Chapter 8

The AgMIP Coordinated Climate-Crop Modeling Project (C3MP): Methods and Protocols

Sonali P. McDermid[1,2], Alexander C. Ruane[2], Cynthia Rosenzweig[2], Nicholas I. Hudson[3], Monica D. Morales[3], Prabodha Agalawatte[55], Shakeel Ahmad[60], L. R. Ahuja[4], Istiqlal Amien[54], Saseendran S. Anapalli[4], Jakarat Anothai[5], Senthold Asseng[6], Jody Biggs[63], Federico Bert[8], Patrick Bertuzzi[9], Virender S. Bhatia[10], Marco Bindi[11], Ian Broad[12], Davide Cammarano[13], Ramiro Carretero[8], Ashfaq Ahmad Chattha[50], Uran Chung[14], Stephanie Debats[56], Paola Deligios[64], Giacomo De Sanctis[15], Thanda Dhliwayo[14], Benjamin Dumont[7], Lyndon Estes[56], Frank Ewert[16], Roberto Ferrise[11], Thomas Gaiser[16], Guillermo Garcia[8], Sika Gbegbelegbe[17], Vellingiri Geethalakshmi[18], Edward Gerardeaux[19], Richard Goldberg[3], Brian Grant[20], Edgardo Guevara[21], Jonathan Hickman[22], Holger Hoffmann[18], Huanping Huang[23], Jamshad Hussain[50], Flavio Barbosa Justino[24], Asha S. Karunaratne[25], Ann-Kristin Koehler[26], Patrice K. Kouakou[61], Soora Naresh Kumar[27], Arunachalam Lakshmanan[18], Mark Lieffering[57], Xiaomao Lin[28], Qunying Luo[29], Graciela Magrin[21], Marco Mancini[11], Fabio Ricardo Marin[52], Anna Dalla Marta[11], Yuji Masutomi[30], Theodoros Mavromatis[31], Greg McLean[32], Santiago Meira[21], Monoranjan Mohanty[33], Marco Moriondo[11], Wajid Nasim[60], Lamyaa Negm[34], Francesca Orlando[11], Simone Orlandini[11], Isik Ozturk[35], Helena Maria Soares Pinto[52], Guillermo Podesta[53], Zhiming Qi[36], Johanna Ramarohetra[37], Muhammad Habib ur Rahman[50], Helene Raynal[38], Gabriel Rodriguez[21], Reimund Rötter[58], Vaishali Sharda[6], Lu Shuo[39], Ward Smith[20], Val Snow[59], Afshin Soltani[40], K. Srinivas[41], Benjamin Sultan[66], Dillip Kumar Swain[42], Fulu Tao[43], Kindie Tesfaye[44], Maria I. Travasso[21], Giacomo Trombi[11], Alex Topaj[65], Eline Vanuytrecht[51], Federico E. Viscarra[45], Syed Aftab Wajid[50], Enli Wang[46], Hong Wang[47], Jing Wang[39], Erandika Wijekoon[55], Lee Byun-Woo[48], Yang Xiaoguang[39], Ban Ho Young[48], Jin I. Yun[49], Zhigan Zhao[39], and Lareef Zubair[55]

[1]*New York University, New York, NY, USA*

[2]*NASA Goddard Institute for Space Studies, New York, NY, USA*

[3]*Columbia University Center for Climate Systems Research, New York, New York*

[4]*United States Department of Agriculture, Agricultural Research Service, Ames, IA, USA*
[5]*Prince of Songkla University, Hat Yai, Thailand*
[6]*University of Florida, Gainesville, FL, USA*
[7]*Université de Liège, Liège, Belgium*
[8]*Universidad de Buenos Aires, Buenos Aires, Argentina*
[9]*INRA, Avignon, France*
[10]*National Research Centre for Soybean, Indore, India*
[11]*University of Florence, Florence, Italy*
[12]*University of Queensland, QLD, Australia*
[13]*James Hutton Institute, Dundee, UK*
[14]*International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico*
[15]*European Commission, Joint Research Center, Ispra, Italy*
[16]*University of Bonn, Bonn, Germany*
[17]*International Maize and Wheat Improvement Center (CIMMYT), Nairobi, Kenya*
[18]*Tamil Nadu Agricultural University, Coimbatore, India*
[19]*CIRAD, Paris, France*
[20]*Agriculture and Agri-Food, Ontario, Canada*
[21]*National Agricultural Technology Institute (INTA), Pergamino, Argentina*
[22]*Agriculture and Food Security Center, Columbia University, New York, NY, USA*
[23]*Chinese Academy of Agricultural Sciences, Beijing, China*
[24]*Universidade Federal de Viçosa, Viçosa, Brazil*
[25]*Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka*
[26]*Univesity of Leeds, Leeds, UK*
[27]*IARI, New Delhi, India*
[28]*Kansas State University, Manhattan, Kansas, USA*
[29]*University of Technology, Sydney, Australia*
[30]*College of Agriculture, Ibaraki University, Japan*
[31]*Aristotle University of Thessaloniki, Thessaloniki, Greece*
[32]*Queensland Dept of Agriculture, Fisheries and Forestry, QLD, Australia*
[33]*Indian Institute of Soil Science, Bhopal, India*
[34]*NC State University, Raleigh, NC, USA*

[35] *Aarhus University, Tjele, Denmark*

[36] *McGill University, Sainte-Anne-de-Bellevue, QC, Canada*

[37] *L'Institut de recherche pour le développement (IRD), Paris, France*

[38] *National Institute of Agronomic Research (INRA), Toulouse, France*

[39] *College of Agronomy and Biotechnology, China Agricultural University, Beijing, China*

[40] *Gorgan University of Agricultural Sciences & Natural Resources, Gorgan, Iran*

[41] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India*

[42] *Indian Institute of Technology Kharagpur, Kharagpur, India*

[43] *Chinese Academy of Sciences, Institute of Geographical Sciences and Natural Resources Research, Beijing, China*

[44] *International Maize and Wheat Improvement Center (CIMMYT), Addis Ababa, Ethiopia*

[45] *Fundacion Amigos de la Naturaleza (FAN), Santa Cruz, Bolivia*

[46] *Commonwealth Scientific and Industrial Research Organisation Land and Water, Canberra, Australia*

[47] *SPARC/AAFC, Swift Current, Canada*

[48] *Seoul National University, Seoul, Republic of Korea*

[49] *Kyung Hee University, Yongin, Republic of Korea*

[50] *University of Agriculture, Faisalabad, Pakistan*

[51] *KU Leuven, Leuven, Belgium*

[52] *University of São Paulo, ESALQ, Piracicaba, SP, Brazil*

[53] *University of Miami, Miami, Florida, USA*

[54] *Agro-climatology and Hydrology Research Institute, Bogor, Indonesia*

[55] *Foundation for Environment Climate and Technology, Kandy, Sri Lanka*

[56] *Princeton University, Princeton, NJ, USA*

[57] *AgResearch New Zealand, Palmerston North, New Zealand*

[58] *MTT Agrifood Research Finland, Mikkeli, Finland*

[59] *AgResearch Limited, Christchurch, New Zealand*

[60] *COMSATS-Institute of Information Technology (CIIT), Vehari, Pakistan*

[61] *Centre d'Etude Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS), Thiès, Sénégal*

[62] *Bahauddin Zakariya University, Multan, Pakistan*

[63] *CSIRO Ecosystem Sciences, Brisbane, Australia*

[64] *University of Sassari, Sassari, Italy*

[65] *Agrophysical Research Institute, Saint-Petersburg, Russia*

[66] *Sorbonne Universités, Paris, France*

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Introduction

Background and motivation

Climate change is expected to alter a multitude of factors important to agricultural systems, including pests, diseases, weeds, extreme climate events, water resources, soil degradation, and socio-economic pressures. Changes to carbon dioxide concentration ([CO_2]), temperature, and water (CTW) will be the primary drivers of change in crop growth and agricultural systems. Therefore, establishing the CTW-change sensitivity of crop yields is an urgent research need and warrants diverse methods of investigation.

