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The Global Gridded Crop Model intercomparison: data and modeling protocols for Phase 1 (v1.0)

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Abstract

We present protocols and input data for Phase 1 of the Global Gridded Crop Model Intercomparison, a project of the Agricultural Model Intercomparison and Improvement Project's (AgMIP's) Gridded Crop Modeling Initiative (AgGRID). The project includes global simulations of yields, phenologies, and many land-surface fluxes by 12–15 modeling groups for many crops, climate forcing datasets, and scenarios over the historical period from 1948–2012. The primary outcomes of the project include (1) a detailed comparison of the major differences and similarities among global models commonly used for large-scale climate impact assessment, (2) an evaluation of model and ensemble hindcasting skill, (3) quantification of key uncertainties from climate input data, model choice, and other sources, and (4) a multi-model analysis of the impacts to agriculture of large-scale climate extremes from the historical record.

1 Introduction

Climate change presents a significant risk for agricultural productivity in many key regions, even under relatively optimistic scenarios for near-term mitigation efforts (Rosenzweig et al., 2014). Consistent global scale evaluation of crop productivity is essential for assessing the likely impacts of climate change and identifying system vulnerabilities and potential adaptations. Over the last several years, many research groups around the world have developed Global Gridded Crop Models (GGCMs) to simulate crop productivity and climate impacts at relatively high spatial resolution over continental and global extents, with a huge diversity of methodologies and assumptions leading to a wide range of results.

In 2012 and 2013, the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013), led a global Fast-Track climate impact assessment in coordination with the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014) that brought together a group of GGCMs to simulate future crop productivity under various climate change and farm management scenarios (Elliott et al., 2014a; Rosenzweig et al., 2014; Piontek et al., 2014; Nelson et al., 2014). Increased application of crop growth models for global-scale analyses and the wide variation in model assumptions and projected outputs found in the Fast-Track, inspired the launch of the AgMIP GRIDded crop modeling initiative (Ag-GRID) and the Global Gridded Crop Model Intercomparison (GGCMI). We define here the simulation protocol for the first phase of the GGCMI, which is designed to, among other things, enable a comprehensive evaluation of model and ensemble skill – with respect to yield levels, variability, and large-scale extreme events – based on comparisons of simulations and observations over the last several decades.

The GGCMI Phase 1 simulation protocol includes participants that run a number of gridded crop models (listed with contacts and short descriptions in Table 1), driven with consistent inputs based on multiple weather data products (to evaluate uncertainties from weather data) and harmonized management practice data (planting date, growing season length, and fertilizer inputs). The results of these different simulation runs will then be compared to 3 distinct reference data sets derived from census and remote sensing data sources (Ray et al., 2013; Iizumi et al., 2013; FAOSTAT data, 2013). GGCMI is a protocol-based simulation experiment for gridded crop models and is open to participation by any model group that simulates crop productivity at the global scale, including models developed for field-scale application, biogeochemical dynamic global vegetation and land-surface scheme models, empirical-process-based hybrid models, and purely empirical models.

In the modeling protocol presented here, we describe the simulation experiments and priorities, central inputs provided to modelers, required outputs to be provided by modelers, and data format conventions. GGCMI protocols are designed to overlap as much as possible with and contribute to the refinement of the modeling protocols of the next phase of ISI-MIP (ISI-MIP2). Modelers participating in GGCMI can directly participate in ISI-MIP2 if they so desire.

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2 Simulation experiments, models, and objectives

The primary goals of Phase 1 of the GGCMI are:

1. intercomparison of models with and without harmonized inputs and assumptions, and with and without explicit nitrogen stress;
2. evaluation of model and ensemble skill over the historical period;
3. detailed characterization of important uncertainties, such as weather data and management systems, in historical crop yield assessment; and
4. multi-model, multi-forcing analysis of the impacts to agriculture of large-scale extremes (primarily drought and heat events) in the historical record.

Groups are asked to simulate agricultural production for various crops under purely rain-fed as well as fully irrigated conditions for different driving input data sets on weather and management. To avoid overtaxing of modeling groups, we define simulation priorities to facilitate central analyses with an as broad as possible group of GGCMs as well as additional analyses of more specific questions, such as the performance of crop models for crops beyond wheat, maize, rice, soy, and the influence of weather data uncertainty on model performance.

