdam.de & katharina.waha@pik-postdam.de,
[27]Division of Environmental Sciences, Indian Agricultural Research Institute, IARI PUSA, New Delhi 110 012, India, email: nareshkumar.soora@gmail.com,
[28]Landscape & Water Sciences, Department of Primary Industries, Horsham 3400, Australia, email: garry.O'leary@dpi.vic.gov.au,
[29]Department of Agroecology, Aarhus University, 8830, Tjele, Denmark, email: jorgene.olesen@agrsci.dk,
[30]NCAS-Climate, Walker Institute, University of Reading, RG6 6BB, UK, email: t.m.osborne@reading.ac.uk,
[31]Computational and Systems Biology Department, Rothamsted Research, Harpenden, Herts, AL5 2JQ, UK, email: mikhail.semenov@bbsrcrothamsted.ac.uk & pierre.stratonovitch@rothamsted.ac.uk
[32]FAO, Rome, Italy, email: Pasquale.Steduto@fao.org,
[33]Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, email: stockle@wsu.edu,
[34]Plant Production Systems & Earth System Science-Climate Change, Wageningen University, 6700AA Wageningen, The Netherlands, email: joost.wolf@wur.nl & iwan.supit@wur.nl,
[35]Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Science, Beijing 100101, China, email: taofl@igsnrr.ac.cn,
[36]Institute for Climate and Water, INTA-CIRN, 1712 Castelar, Argentina, email: mtravasso@cnia.inta.gov.ar,
[37]INRA, UMR 1248 Agrosystèmes et développement territorial (AGIR), 31326 Castanet-Tolosan Cedex, France, email: daniel.wallach@toulouse.inra.fr,
[38]Arid-Land Agricultural Research Center, Maricopa, AZ 85138, USA, email: jeffrey.white@ars.usda.gov,
[39]Texas A&M University, USA, jwilliams@brc.tamus.edu.
[40] CGIAR-ESSP Program on Climate Change, Agriculture and Food Security, International Centre for Tropical Agriculture (CIAT), A.A. 6713, Cali, Colombia.
[#] Dr. Nadine Brisson passed away in 2011 while this work was being carried out.

Projections of climate change impacts on crop yields are inherently uncertain[1]. Uncertainty is often quantified when projecting future greenhouse gas emissions and their influence on climate[2]. However, multi-model uncertainty analysis of crop responses to climate change is rare since systematic and objective comparisons among process-based crop simulation models[1, 3] are difficult[4]. Here we present the largest standardized model intercomparison for climate change impacts to date. We found that individual crop models are able to simulate measured wheat grain yields accurately under a range of environments, particularly if the input information is sufficient. However, simulated climate change impacts vary across models due to differences in model structures and parameter values.

A greater proportion of the uncertainty in climate change impact projections was due to variations among crop models than to variations among downscaled general circulation models (GCMs). Uncertainties in simulated impacts increased with CO_2 concentrations and associated warming. These impact uncertainties can be reduced by improving temperature and CO_2 relationships in models and better quantified through use of multi-model ensembles. Less uncertainty in describing how climate change may affect agricultural productivity will aid adaptation strategy development and policymaking.

Uncertainties in projections of climate change impacts on future crop yields derive from different sources in modeling. The trajectories of future greenhouse gas emissions cannot be projected easily as they are strongly influenced by political and socio-economic development. A range of plausible projections (scenarios) of emissions are used instead[2]. Projecting the effects of emissions on climate and the downscaling of climate data itself, are both inherently uncertain, since different general circulation model ensembles[5] and downscaling methods[6] give different results. Finally, uncertainty in simulating the response of crops to altered climate can be attributed to differences in the structures of crop models and how model parameters are set. Process-based crop models account for many of the interactions among climate, crop, soil and management effects and are the most common tools for assessing climate change impacts on crop productivity. Many crop model impact assessments have been carried out for specific locations[7], agricultural regions[8], and the globe[9]. Statistical methods have also been used to analyze trends in yields driven by climate[10], but interactions between climate and non-climate factors confound results[11]. This hinders the attribution of causality[12] and development of appropriate adaptation strategies.