Crop models provide a biophysical, process-based tool to investigate crop responses across varying environmental conditions and farm management techniques, and have been applied in climate impact assessment by using a variety of methods (White *et al.*, 2011, and references therein). However, there is a significant amount of divergence between various crop models' responses to CTW changes (Rötter *et al.*, 2011). While the application of a site-based crop model is relatively simple, the coordination of such agricultural impact assessments on larger scales requires consistent and timely contributions from a large number of crop modelers, each time a new global climate model (GCM) scenario or downscaling technique is created. A coordinated, global effort to rapidly examine CTW sensitivity across multiple crops, crop models, and sites is needed to aid model development and enhance the assessment of climate impacts (Deser *et al.*, 2012).

To fulfill this need, the Coordinated Climate-Crop Modeling Project (C3MP) (Ruane *et al.*, 2014) was initiated within the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig *et al.*, 2013). The submitted results from C3MP Phase 1 (February 15, 2013–December 31, 2013) are currently being analyzed. This chapter serves to present and update the C3MP protocols, discuss the initial participation and general findings, comment on needed adjustments, and describe continued and future development.

AgMIP aims to improve substantially the climate, crop, and economic simulation tools that are used to characterize the agricultural sector, to assess future world food security under changing climate conditions, and to enhance adaptation capacity both globally and regionally. To understand better and improve the modeled crop responses, AgMIP has conducted detailed crop model intercomparisons at closely observed field sites for wheat (Asseng *et al.*, 2013), rice (Li *et al.*, in review), maize (Bassu *et al.*, 2014), and sugarcane (Singels *et al.*, 2013). A coordinated modeling exercise was one of the original motivations for AgMIP, and C3MP provides rapid estimation of crop responses to CO_2, water, and temperature (CTW) changes,

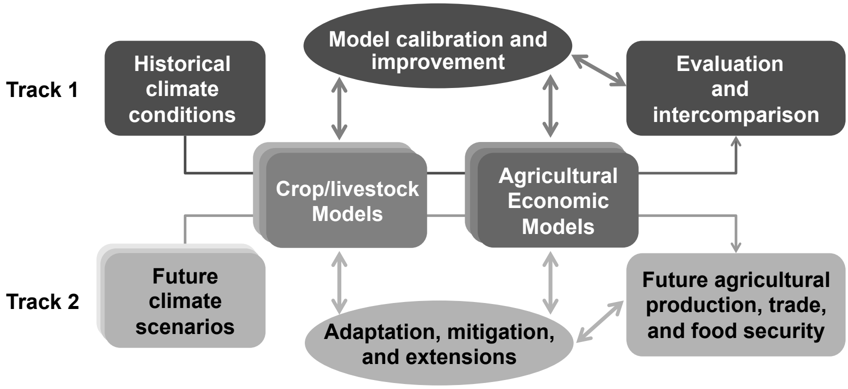


Fig. 1. The AgMIP two-track approach. Track 1: Multi-model intercomparison and improvement, Track 2: Climate change multi-model assessment. C3MP is a pilot activity for climate and crop activities of Track 2. Reproduced from Rosenzweig *et al.* (2012), with permission from Elsevier.

adding dimension and insight into the crop model intercomparisons, while facilitating interactions within the global community of modelers. C3MP also contributes a fast-track, multi-model climate sensitivity assessment for the AgMIP climate and crop modeling teams on Research Track 2 (Fig. 1), which seeks to understand the impact of projected climatic changes on crop production and food security (Rosenzweig *et al.*, 2013; Ruane *et al.*, 2014).

Objectives and ongoing contributions to greater AgMIP activities

C3MP is engaging the global community of crop modelers to expand the understanding of crop responses and sensitivities to the projected range of CTW changes; mobilizing and engaging the international community of crop modelers in coordinated climate-crop assessments; and improving the overall utility of crop model applications (Rötter *et al.*, 2011; White *et al.*, 2011).

To achieve these goals, C3MP participants are contributing to four major objectives:

- To expand further the international network of crop modelers and continue to build the C3MP database of simulation sites through a strong web-based community and information-exchange platform.
- To explore the range of simulated agricultural responses to CTW changes through rapid, easily executed sensitivity tests and associated impact-response emulators.
- To identify climate-related vulnerabilities highlighted by these analyses across regions, among crops, and between different farming systems.
- To analyze uncertainty that arises from projected climate changes and the impacts on crop production across crops, models, and sites.

In addition, participants are experiencing a wide range of benefits by contributing to C3MP, including:

- Representation of their individual research sites and results in global studies.
- Recognition of contributions to the C3MP database.
- International networking and collaborative research opportunities.
- Early access to the full database of global C3MP results.
- Potential co-authorship of C3MP studies.

Furthermore, interactions among participants using different crop models across a multitude of sites are fostering model improvement and development.

C3MP is also contributing site-based results from many agricultural regions to other ongoing AgMIP crop modeling activities, including the detailed crop model intercomparisons at platinum sentinel sites led by the AgMIP crops team (Asseng *et al.*, 2013; Bassu *et al.*, 2014; Li *et al.*, 2014; Singels *et al.*, 2013). These sentinel sites represent the highest quality observed experiment data for model intercomparisons, evaluation, and improvement, with the full complement of variables, including in-season and end-of-season measurements (more information is available at http://www.agmip.org/sentinel-sites/). Additionally, C3MP is aiding the utilization and improvement of global gridded crop models by the AgMIP GRIDded Crop Modeling Initiative (AgGRID) that simulates global agricultural production on high-resolution grids (e.g., Rosenzweig *et al.*, 2013; see also Part 1, Chapter 7 in this volume).

The C3MP Methodology and Participation Protocols

C3MP methodology

The C3MP methods and protocols are described in detail in Ruane *et al.* (2014), and are summarized here. Each C3MP contributor simulates yields with their site-calibrated crop model under a common set of 99 sensitivity tests designed to sample the specified CTW change uncertainty space uniformly. These CTW changes lie within a specified range (shown in Table 1) that spans the climate extremes projected by GCMs for the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2009) for the majority of agricultural lands (Ruane *et al.*, 2014).

Table 1. Ranges tested in C3MP climate sensitivity simulations.

Climate metric	Lower bound	Upper bound
T = Temperature change (ΔT)	$-1°C$	$+8°C$
P = Precipitation change (ΔP)	-50%	$+50\%$
CO_2 = Carbon dioxide concentration [CO_2]	330 ppm	900 ppm

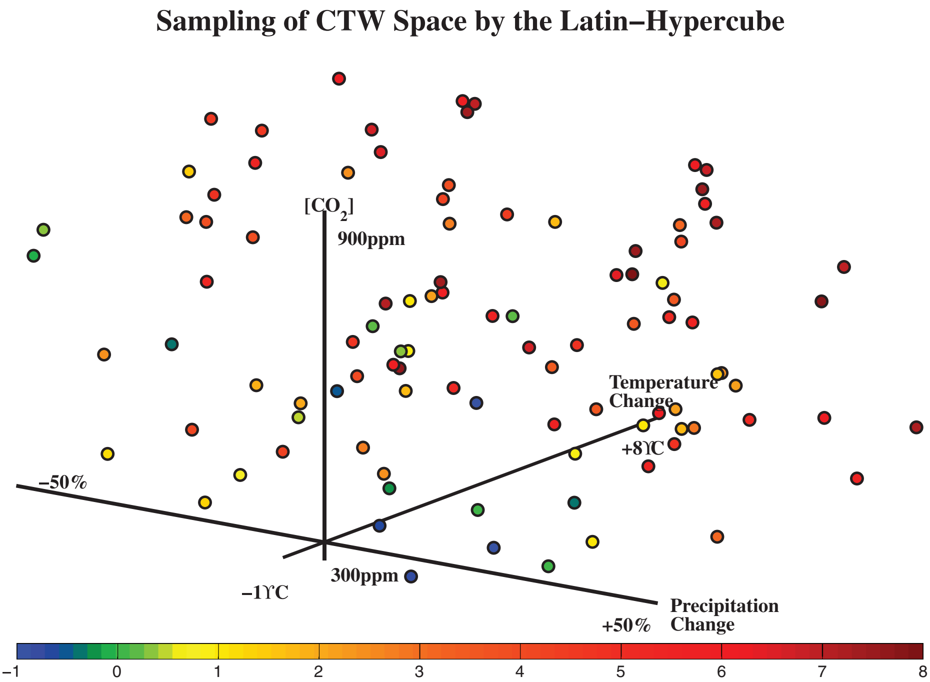


Fig. 2. Three-dimensional carbon dioxide concentration [CO_2], temperature, and water (CTW) uncertainty space. The points represent each of the 99 Latin Hypercube-generated sensitivity tests, which include a change in [CO_2], temperature, and precipitation based upon the ranges shown in Table 1. The colored bar also indicates the change in temperature, in order to illustrate the distribution of simulations better.