2.1 Crops and management systems to simulate

We define a two-tiered priority structure that takes into account both the crops that are most important for questions of (primarily global) food security and economics, and the crops that are most commonly simulated in available models. The three main cereal crops (maize, wheat, and rice) alone account for about 43 % of total food energy intake (FAOSTAT data, 2013). Along with soybean, which is the largest single source of oilseeds globally and an essential source of protein and animal feed, these crops have been the focus of most crop yield and climate impact modeling work, and are generally simulated by all the models participating in GGCMI. Thus, we define them as our Priority-1 crops, representing the minimum set for our analyses (Table 2). Many other crops are important staple food, feed, or energy crops in economically or climate-sensitive regions, and most contributing models within GGCMI do simulate one or more of these secondary (or Priority-2) crops. In order to consider as many crops as possible, we ask modelers to supply data on all crops that they can simulate, and consider any crop simulated by at least three models as valid for a multi-model intercomparison analysis. The participating models cover a broad range of annual crops as well as managed grassland, but provide no modeling capacities for perennial crops (Table 2).

We define three distinct types of model configurations (Table 3) for the simulations in Phase 1. First, each group is to develop their own "default" configuration based on the assumptions and inputs they typically use for simulations in the historical period. Each group must also prepare a "harmonized" configuration using input data, parameters, and definitions provided by the GGCMI coordinators. Finally, each model that considers nitrogen (whether with explicit fertilizers or an empirical calibration) is also to be run in a configuration without nitrogen stress, "harmnon", to allow for direct comparison with models that do not explicitly consider the nitrogen cycle. For the purposes of various analyses, especially in the context of so-called yield gaps, we define the "hamrnon_firr", which has zero (or near-zero) stress from both nitrogen and water, as "potential yield."

All modelers are asked to simulate all crops across the globe, irrespective of current cropping areas for purely rain-fed as well as irrigated conditions. This approach allows for addressing uncertainties in assumed distributions of cropland in post-processing analysis. The minimum spatial extent of historical simulations is current agricultural land, and we require that all crops be simulated on all agricultural lands, rather than just on the land where they are currently grown.

We assume that irrigated systems are not limited by freshwater availability and have no water losses during conveyance and application. While the latter assumption has no implications for crop growth, it helps to make reported irrigation water quantities comparable across models.

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Table 4 summarizes the outputs requested from GGCMI simulations. We require that all models provide two central outputs, dry matter equivalent crop yield and (for irrigated scenarios) total irrigation water requirements. Due to the unique characteristics of different models, few other output variables are available to be contributed by all groups. Rather than limit the project only to those variables that are universally produced (crop yields and applied irrigation water), we list in Table 4 many additional optional outputs that are to be provided as possible. These optional outputs include, for example, aboveground biomass, accumulated water applied and transpired, accumulated nitrogen applied and lost through leaching, key phenological dates, and growing season climate characteristics. This approach will facilitate better analyses and interpretation of results and will allow GGCMI participants to further leverage the archives for scientific deliverables and overall project impacts.

We ask that modelers archive model versions used for the simulations and all primary outputs generated, in order to allow for reproducibility and facilitate extraction of additional or more detailed (e.g., higher temporal resolution) data that may be found to be necessary for analyses not yet planned.

As far as possible for the models, all modelers should supply yield and irrigation water amounts for at least the four main crops: wheat, maize, rice and soy (Table 2). Simulations should be conducted for default and harmonized management assumptions as well as for different weather data sets. If modeling capacities are constrained, modelers should supply at least the four priority 1 crops (Table 2) and selected weather-management combinations to allow for a comprehensive model intercomparison across a limited set of scenarios and for analyses of input and assumption uncertainties with those models that contributed (Table 5). *Priority 1* denotes the minimum simulations required for participation unless model capacities do not allow for covering the full spectrum of priority 1 simulations (e.g., because not all crops are implemented, or because a model requires special weather data inputs).

Priority 2 includes two distinct simulation tracks designed around specific science objectives and expected publications. Simulations in the “climate track” (Priority 2.1)

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are designed to evaluate differences among the forcing products through an agro-climatic lens, enabling assessment of the relative importance of different reanalysis products, bias correction techniques, and target datasets used for bias-correction. The "crop track" (Priority 2.2) will allow us to expand our analysis to crops that have not been studied as thoroughly as the primary four food crops or that are only important regionally or in non-food contexts (such as energy crops). At minimum this expanded set is expected to include managed grass, sugarcane, sorghum, millet, rapeseed, sugar beet, and cassava.

2.2 Conventions for simulation outputs

In order to facilitate analysis, portability, and processing of outputs, results will be collected in compressed, self-describing NetCDF v4 files with consistent and relatively simple data, meta-data, and file-naming conventions described below.

File names: each file must contain a single output variable and be named according to the following convention (see definitions in Table 6):

[*model*]_[*climate*]_[*clim.scenario*]_[*sim.scenario*]_[*variable*]_[*crop*]_[*timestep*]_[*start-year*]_[*end-year*].nc4

For example:

pdssat_watch_hist_default_noirr_yield_mai_annual_1958_2001.nc4

Geographical extent: data must be submitted for the ranges 89.75 to −89.75° latitude, and −179.75 to 179.75° longitude. Thus, each file will contain 360 rows and 720 columns for a total of 259 200 grid cells. All ocean grid cells must be filled with the fill value (Table 7). Modelers need not simulate Greenland, the Arctic, or Antarctica but must submit output completely filled for the entire range from latitude 89.75 to −89.75. Output data must be reported row-wise starting at 89.75 and −179.75, and ending at −89.75 and 179.75. As is standard in NetCDF files, latitude, longitude and time must be included as variables in each file explicitly defining their extent.