Uncertainty, any departure from the unachievable ideal of completely deterministic knowledge of a system[13], has been addressed by the climate science community through probabilistic projections based on multiple GCMs or regional climate model ensembles[14]. However, most climate change agricultural impact assessments have used a single crop model[3], limiting the quantification of uncertainty[15]. Since crop models differ in the way they simulate dynamic processes, set parameters, and use input variables[3], large differences in simulation results have been reported[16]. While uncertainty of crop model projections is sometimes assessed by using more than one crop model[16] or by perturbing crop model parameters[17], coordinating comprehensive assessments has proven difficult[4].

To estimate the uncertainty associated with studies of climate impacts on crop yields, we used 27 different wheat crop models (Supplementary Tables S1 and S2) at four sites representing very different production environments (Fig. 1a). Simulated grain yields varied widely, although median values were close to observed grain yields across single-year-experiments for four representative environments (Supplementary Table S3) in The Netherlands, Argentina, India and Australia (Fig.1a, b). This phenomenon was previously reported in another multi-model comparison with fewer models[16], and is comparable to the improved seasonal climate simulations produced with multiple GCMs[18]. The range of simulated yields was reduced significantly after full calibration, such that >50% of yields from calibrated models were within the mean coefficient of variation (CV%) (+/- 13.5%) of >300 wheat field experiments[19] (Fig. 1c). Similar patterns were found for other simulated aspects of wheat growth (Fig. 1d). Hence, crop models are able to simulate measured grain yield and other crop components accurately under diverse environments if input information is sufficient.

To illustrate the possible changes in uncertainty of simulated impacts, we analyzed the sensitivity of models to a combination of changes in precipitation and increases in both temperature and atmospheric CO_2 concentration (734 ppm, compared to baseline at 360 ppm) based on a location-specific scenario that best approximated the ensemble of high-emission late-century climate projections (see Supplementary Table S3). Simulated climate change yield responses of all partially calibrated crop models had CV values between 20% and 30% (Fig. 2a); these were reduced by 2% to 7% when models were fully calibrated. However, the CV of simulated impacts using the 50% best-performing calibrated models (based on RMSE across all locations) was about 2% higher than using all models, and this only decreased when the 50% of models closest to observed yields at each location were used (Fig. 2a). Uncertainty in simulated climate change impacts differed across the environments (Fig. 2a). In addition, uncertainty in simulated impacts varied with soil (Fig. 2b) and crop management (Fig. 2c and d). Hence, the overall growing environment, in particular the soil and crop management, affects the range of simulated grain yields across models, thus adding to uncertainty in responses coming from individual models. Therefore, selecting a subset of models that perform best in current environments does not reduce uncertainty in simulated climate change impacts.

Changes in atmospheric CO_2, temperature and precipitation are key drivers of the responses of crops to climate change[20]. Simulated impacts of elevated CO_2 on yields varied relatively little across models (50% of model results were within +/- 20% of the median response) (Fig. 3a-d and Supplementary Fig. S5), but the variation across 80% of the crop models increased under elevated CO_2 concentration mostly in the low-yielding environment of Australia (see box-plot whiskers in Fig. 3d). However, the uncertainty in simulated yields did not increase with increasing CO_2 in the other environments. This is not surprising as elevated CO_2 affects fewer processes than increased temperature and because several of the wheat models have used observations from free-air CO_2 enrichment (FACE) experiments to improve model processes related to high CO_2[21, 22]. But none of the models have been tested with elevated CO_2 in combination with high temperature. The majority of simulated yield responses to an 180 ppm CO_2 increase at current temperatures (Fig. 3a-d) were within the range of measured responses, ranging from 8% to 26% with elevated atmospheric CO_2 concentrations (Fig. 3e) across experiments conducted in the USA, Germany and China[23, 24] (see also Supplementary Information, page 11 last paragraph).