Furthermore, C3MP has extended these ranges slightly beyond the GCM-projected ranges so that contributed results will remain relevant in the event that more extreme projections become plausible (Fig. 2). In addition to the range of projected temperature increases, sensitivity tests also extend to a 1°C cooling in order to account for potentially optimal growing conditions, which may occur at temperatures cooler than the historical baseline. As the C3MP protocols require the same sensitivity tests for all crop modeling locations, the range of precipitation changes was limited to +/–50% to prevent the sensitivity tests being too sparse in the precipitation change uncertainty space, and so that we might accommodate more arid regions, where future projections could result in large percentage changes to small historical precipitation totals.

We note that changes in rainfall are restricted to changes in total amount, as precipitation variability is not yet considered in C3MP, although it is important in understanding yield response (Baigorria *et al.*, 2007). While in the highest representative concentration pathway (RCP8.5; Moss *et al.*, 2010), the final years of the 21st century have a [CO_2] higher than 900 ppm, the 30-year end-of-century time-slice

(2070–2099) has a central-year [CO_2] of 801 ppm. The 330 ppm lower limit of the [CO_2] range helps resolve CO_2 sensitivities around the 1980–2010 historical baseline's central year ([CO_2] in 1995 = 360 ppm).

The 99 sensitivity tests (shown in Table 2) were generated by using a Latin Hypercube sampling method, and include altered [CO_2] values and changes in temperature and precipitation that are applied to a baseline (1980–2009) daily weather series. A Latin Hypercube approach enables an evenly distributed and comprehensive sampling of a given uncertainty space, such as that specified by the CTW changes in Table 1. These [CO_2], temperature, and precipitation ranges are divided into 99 bins, and each bin is considered to be equally probable. A random value is then sampled from the first [CO_2], temperature-change, and precipitation-change bins, and these are combined to create "Sensitivity Test 1", which is applied to the baseline climate series for use in crop model simulations. The process is continued until all bins have been sampled for each CTW variable to form the 99 C3MP sensitivity tests, all of which are shown in Table 2, and are to be utilized by all participants. Figure 2 shows each of the 99 sensitivity tests plotted within the bounded CTW uncertainty space, and this demonstrates the relatively comprehensive sampling achieved using this method (a movable 3D image is available at www.agmip.org/c3mp). Ninety-nine tests were selected in order to facilitate crop model operation, and to obtain a large sampling of resultant yields without participants needing to perform numerous, successive model simulations.

To apply the sensitivity tests in crop model simulations, these CTW changes are implemented as an additive change in temperature (Table 2, column 2), a multiplicative change in precipitation (Table 2, column 4), and an imposed concentration of carbon dioxide [CO_2] (Table 2, column 5). For each sensitivity test, these temperature and precipitation changes are applied by directly modifying each day in the 1980–2009 daily climate time-series specific to the site being simulated. Repeating this process for each of the 99 sensitivity tests results in 2970 (99 tests $\times$ 30 years) yields per simulation.

The 30-year mean yield (Y) is then calculated for each sensitivity test. To understand how climate changes may affect yield variability, the coefficient of variation for yield across the 30 years (CV) is also calculated (Osborne and Wheeler, 2013). This enables the least-squares fitting of a quadratic crop model emulator for Y and CV for any given simulation location as a function of carbon dioxide concentration (CO_2), temperature change (T), and precipitation change (P) to determine coefficients a–k in each of the following equations:

$$\begin{aligned} Y(CO_2, T, P) = {} & a + b(T) + c(T)^2 + d(P) + e(P)^2 + f(CO_2) \\ & + g(CO_2)^2 + h(T^* P) + i(T^* CO_2) + j(P^* CO_2) \\ & + k(T^* P^* CO_2), \end{aligned} \quad (1)$$

Table 2. The 99 C3MP sensitivity tests.

Sensitivity test number	Change in temperature (°C)	Precipitation change (%)	Precipitation multiplier (fraction of baseline)	CO_2 concentration (ppm)
1	0.7	−17	0.83	418
2	0.0	23	1.23	458
3	1.9	−22	0.78	524
4	7.5	10	1.10	766
5	3.6	24	1.24	673
6	1.0	34	1.34	403
7	2.8	38	1.38	551
8	4.8	8	1.08	576
9	3.9	−42	0.58	700
10	4.3	−33	0.67	333
11	6.9	35	1.35	704
12	2.5	−12	0.88	875
13	5.4	15	1.15	377
14	0.2	27	1.27	777
15	2.1	3	1.03	714
16	6.5	−32	0.68	768
17	2.4	−48	0.52	510
18	7.8	26	1.26	607
19	4.2	−46	0.54	346
20	7.3	−28	0.72	544
21	7.1	−35	0.65	500
22	6.8	15	1.15	825
23	1.1	41	1.41	604
24	5.8	21	1.21	807
25	5.1	32	1.32	494
26	3.2	39	1.39	366
27	3.1	−40	0.60	732
28	7.9	−3	0.97	591
29	3.1	34	1.34	866
30	3.4	13	1.13	585
31	5.6	45	1.45	412
32	2.5	44	1.44	660
33	−0.1	−43	0.57	744
34	5.5	−9	0.91	572
35	4.0	−20	0.80	490
36	4.6	−38	0.62	839
37	6.3	−37	0.63	883
38	0.9	32	1.32	545
39	7.2	44	1.44	453
40	1.6	49	1.49	691
41	5.2	−13	0.87	454
42	2.0	−16	0.84	504
43	0.5	−7	0.93	537
44	4.7	−25	0.75	518

(*Continued*)

Table 2. (*Continued*)

Sensitivity test number	Change in temperature (°C)	Precipitation change (%)	Precipitation multiplier (fraction of baseline)	CO_2 concentration (ppm)
45	6.7	−11	0.89	486
46	1.3	−26	0.74	340
47	2.7	−11	0.89	424
48	5.9	−19	0.81	580
49	4.3	−9	0.91	793
50	−0.9	31	1.31	435
51	0.1	33	1.33	384
52	4.9	22	1.22	440
53	3.6	30	1.30	724
54	3.8	−5	0.95	836
55	6.4	4	1.04	642
56	6.3	11	1.11	433
57	1.4	−29	0.71	871
58	−0.2	11	1.11	475
59	7.0	−21	0.79	856
60	7.3	−24	0.76	829
61	4.5	−45	0.55	847
62	−0.3	−21	0.79	648
63	−0.5	5	1.05	629
64	0.6	47	1.47	861
65	−0.8	18	1.18	355
66	5.1	20	1.20	638
67	0.2	6	1.06	719
68	4.4	0	1.00	783
69	6.1	37	1.37	482
70	2.4	−6	0.94	399
71	6.6	−34	0.66	798
72	1.7	24	1.24	887
73	1.8	1	1.01	563
74	5.9	−16	0.84	898
75	3.5	19	1.19	526
76	1.2	−40	0.60	394
77	5.2	−50	0.50	554
78	0.4	9	1.09	679
79	7.2	14	1.14	727
80	0.9	7	1.07	663
81	−0.4	40	1.40	514
82	−0.6	12	1.12	426
83	5.7	−1	0.99	406
84	5.4	−44	0.56	754
85	5.5	21	1.21	621
86	7.6	−36	0.64	380
87	6.0	−27	0.73	444

(*Continued*)

Table 2. (*Continued*)

Sensitivity test number	Change in temperature (°C)	Precipitation change (%)	Precipitation multiplier (fraction of baseline)	CO_2 concentration (ppm)
88	2.7	2	1.02	815
89	7.5	0	1.00	645
90	−1.0	29	1.29	670
91	4.1	28	1.28	802
92	2.2	48	1.48	655
93	3.9	−35	0.65	689
94	1.7	43	1.43	587
95	0.3	−44	0.56	774
96	4.9	−47	0.53	709
97	6.2	17	1.17	852
98	2.2	39	1.39	599
99	1.1	6	1.06	737

and

$$\begin{aligned} CV(CO_2, T, P) = {} & a' + b'(T) + c'(T)^2 + d'(P) + e'(P)^2 + f'(CO_2) \\ & + g'(CO_2)^2 + h'(T^* P) + i'(T^* CO_2) + j'(P^* CO_2) \\ & + k'(T^* P^* CO_2). \end{aligned} \quad (2)$$

The emulators for mean yield and yield CV are fitted separately, and the values of coefficients $a{-}k$ in Equation 1 will not be the same as $a{-}k$ in Equation 2 (Ruane *et al.*, 2013b). Ruane *et al.* (2013b) utilized similar second-order polynomials to emulate impact-response surfaces for maize in Panama to represent peak yields under optimal conditions. These emulators define an impact-response surface that highlights the crop sensitivity to the specified CTW changes. The formulation of this crop model emulator is an important area of continuing research in C3MP, as it is possible that some locations' mean yield or yield CV responses may be better captured by polynomials of a different order or by using logarithmic functions.

The introduced cross-variable terms in Equations 1 and 2 are a unique feature of the C3MP emulators, which allow for non-orthogonal curvature in the crop response space that result from interactions between the CTW variables in crop models (Ruane *et al.*, 2014). Such terms can aid understanding of how CTW variables impact yields in combination (Sheehy *et al.*, 2006). In addition, Ramankutty *et al.* (2013) tested linear, non-linear, and spline fits for a grassland site in Australia, which could be repeated for any site participating in C3MP. Lobell and Burke (2010) performed a similar regression using crop model simulations of interannual variability, and found that quadratic regressions outperformed linear models, which lends further support to the C3MP approach. In the particular cases in which the above emulator does not fully capture a crop's response at a specific location, for instance in marginal growing areas where the crop response may not be linear or quadratic, C3MP is working with participants to facilitate the development and use of additional or alternative emulators at those sites.

Climate data and information

To ensure consistency across sites and encourage the contribution of crop modeling simulations from regions where climate information does not exist or is not available, C3MP provides an estimated daily climate time-series for the 1980–2010 historical baseline period. Based on the outputs of the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA; Rienecker *et al.*, 2010), MERRA-Land (Reichle *et al.*, 2011) outputs and NASA-GEWEX Solar Radiation Budget daily radiation data (Zhang *et al.*, 2007), these AgMERRA data were developed for agricultural impacts applications and are adjusted to eliminate apparent monthly biases in comparison to an ensemble of gridded observational data from weather stations and satellites (Ruane *et al.*, 2014, and references therein).

Some participants may have access to complete (i.e., with no gaps, missing years, or spurious values) 1980–2010 observed historical climate datasets that are also publicly available. In such cases, participants are encouraged to apply the 99 sensitivity tests to these observed datasets and perform their C3MP crop model simulations while also conducting the simulations with AgMERRA data, to enable location-specific comparisons. Simulations using both observed and AgMERRA-based weather can be submitted to the C3MP database, and the crop impacts are investigated by using the emulator approach described above.

Participating in C3MP

To participate, prospective contributors register their interest at https://www.agmip.org/c3mp-registration/ and complete a C3MP questionnaire, which provides supplementary material and information to C3MP coordination regarding the proposed simulations. For each of their proposed simulation contributions, participants provide the following information and details:

- Simulation location (latitude, longitude, and elevation).
- Public availability of weather data.
- Crop species, cultivar, water regime, and any other relevant crop information.
- Planting and harvest months.
- Crop model version and components.
- Nitrogen application (approximate amount).
- Soil-profile source, including relevant references.
- Calibration procedures, including relevant references.
- Reference to a previous study that uses the specified model and information.

The above details must be provided for each new simulation, as these constitute a unique simulation set. For example, some participants have simulated the same crop/location multiple times with an identical model setup, but varying only the amount of nitrogen applied. These are considered separate, unique simulations sets based upon the varying nitrogen levels.

Upon completion and submission of the questionnaire that describes the simulations sets, C3MP provides participants with a 30-year (1980–2009) AgMERRA daily weather time-series, based on their specified latitude and longitude, along with the 99 sensitivity test parameters (Table 2) needed to complete the C3MP simulations. Once the sensitivity simulations are completed, participants are given an Excel-based results reporting template (available at http://www.agmip.org/c3mp-downloads/) that is designed to help format their crop yield results for entry into the C3MP database. Multiple simulations sets may be reported by using the results reporting template. When completed participants email the file to C3MP coordination for processing and archiving. There is currently no limit on the number of simulation sets, sites, crops, and models that any one participant can contribute, and all participants are encouraged to submit as many site-calibrated simulations as they are able.

C3MP recent developments and updates

Since launching in February 2013, C3MP has received well over 1000 simulated results using the above-described methodology, and additional and new results are contributed regularly. Efforts are underway to create and improve a C3MP networking platform, expand and evaluate contributed results through a comprehensive database, and develop a range of climate-crop analyses for distribution and feedback. A major advance has been the release of the entire C3MP contributions archive and results database via a secure, online "C3MP Research" platform, which is accessible to, and benefits, all participants who have contributed simulated results. Contributors are now able to access all the C3MP submissions to date, and also have access to various analysis tools in development by C3MP Coordination Team, which will facilitate further various studies and collaborations.

Another major task C3MP has undertaken is to evaluate and vet the contributed results of Phase 1. Preliminary assessments are presented below to demonstrate how representative the C3MP emulator and approach are with respect to the submitted simulations. Additional checks and evaluations will be pursued as Phase 1 analyses continue.

C3MP is also identifying areas for improvement of the protocols, and additional information needed from participants to understand and analyze the submitted results. These improvements and methodological adjustments are discussed below, and will be incorporated in C3MP Phase 2.

Furthermore, the C3MP Research site also hosts a C3MP forum, in which contributors are invited to post questions, discuss results, and explore avenues for collaboration. The forum is a utility that further expands and strengthens the global network of crop modelers, particularly for coordinated crop model assessments. The current, detailed C3MP protocols are freely available at http://www.agmip.org/c3mp-downloads/. More information about the project and registration can be found at www.agmip.org/c3mp.

C3MP participation to date: Coverage and scope

C3MP currently benefits from contributions covering over 18 crops (Table 3), over 56 countries (Table 4), and 23 crop models (Table 5). Figure 3 shows major global cropped areas (green regions, Monfreda *et al.*, 2008), with all contributed C3MP sites superimposed (red dots).

Table 3 shows the diversity of crops that have been simulated and contributed for C3MP Phase 1. The majority of the submitted results simulate yields for the major global commodities: wheat, rice, maize, and soybean, with the number of contributions of these crops' simulations increasing across the globe. However, C3MP has also received simulations for less-frequently modeled crops, such as grapevine, sunflower, and even Bambara groundnut, an indigenous variety found in West Africa

Table 3. Crop distribution of contributed C3MP simulations.