In contrast to the mean response of yields to CO_2, uncertainty in simulated yield showed a strong dependency on temperature, particularly when the temperature increase exceeded 3^{o}C with associated changes in atmospheric CO_2. The median model response to a 3^{o}C increase in temperature (Fig. 3a-d and Supplementary Fig. S5) is consistent with general field observations (Fig. 3e); observed wheat grain yields declined by 3% to 10% per ^{o}C increase in mean temperature[24,10] (see also Supplementary Information, page 11 last paragraph). The increased range of impacts at high temperatures (50% of models were between 20% and 40% of the median response on either side) indicated an increased model uncertainty with increasing temperature, partly related to simulated phenology (Supplementary Fig. S3), e.g. phenology is often enhanced with increasing temperature resulting in less time for light interception and photosynthesis and consequently less biomass and yield, an increased frequency of high temperature events and its simulated impact on crop growth (Supplementary Fig. S4)[25], and high temperature interactions with elevated CO_2 (Fig. 3). However, accounting for a process such as high temperature stress impact in a model does not necessarily result in correctly simulating that effect (Supplementary Fig. S4), as the modelled process itself, e.g. leaf area or biomass growth interacts with other model processes in determining the final yield response of a model. Precipitation affected simulated yields, but precipitation change had little impact on the range of simulated responses (Supplementary Fig. S2).

If averaging multi-model simulations is superior to a single crop[4] or climate[26] model simulation because the ratio of signal (mean change) to noise (variation) increases with the number of models and errors tend to cancel each other out, we should be able, with caution[27], to estimate how many models would be required for robust projections. We assessed this by randomly choosing 260 subsets of the crop models, and computing the mean and spread of simulated results (Supplementary Fig. S1). As the variation in yields was about 13.5% around the mean in field experiments[19], we considered projections to be robust if the range of projections was within 13.5% of the mean. The number of models required for robust assessments of climate change varied depending on the magnitude of temperature change and interactions with the change in atmospheric CO_2 (Fig. 4a). For example, at least five models are needed for robust assessments of yield impacts for increases of up to 3°C and 540 ppm of CO_2. Fewer models are needed for smaller changes and more models for greater changes in temperature (Fig. 4a).

When simulating impacts assuming a mid-century A2 emissions scenario (556 ppm of CO_2) for climate projections from 16 downscaled GCMs using 26 wheat models, a greater proportion of the uncertainty in yields was due to variations among crop models than to variations among the downscaled GCMs (Fig. 4b). In contrast, GCM uncertainty tends to dominate in perturbed single crop model parameter studies[28]. The variation of simulated yields for the scenario ensemble was greater for low-yielding environments, while absolute values were similar to observations across yield levels and within the range of field experimental variation[19]. Smaller projected climate changes, e.g. for low emissions or early-century timeframes, result in less variation in simulated impacts, larger climate changes result in more variation (Figure 3).

We conclude that projections from individual crop models fail to represent the significant uncertainties known to exist in crop responses to climate change. On the other hand, model ensembles have the potential to quantify the significant, and hitherto uncharacterized, crop component of uncertainty. Crop models need to be improved to more accurately reflect how heat stress and high temperature-by-CO_2 interactions affect plant growth and yield formation.

Methods

Twenty-seven wheat crop simulation models (Supplementary Table S1 and S2) were tested within the Agricultural Model Intercomparison and Improvement Project[29] (AgMIP; www.agmip.org), with data from quality-assessed field experiments (sentinel site data) from four contrasting environments using standardized protocols, including partial and full model calibration experiments, to assess the role of crop model-based uncertainties in projections of climate change impacts (Fig. 1a; Supplementary Information). Model simulations were executed by individual modeling groups.

Figure captions

Figure 1 | Wheat model-observation comparisons. (**a**) Global map of wheat production[30] showing experimental sites (stars) representative of CIMMYT mega-environments (ME, broadly indicated by circles, http://wheatatlas.cimmyt.org). (**b**) Observed (x) and simulated (box plots) grain yields from single-year-experiments for The Netherlands (NL), Argentina (AR), India (IN) and Australia (AU). Simulated yields are from 27 different wheat crop models. Partially calibrated simulated yields (larger boxes) - researchers had no access to observed grain yields and growth dynamics (blind test). Calibrated simulated yields (smaller boxes) - researchers had access to observed grain yields and growth dynamics. In each box plot, vertical lines represent, from left to right, the 10^{th} percentile, 25^{th} percentile, median, 75^{th} percentile and 90^{th} percentile of simulations. Standard deviation for observed yields (based on measurements of four replicates) is shown as an error bar if known. (**c**) Number of models within mean field experimental variation (13.5%)[19] for partially calibrated (open bars) and fully calibrated models (grey bars) for single locations (NL, AR, IN and AU for each country) and combinations of locations. (**d**) Relative root mean square errors (RMSE) of simulation-observation comparisons for partially calibrated (open bar) and fully calibrated models (grey bars) of grain yield components across all four locations. LAI, leaf area index; ET, evapotranspiration.