Crop	Number	Percent
Bambara groundnut	2	0.17
Barley	10	0.87
Canola	3	0.26
Chickpea	3	0.26
Cotton	2	0.17
Grapevine	1	0.09
Lentil	1	0.09
Maize	291	25.35
Millet	75	6.53
Pasture	39	3.40
Peanut	29	2.53
Potato	10	0.87
Rice	119	10.37
Rye	2	0.17
Sorghum	14	1.22
Soybeans	184	16.03
Sugarcane	13	1.13
Wheat	350	30.49

Table 4. Country distribution of contributed C3MP simulations.

Country	Number	Percentage	Country	Number	Percentage
Argentina	49	4.5	Japan	9	0.8
Australia	27	2.5	Kazakhstan	11	1
Austria	8	0.7	Lithuania	2	0.2
Bangladesh	48	4.4	Madagascar	1	0.1
Belarus	8	0.7	Malawi	4	0.4
Belgium	7	0.6	Mali	8	0.7
Benin	2	0.2	Mauritania	4	0.4
Bolivia	18	1.6	Mexico	3	0.3
Botswana	2	0.2	New Zealand	20	1.8
Brazil	27	2.5	Niger	10	0.9
Burkina Faso	12	1.1	Pakistan	11	1
Cameroon	1	0.1	Panama	4	0.4
Canada	8	0.7	Philippines	6	0.5
China	63	5.7	Poland	3	0.3
Czech Republic	4	0.4	Republic of Korea	8	0.7
Denmark	7	0.6	Russia	16	1.5
Egypt	7	0.6	Senegal	19	1.7
Finland	1	0.1	South Africa	6	0.5
France	6	0.5	Spain	12	1.1
Germany	3	0.3	Sri Lanka	35	3.2
Ghana	8	0.7	Thailand	7	0.6
Greece	12	1.1	The Gambia	6	0.5
Guinea	2	0.2	The Netherlands	5	0.5
Guinea-Bissau	6	0.5	Togo	2	0.2
India	42	3.8	Ukraine	17	1.5
Indonesia	5	0.5	United Kingdom	2	0.2
Iran	9	0.8	United States	459	41.8
Italy	16	1.5			

(Karunaratne *et al.*, 2011). All crops are encouraged, and C3MP welcomes the modeling of both major and minor crops at diverse sites in order to facilitate a range of analyses of these crops' sensitivity to climate change.

Nearly 42% of the contributed sites are from the US (Table 4), facilitated by the US's extensive crop modeling network, but the number of countries from which sites have been contributed is growing. The crop coverage obtained in Phase 1 represents many agricultural regions, but C3MP has also identified those regions where gaps in coverage exist, such as the Middle East, Mesoamerica, East Africa, and Southeast Asia, and is actively recruiting participants to contribute crops/sites in these gap regions. In particular, representation is needed from developing countries, marginal regions that might display significantly different crop responses, and also those regions that are expected to be the most vulnerable to future climatic changes (such as those regions that are already affected by sea-level rise and other indirect

Table 5. Crop model distribution of contributed C3MP simulations.

Crop	Number	Percentage
APSIM	69	6.3
AquaCROP	7	0.6
CropSyst	20	1.8
DailyDaycent	4	0.4
DRAINMOD-DSSAT	1	0.1
DSSAT	872	79.4
Fasset	1	0.1
GLAM	1	0.1
InfoCrop	11	1
Lintul	2	0.2
MCWLA	3	0.3
RZWQM	2	0.2
RZWQM-DSSAT	4	0.4
SARRA-H	70	6.4
Sirius Quality	13	1.2
SPRiGS	1	0.1
SSM	9	0.8
STICS	7	0.6
VITE model	1	0.1

forcings). Additionally, C3MP encourages existing participants in each country to submit additional sites, and to engage with new participants by leveraging the global C3MP network of crop modelers.

A majority of the submitted simulation sets was performed with the Decision Support System for Agrotechnology Transfer (DSSAT, Hoogenboom *et al.*, 2012, see Table 5). The DSSAT modeling community is well integrated, and has a particularly strong network with which to disseminate information regarding C3MP participation and other initiatives, with the assurance that such information will reach most of the community. DSSAT also provides a means by which to rapidly and efficiently modify weather-related crop model inputs, via adjustment of the "environmental modifications" in the crop model simulation setup (Jones *et al.*, 2003; Hoogenboom *et al.*, 2012). C3MP has created a template based on the syntax of these environmental modifications, which DSSAT users may download and utilize to rapidly execute their 99 sensitivity simulations. For these reasons, a majority of contributed results were simulated by using DSSAT model versions.

Similar to the DSSAT environmental modifications template, C3MP has also created a similar tool for the Agricultural Production Systems Simulator (APSIM, Keating *et al.*, 2003) to apply more easily the sensitivity tests to climate data for APSIM crop model simulations. The tools are contained in a downloadable package

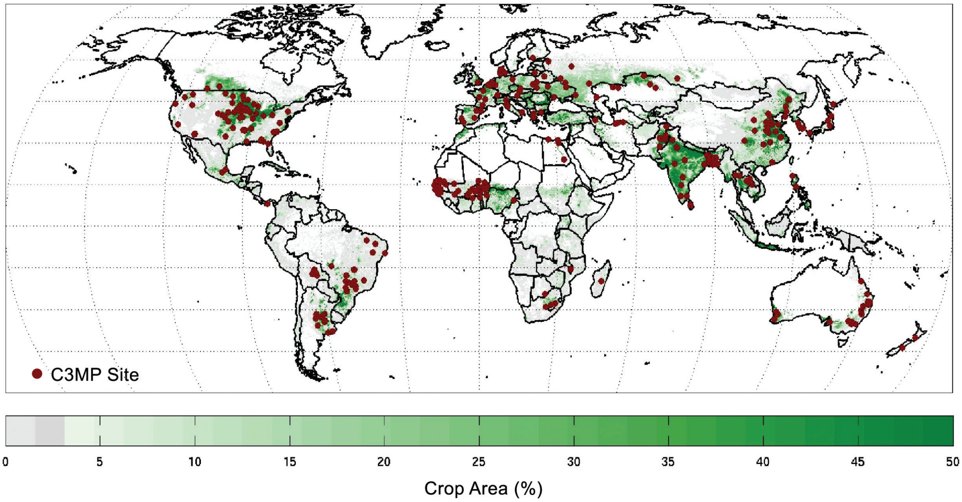


Fig. 3. Major cropped areas (green, Monfreda *et al.*, 2008) and C3MP contributed sites (red dots).

on the C3MP downloads page (www.agmip.org/c3mp/downloads), and have enabled more APSIM users to contribute to these coordinated experiments in a streamlined, efficient manner. Likewise, C3MP is making a dedicated effort to create tools for other modeling platforms, such as the French National Research Institute for Agricultural Research STICS crop growth model (Brisson *et al.*, 2003; Ripoche, personal communication), which will enable fast and efficient contributions from these communities. C3MP is also working to broaden communications and reach other crop modeling communities by identifying listserves, presenting C3MP at international conferences, and soliciting individuals and groups of model users. Additionally, C3MP has recently engaged the international livestock and pasture modeling community to contribute results (Snow *et al.*, 2014).

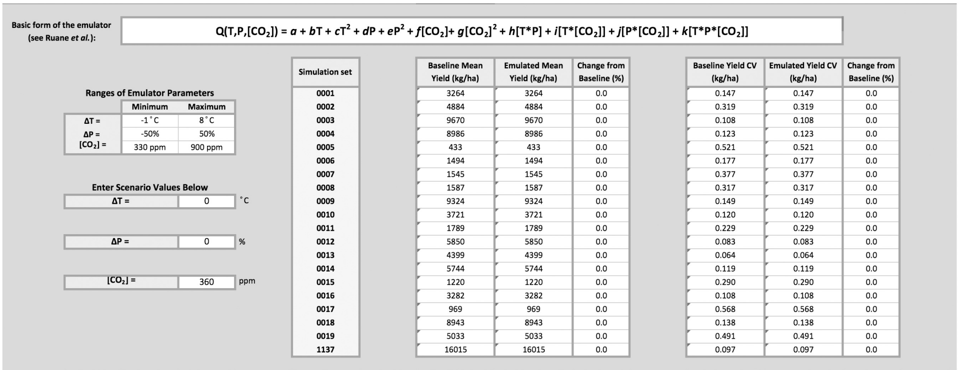
The C3MP Database and Evaluation

The C3MP database: Access and tools

The C3MP database was made exclusively available to active C3MP contributors in January 2014. This database will be released in phases over the duration of the project, enabling and facilitating collaborations and the undertaking of additional studies through the C3MP Research website. The C3MP database will be open for public access in January 2015, which corresponds to Phase 2 of the project; however the Research website will remain accessible to project contributors only. Research website users are able to access all emulated results at each site, any figures, analyses, and/or impacts response surfaces (Ruane *et al.*, 2014) generated at each site, a comprehensive metadata file that details the specifications for each simulation, a forum where questions and comments can be exchanged, and a host of tools that will aid in the analysis and interpretation of results. In addition, the emulator coefficients that were obtained for each simulation are also made available to enable further analysis and discussion. Each simulated set of results posted on the research website has been assigned a unique four-digit identification number which can be used to determine the metadata for each set (e.g., location, crop, crop model, irrigation, etc.) Downloadable AgMERRA daily climate time-series over the 1980–2010 time-period are also provided for each of the simulated locations. This provides the C3MP community with all of the data necessary to conduct climate assessments on the submitted results. The site is continuously updated as more submissions are contributed.

C3MP is actively constructing and adding to a tool-shed that is available via the C3MP research site. A number of tools have been created to facilitate contributors' crop model simulations, to make the submitted and emulated results easily accessible, and to enable collaborative research within the C3MP community. One such tool is a downloadable package containing an executable program designed to apply the 99 sensitivity tests to weather datasets in an APSIM-compatible format, which eases the completion of the necessary C3MP simulations for APSIM users. C3MP coordination is in the process of creating a similar tool for contributors who model crops by using STICS, and will be interacting with other modeling communities to identify ways to make the application of the C3MP protocols simple and efficient. It is also likely that individual participants may have, or will, create their own tools to execute the sensitivity tests (or perform various analyses for their crops/sites). In these cases, C3MP encourages participants to share their simulation tools, and will facilitate the connection of participants and distribution of these tools, while establishing proper credits and attribution.

C3MP coordination team has also made available an "Emulator Calculator" tool, which allows participants to determine quickly the emulated mean yields and yield coefficients of variation (CV) of up to 20 user-specified simulation sets (Fig. 4). This calculator is defined by the emulator equation discussed above (Ruane *et al.*, 2014). The user first enters the climate variable values (temperature, precipitation, and [CO_2]) to be emulated by the calculator, followed by the four-digit code for the simulations of interest (up to 20). After setting these parameters, the calculator displays the emulated baseline (where $\Delta T = 0°\text{C}$, $\Delta P = 0\%$, and [CO_2] = 360 ppm) and emulated values as determined by the user-defined climate variables for both mean yield and yield CV. The calculator also shows the percent change from the baseline scenario of the user-defined emulation for mean yield and yield CV.



Basic form of the emulator (see Ruane *et al.*):

$$Q(T,P,[CO_2]) = a + bT + cT^2 + dP + eP^2 + f[CO_2] + g[CO_2]^2 + h[T*P] + i[T*[CO_2]] + j[P*[CO_2]] + k[T*P*[CO_2]]$$

Ranges of Emulator Parameters

	Minimum	Maximum
ΔT =	-1 °C	8 °C
ΔP =	-50%	50%
$[CO_2]$ =	330 ppm	900 ppm

Enter Scenario Values Below

ΔT =	0	°C
ΔP =	0	%
$[CO_2]$ =	360	ppm

Simulation set	Baseline Mean Yield (kg/ha)	Emulated Mean Yield (kg/ha)	Change from Baseline (%)	Baseline Yield CV (kg/ha)	Emulated Yield CV (kg/ha)	Change from Baseline (%)
0001	3264	3264	0.0	0.147	0.147	0.0
0002	4884	4884	0.0	0.319	0.319	0.0
0003	9670	9670	0.0	0.108	0.108	0.0
0004	8986	8986	0.0	0.123	0.123	0.0
0005	433	433	0.0	0.521	0.521	0.0
0006	1494	1494	0.0	0.177	0.177	0.0
0007	1545	1545	0.0	0.377	0.377	0.0
0008	1587	1587	0.0	0.317	0.317	0.0
0009	9324	9324	0.0	0.149	0.149	0.0
0010	3721	3721	0.0	0.120	0.120	0.0
0011	1789	1789	0.0	0.229	0.229	0.0
0012	5850	5850	0.0	0.083	0.083	0.0
0013	4399	4399	0.0	0.064	0.064	0.0
0014	5744	5744	0.0	0.119	0.119	0.0
0015	1220	1220	0.0	0.290	0.290	0.0
0016	3282	3282	0.0	0.108	0.108	0.0
0017	969	969	0.0	0.568	0.568	0.0
0018	8943	8943	0.0	0.138	0.138	0.0
0019	5033	5033	0.0	0.491	0.491	0.0
1137	16015	16015	0.0	0.097	0.097	0.0

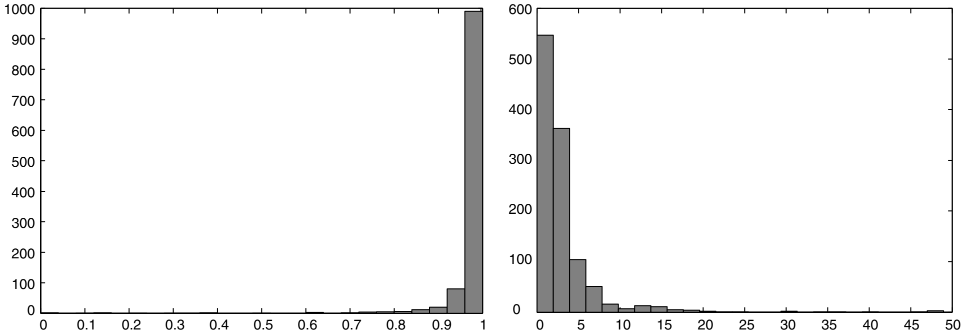
Fig. 4. Screenshot of the "Emulator Calculator". This tool allows the user to view the emulated mean yield and yield CV of 20 user-selected simulation sets. The user can adjust the climate parameters to change the emulated mean and CV. The emulated baseline (where temperature change is 0°C, precipitation change is 0%, and atmospheric carbon dioxide concentration is 360 ppm) is always shown for the selected simulation sets, as is the percentage change of the user-defined emulation from the emulated baseline values.

Lastly, the C3MP Research website has developed an online message board to act as a forum for the community. This online forum allows C3MP Coordination to inform the community of changes and updates to the datasets while notifying the community of new tools and other upcoming events related to C3MP. The message board encourages discussion between contributors, provides opportunities for greater collaboration on ongoing research efforts, and maintains a public space for posting figures and other research results.

Evaluating the fit of emulated responses

A major objective of Phase 1 is to evaluate the efficacy of the C3MP emulator to capture yield responses for the wide array of potential carbon dioxide, temperature, and water (CTW) changes, and to assess C3MP's overall methodology and ability to serve the analysis needs of the global crop modeling community. As an initial assessment, the r^2 correlation coefficient and the root-mean-square error (RMSE) are presented for the comparison of the C3MP emulated results to the crop model simulated yields at each of the 1100+ existing C3MP sites (Fig. 5). For a large majority of the contributed sites, the emulator displays an $r^2 > 0.95$ and an RMSE $< 5\%$, which suggests that for most contributed locations, the described C3MP emulator does well to capture the major modeled crop–climate interactions and CTW responses.