Figure 2 | Variability in impact model uncertainty. (**a**) Coefficient of variation (CV%) for simulated yield response to a location-specific scenario representing GCM projections for the high-emission (A2) scenario for the late century (in relation to baseline 1981-2010, see Supplementary Table S3) with 27 crop models. Models were partially calibrated (black) or fully calibrated (green). Alternatively, 50% of models with the closest simulations to the observed yields across all locations were used (blue) or 50% of models with the closest simulations to the observed yields per location (red). CV% of simulated yield response with 27 fully calibrated crop models to the climate change scenario with (**b**) increased (solid red) and reduced (dashed red) soil water holding capacity, (**c**) early (solid red) and delayed (dashed red) sowing dates and (**d**) increased (solid red) and reduced (dashed red) N fertilizer applications (only 20 models included N dynamics); fully calibrated 20 models which included N dynamics (dashed green). The fully calibrated simulation (green) from (**a**) is reproduced in (**b**), (**c**) and (**d**) for comparison. The Netherlands (NL), Argentina (AR), India (IN) and Australia (AU).

Figure 3 | Sensitivity of simulated and observed wheat to temperature and CO_2 change. Simulated relative mean (30-year average, 1981-2010) grain yield change for increased temperatures and elevated atmospheric CO_2 concentrations for (**a**) The Netherlands (NL), (**b**) Argentina (AR), (**c**) India (IN) and (**d**) Australia (AU). For each box plot, vertical lines represent, from left to right, the 10^{th} percentile, 25^{th} percentile, median, 75^{th} percentile and 90^{th} percentile of simulations based on multi-models. (**e**) Observed range of yield impacts with elevated CO_2[23, 24]. Observed range of yield impacts with increased temperature[24,10] .(extrapolated, based on separate experiments with 40-345 ppm elevated CO_2 and 1.4-4.0 ºC temperature increase, see Supplementary Information)

Figure 4 | Size of model ensembles and impact model uncertainty. (**a**) Average number of crop models across locations required to reduce the simulated yield impact variation to within the mean field experimental coefficient of variation (CV%) of 13.5%[19]. Different colours indicate elevated atmospheric CO_2 concentrations (black = 360 ppm, red = 450 ppm, blue = 540 ppm, green = 630 ppm, dark yellow = 720 ppm) in combinations with temperature changes. Error bars show s.d. (**b**) Coefficient of variation due to crop model uncertainty (using 10^{th} percentile to 90^{th} percentile of simulations based on crop multi-models) in simulated 30-year average climate change yield impact (black) and due to variation in 16 downscaled GCM (red, see Supplementary Tables S6 and S7) mid-century A2 emission scenarios (2040-2069). Numbers indicate current yields at each location (Supplementary Table S3).

References

1. Godfray, H.C.J. et al. Food Security: The Challenge of Feeding 9 Billion People. *Science* **327**, 812-818 (2010).
2. Moss, R.H. et al. The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747-756 (2010).
3. White, J.W., Hoogenboom, G., Kimball, B.A. & Wall, G.W. Methodologies for simulating impacts of climate change on crop production. *Field Crops Research* **124**, 357-368 (2011).
4. Rötter, R.P., Carter, T.R., Olesen, J.E. & Porter, J.R. Crop-climate models need an overhaul. *Nature Climate Change* **1**, 175-177 (2011).
5. Meehl, G.A. et al. The WCRP CMIP3 multimodel dataset - A new era in climate change research. *Bulletin of the American Meteorological Society* **88**, 1383-1394 (2007).
6. Wilby, R.L. et al. A review of climate risk information for adaptation and development planning. *International Journal of Climatology* **29**, 1193-1215 (2009).
7. Semenov, M.A., Wolf, J., Evans, L.G., Eckersten, H. & Iglesias, A. Comparison of wheat simulation models under climate change .2. Application of climate change scenarios. *Climate Research* **7**, 271-281 (1996).
8. Tao, F., Zhang, Z., Liu, J. & Yokozawa, M. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology* **149**, 1266-1278 (2009).
9. Rosenzweig, C. & Parry, M.L. Potential impact of climate change on world food supply. *Nature* **367**, 133-138 (1994).
10. Lobell, D.B., Schlenker, W. & Costa-Roberts, J. Climate Trends and Global Crop Production Since 1980. *Science* **333**, 616-620 (2011).
11. Lobell, D.B. & Burke, M.B. On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology* **150**, 1443-1452 (2010).
12. Gifford, R. et al. Climate change and Australian wheat yield. *Nature* **391**, 448-449 (1998).
13. Harris, G.R., Collins, M., Sexton, D.M.H., Murphy, J.M. & Booth, B.B.B. Probabilistic projections for 21st century European climate. *Natural Hazards and Earth System Sciences* **10**, 2009-2020 (2010).
14. Semenov, M.A. & Stratonovitch, P. Use of multi-model ensembles from global climate models for assessment of climate change impacts. *Climate Research* **41**, 1-14 (2010).
15. Müller, C. Agriculture: Harvesting from uncertainties. *Nature Climate Change* **1**, 253-254 (2011).
16. Palosuo, T. et al. Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. *European Journal of Agronomy* **35**, 103-114 (2011).
17. Challinor, A.J., Simelton, E.S., Fraser, E.D.G., Hemming, D. & Collins, M. Increased crop failure due to climate change: assessing adaptation options using