However, there are sites where the C3MP emulator does not display a completely representative fit to the simulated results. C3MP coordination is currently identifying these sites and interacting with the respective contributors to understand and attribute the differences between the emulated and simulated results. The emulator



(a) r^2 correlation for Emulator Fit (b) RMSE for Emulator Fit

Fig. 5. Correlation and RMSE for emulator fit to 1000+ C3MP contributed simulations.

terms may not sufficiently characterize all the important CTW interactions that occur at some unique sites. In these cases, C3MP is engaging with contributors to develop emulators that better represent these specific crops/sites and crop sensitivities to CTW changes.

Quality assessment and quality control

C3MP is also currently investigating the general patterns of specific crops' responses that are emerging globally and regionally from the contributed simulation sets, and identifying locations that appear to have anomalous responses relative to similar, nearby locations. As an example, Fig. 6 shows all the contributed simulation sets for rainfed maize. Although more sites are needed to ascertain a global response pattern confidently, these initial contributions generally indicate that a 4°C increase in temperature, and declines in rainfall of 25% can adversely impact yields; this is a consistent response across the sites. Increases in [CO_2] to 720 ppm (keeping temperature and rainfall at current conditions) result in slightly positive crop yield responses, particularly at higher latitudes and across North America. While these results appear to be fairly consistent across the sites, there are locations where the response differs from neighboring sites, and in these cases, the anomalous response is flagged for further scrutiny.

C3MP has encouraged participants to submit simulated yields for the same site using a variety of input parameters (such as N applications) to allow future intercomparison. This has occasionally led to instances in which the modelers were attempting to simulate yields of crops at sites where these crops are unviable, or to impose rainfed water-management strategies in locations heavily reliant upon irrigation. The latter is illustrated, for example, for rainfed maize by low baseline emulated yields (Fig. 6a) and a largely positive response to a 4°C temperature increase (Fig. 6b) in

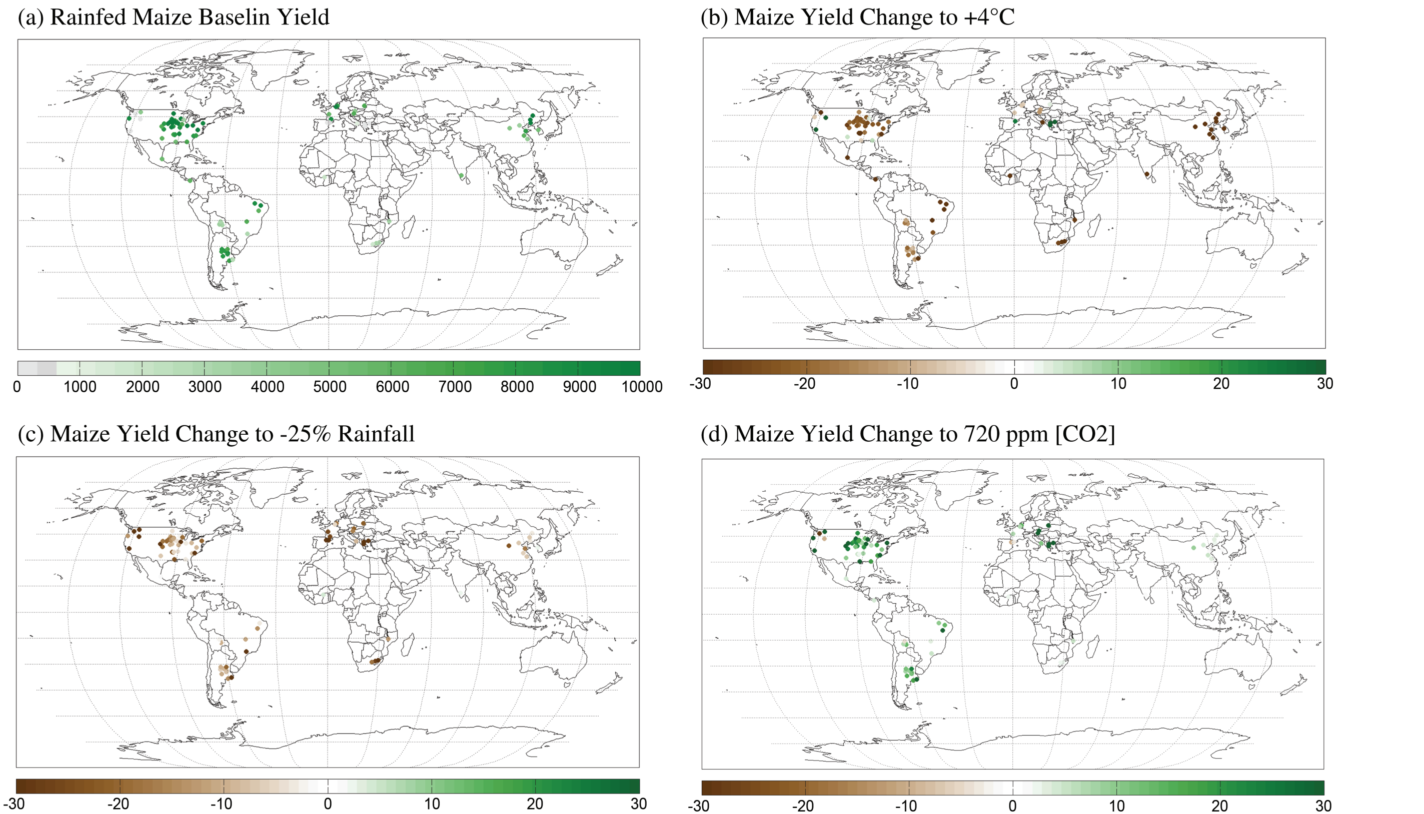


Fig. 6. (a) Baseline yield for rainfed maize, and (b, c, d) rainfed maize: 4°C increase in temperature, 25% decrease in rainfall, and 720 ppm [CO_2], respectively.

the northwest USA, which are actually irrigated sites. Such simulations prove difficult to accurately emulate, and, in some cases such as the northwest US, may not be representative of site-specific practices or conditions that allow the crop to be viable.

C3MP has indicated such anomalous crop responses with a "flag" in the simulation database available currently to active contributors. Contributors are encouraged to help diagnose and investigate the causes of incongruity, thereby harnessing the collective expertise of the global crop modeling community. These analyses and contributor interactions can help to catch unintended errors in simulations, and assess the best or most suitable site-specific conditions and management for current crop viability. Establishing the site-specific conditions of current crop viability will also lead to more accurate and informative future climate impacts assessments at that site. Such participant-led evaluations will further provide more robust assessments of crop model differences and identify areas of potential model improvement and refinements in model calibration.

C3MP Phase 1: Lessons Learned and Initial Findings

Lessons learned

In Phase 1, C3MP endeavored to obtain a sufficient amount of simulation information from contributors, while minimizing their time and effort commitment. However, as C3MP begins to evaluate and understand the variety of crop, location, and model responses to carbon dioxide, temperature, and water (CTW) changes, the coordination has identified additional pieces of information that prove important in evaluating the contributed results.

C3MP had originally decided not to ask for simulated baseline yield values, in order to allow participants to retain ownership of their crop model configuration. However, the baseline yields do provide crucial context for emulator validation, and could enable other assessments that add to the richness and utility of the project. A baseline simulation, and the contribution of baseline yields, is relatively simple to perform and computationally inexpensive. C3MP will request this additional baseline simulated yield information in Phase 2, and will make every effort to maintain and accredit participants' ownership of their crop model setup.

Additionally, C3MP had requested the average planting and harvest months for archival and metadata purposes, but there is much interest in understanding how the yearly planting and harvest dates may change with climate change. Therefore, in Phase 2, C3MP will also ask for the yearly planting and harvest dates. This will also allow for better identification of sources of variability, isolation of the year-to-year crop response during the prime growing season, and can enable a number of analyses across crops and regions, such as the impact and/or avoidance of drought or frost conditions. In some crop models, a failure to mature in one year can allow the plant to carry-over and mature the following year, which leads to some inconsistencies in the yearly harvest dates. This can be better identified if the yearly information is collected and assessed.

Findings and analyses

The C3MP coordination team has identified some general responses that warrant further explanation and interaction with the greater community of collaborators. Firstly, crop model calibrations may be achieved with respect to the optimal temperature for the specific crop/cultivar at a particular site. However, in the responses for many major crops across numerous simulations, small changes in temperature from the baseline result in yield improvements, before deteriorating under greater temperature changes. This would suggest that some of the models were not necessarily calibrated for the optimal crop growth temperature at these locations. Additional work by the C3MP and field experimenter community could aid in deeper understanding of the crop response to small temperature changes.

Secondly, C3MP is continuing assessments of the crop impact response surfaces generated for each simulation set. Ruane *et al.* (2014) illustrates a prototype C3MP analysis for peanut in Henry County, Alabama, and describes the crop impact response surface, which is taken at the zero-change cross-sections of the CTW uncertainty space. These response surfaces can also be constructed for the mean peanut response (or any crop in the C3MP database) across multiple locations. For example, results have also been contributed for peanut simulations from locations in India, Ghana, Thailand, and additional sites in the US. Many aspects of these simulations and model calibration differ across the sites, which makes direct comparison between simulation sets challenging. However, as participation grows, C3MP anticipates large increases in the number of contributed sites for each crop, which can enable a variety of analyses. Participants will have the ability to access all contributed simulation-set results to understand their crop response within the context of the mean response across all locations or a selected subset of the submitted simulations. This will allow participants to compare their results to those of the larger research community.

Thirdly, C3MP has also identified multiple simulations sets that are either co-located or are characterized by similar climates (i.e., similar temperature and rainfall), but display largely disparate mean yield values between different crop models. This may be attributed to many factors, including differing soils, cultivars, fertilizer applications, management, etc. There may also be mean yield biases between models that are being investigated by AgMIP Crop Teams (Asseng *et al.*, 2013; Bassu *et al.*, 2014; Li *et al.*, 2014; Singels *et al.*, 2013), and also warrant further investigation by the greater C3MP community, particularly participants who are using different crop models to simulate similar environmental conditions. For the purposes of near-term investigations and analyses, C3MP will focus on the yield responses (percent change and change in CV), rather than the absolute mean yields.

C3MP is actively working both to integrate the lessons learned in the updated protocols for Phase 2 of the project, and also to understand and share these and other recent findings. Continuous interactions with the greater C3MP community can help to prioritize and organize these activities, and create new opportunities for study and evaluation.

Continuing C3MP Efforts and Future Work

C3MP will review all contributed simulation sets and work with participants to rectify and/or explain any discrepancies between simulated and emulated values, or anomalous results. As the database of contributed sites continues to grow and improve in quality, C3MP has identified major analyses that can be performed at any location and pursued for publication. These include, but are not limited to:

- *Analyses of current sensitivity*: By examining the slope of the emulated response surfaces at the historical baseline climate's location ($\Delta T = 0$°C; $\Delta P = 0\%$; [CO2] $= 360$ ppm), it is possible to examine the sensitivity of yield to each climate variable. Simulation sites where immediate sensitivity and potential for damages are high can be highlighted in regard to climate risks and vulnerability.
- *Climate change analyses (including CMIP5 GCMs)*: Emulated impact response surfaces also facilitate assessments of projected climate impacts on a given region and crop. By examining CMIP5 GCM outputs that correspond to simulation-site locations, distributions of projected changes in growing season temperature and precipitation can be determined and coupled with [CO_2] values from the corresponding representative concentration pathway (Moss *et al.*, 2010) for any given time-slice. These projections may then be used to calculate probabilistic yield-change estimates by using the emulated response surfaces. A similar approach would also be possible with other climate model ensembles, in addition to data from various downscaling approaches or scenario-generation techniques.
- *Exploring uncertainties by using the network of C3MP locations*: In addition to climate vulnerability analyses, C3MP will generate maps of crop modeling simulation locations that can be used to build the network of AgMIP sites and crop modelers around the world to facilitate comparison and collaboration in future studies. Such comparisons and crop response evaluations at multiple sites can also allow detailed investigations of model and crop response uncertainty, which may be characterized across models, geographic areas, and other factors.

- *Regional-based analysis*: If enough simulation sites are contributed for a particular region (e.g., southeast South America), it may become possible for C3MP participants to undertake a more detailed investigation of that region. Such regional analyses include comparisons of simulation-set coverage relative to major agricultural regions, assessments examining the relative impacts of climate change on different subregions, or evaluations of the implications of updated climate scenarios or downscaled datasets on a particular region.
- *Crop-based analysis*: Similarly, if enough simulation sites are contributed for a particular crop (e.g., sorghum), it will become possible for C3MP participants to undertake a more detailed investigation of C3MP results for that particular crop. Possible areas of investigation include a comparison of the global coverage of the crop model simulations relative to the crop's major growing regions, an evaluation of the crop models that are employed that also compares model similarities and differences, and the interactions between the crop response and other environmental factors that distinguish particular simulations. The global community of modelers for each crop that has contributed to C3MP is highly encouraged to undertake and lead these assessments. Discussion may be easily facilitated via the C3MP Research website and forum.
- *Crop model-based analysis*: Finally, if a sufficient number of simulated sites are contributed for a particular crop model (e.g., APSIM, STICS, etc.), it may become possible for C3MP participants to undertake a more detailed investigation of C3MP results for that crop model. Potential areas of study may include the lessons learned about the sensitivity of the crop model to key climate change factors. Furthermore, efforts are underway by AgGRID (Rosenzweig *et al.*, 2014; see also Part 1, Chapter 7 in this volume) to execute the C3MP sensitivity tests for various global gridded crop models. Though direct comparisons with the C3MP results submitted from point-based crop models are challenging, the consistency between these and the global gridded model C3MP results can provide insight into broad, regional, and global crop responses and patterns to CTW changes. A large network of C3MP point-based simulations can also aid AgGRID model development, by providing a potential means for evaluating their spatial performance (if not a true model validation).

C3MP regional, crop-specific, and crop model analyses hold great potential for thorough analyses and motivate more detailed follow-on studies. Participants are invited to design extensions and analyses and ideas and discussion are welcomed via c3mp@agmip.org.

C3MP will continue to welcome more participants, accept additional results from existing or new members, vet and evaluate the existing contributions, refine the emulator approach for various sites, and expand participation among additional crop modeling teams, and encourage coverage by modelers of under-represented countries and regions. C3MP will work to identify opportunities for collaboration among participants and coordinate publications and studies. Registration is and will remain open at www.agmip.org/c3mp. Interested parties may contact c3mp@agmip.org at any time for further information on how to contribute to this unique and rigorous global research effort.

Frequently Asked Questions (FAQs)

— *Do I have to run other groups' sites?*
C3MP: No. Participants will only simulate their own sites.

— *Can I only run a site if it corresponds to a detailed field-trial experiment?*
C3MP: No. Multiple sites can utilize the same management and cultivars if they are reasonable representations of local practices.

— *What defines a unique C3MP site?*
C3MP: A C3MP site is unique if it has unique climate, soil, management, or cultivar.

— *What is the minimum number of sites that I'd have to run in order to participate?*
C3MP: One. We welcome contributions of any size.

— *Do I have to submit simulation-set configuration files and all inputs and outputs?*
C3MP: No. Participants will complete a questionnaire that provides C3MP with the basic information about each of your simulations. Upon submission of the questionnaire, C3MP will send further instructions on how to run the sensitivity tests as well as a results reporting template to standardize the results submissions.

— *Will I receive credit for my contributions?*
C3MP: Yes. Participants will be co-authors on coordinated C3MP publications and will get access to the full C3MP archive for coordinated research activities prior to its full public release. Each dataset will also be associated with its authors in order to facilitate future collaborations and data exchanges.

— *Is C3MP going to be used as a basis for detailed intercomparison of crop models?*
C3MP: Not in Phase 1. C3MP's diverse model configurations limit systematic intercomparison of crop models. C3MP multi-model analysis will be limited to identifying consistency or inconsistency across models in a given region in order to motivate more detailed analysis, and potential targeted intercomparisons, as the project progresses.

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