models and socio-economic data for wheat in China. *Environmental Research Letters* **5** (2010).
18. Hagedorn, R., Doblas-Reyes, F.J. & Palmer, T.N. The rationale behind the success of multi-model ensembles in seasonal forecasting - I. Basic concept. *Tellus Series a-Dynamic Meteorology and Oceanography* **57**, 219-233 (2005).
19. Taylor, S.L., Payton, M.E. & Raun, W.R. Relationship between mean yield, coefficient of variation, mean square error, and plot size in wheat field experiments. *Communications in Soil Science and Plant Analysis* **30**, 1439-1447 (1999).
20. Hatfield, J.L. et al. Climate Impacts on Agriculture: Implications for Crop Production. *Agronomy Journal* **103**, 351-370 (2011).
21. Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J. & Ort, D.R. Food for thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science* **312**, 1918-1921 (2006).
22. Ewert, F., Porter, J.R. & Rounsevell, M.D.A. Crop models, CO2, and climate change. *Science* **315**, 459-459 (2007).
23. Kimball, B.A. in Handbook of climate change and agroecosystems - Impacts, adaptation, and mitigation (eds. Hillel, D. & Rosenzweig, C.) 87 -107 (Imperial College Press, Covent Garden, London, 2011).
24. Amthor, J.S. Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. *Field Crops Research* **73**, 1-34 (2001).
25. Asseng, S., Foster, I. & Turner, N.C. The impact of temperature variability on wheat yields. *Global Change Biology* **17**, 997-1012 (2011).
26. Tebaldi, C. & Knutti, R. The use of the multi-model ensemble in probabilistic climate projections. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences* **365**, 2053-2075 (2007).
27. Knutti, R. The end of model democracy? *Climatic Change* **102**, 395-404 (2010).
28. Challinor, A.J., Wheeler, T., Hemming, D. & Upadhyaya, H.D. Ensemble yield simulations: crop and climate uncertainties, sensitivity to temperature and genotypic adaptation to climate change. *Climate Research* **38**, 117-127 (2009).
29. Rosenzweig, C. et al. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural Forestry and Meteorology* (2012).
30. Monfreda, C., Ramankutty, N. & Foley, J.A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles* **22** (2008).

Corresponding author

Senthold Asseng, University of Florida, Email: sasseng@ufl.edu

Author contribution

S.A., F.E., C.R., J.W.J., J.L.H. motivated the study, S.A., F.E. coordinated the study, S.A., F.E. D.W., P.M., D.C., A.R. analysed data, D.C., A.R., P.T., R.P.R., N.B., B.B., D.R., P.B., P.S., L.H., M.A.S., P.S., C.S., G.O.L., P.K.A., S.N.K., R.C.I., J.W.W.,

L.A.H., R.G., K.C.K., T.P., J.H., T.O., J.W., I.S., J.E.O., J.D., C.N., S.G., J.I., E.P., T.S., F.T., C.M., K.W., R.G., C.A., I.S., C.B., J.R.W., A.J.C. carried out crop model simulations and discussed the results, M.T., S.N.K., provided experimental data, S.A., F.E., C.R., J.W.J. wrote the paper.