Date reporting convention: the analysis of inter-seasonal variability of crop yields is complicated by reporting conventions involving the assignment of reported production

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to calendar years. This issue is especially problematic in the Southern Hemisphere, where harvest sometimes occurs in a window around 31 December so that assignment to calendar years based on the harvest date gives double harvests (e.g., one in early January and the next in late December of the same calendar year) in some years and no harvest in others. The data reporting convention for GGCMI thus is not calendar year but growing season based. That is, results are to be reported as a sequence of growing seasons, irrespective of whether that growing season actually spans two calendar years or if harvests occur just before or just after 31 December. Cumulative growing season variables as e.g., actual evapo-transpiration or precipitation are to be accumulated over the growing season, again irrespective of any calendar year definitions, and are to be reported in the same sequence as the harvest events (yield, above ground biomass). The unit of the time dimension of the NetCDF v4 output file is thus "growing seasons since 1 January YYYY 00:00:00" (Table 7). The first season in the file (with value time=1) is then the first *complete* growing season of the time period provided by the input data without any assumed spin-up data, which equates to the growing season with the first planting after this date. This convention roughly corresponds to an annual reporting scheme but allows for a better separation and analysis of outputs. The artificial separation of harvest seasons into two different calendar years may, however, also be present in observational data and may complicate evaluation of model skills in these regions anyway.

3 Central input data

In order to ensure comparability of simulation results across models and to investigate the importance of uncertainties with respect to weather and management data, we supply central input data to all participating modelers. The GGCMI Phase 1 protocols include a set of assumptions, definitions, and input data products that will be used to harmonize participating models as closely as possible in the *fullharm* and *harm-non* configurations (Table 8). During project pre-planning we have established data

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sharing arrangements with leading agricultural data groups that will contribute global high-resolution crop-specific data on key management inputs covering sowing dates, growing season length, fertilizer application rates (including nitrogen, phosphorus, and potassium), manure use, and historical atmospheric CO_2 concentration. We will also harmonize a set of definitions and parameter choices among models, ensuring that output data is directly comparable to the greatest extent possible.

3.1 Weather data inputs

In total we will use six historical retrospective-analysis-based forcing datasets (bias-corrected at monthly time-scales against observational products such as CRU and GPCC) and two raw (non-bias-corrected) reanalysis products (Table 9). Within the cropping areas of the major crops, these weather products display some uncertainty with respect to mean and variability of weather variables such as temperature (Fig. 1) and precipitation (Fig. 2). For models that require spin-up periods, we will use the Princeton global forcing dataset for years after 1948, and a decade of generic pre-industrial weather for all preceding years. We will also consider two versions of WFDEI, with biases corrected separately using either the GPCC or CRU data as targets, for a total of nine distinct data products and about 350 years of daily data. In total, this collection provides one or more weather data inputs for every year from 1948 to 2012. All products cover the 30 year period from 1980–2009 (which will serve as our primary analysis period) except WATCH (1958–2001) and Princeton (1948–2008).

Different GGCMs can require different weather variables, which are supplied by the different forcing data sets. Models that require weather variables not included in some data products (e.g., long-wave downward radiation, Table 10) should use the equivalent variable from another data set. As weather variables are bias-corrected individually and there is consequently no consistency between the individual variables within one data set, and as all data refer to the historic period, we assume that the errors introduced by this approach are small.

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3.2 Harmonized growing season definitions

We supply harmonized growing season data (planting and maturity dates) for all priority 1 crops (wheat, maize, rice, soybean, see Table 2) plus data for the priority 2 crops barley, cassava, groundnuts, millet, potatoes, pulses, rapeseed, rye, sorghum, sugarbeet, sugarcane, and sunflower. Of the priority 2 crops, we lack information for cotton, while managed grassland is assumed to grow all year round. We compile growing season data from two existing global crop calendars, MIRCA2000[1] (Portmann et al., 2010) and SAGE[2] (Sacks et al., 2010), supplementing those data by a rule-based approach as implemented in LPJmL[3] (Waha et al., 2013) to provide as much coverage of the global land surface as possible.

3.2.1 Methodology

We use data from two global cropping calendars, MIRCA2000 (Portmann et al., 2010) and SAGE (Sacks et al., 2010) for current cropping regions (or administrative units with cropping activity). To fill areas not covered by MIRCA2000 and SAGE, we use the planting and harvest dates as computed by LPJmL (Waha et al., 2012) as implemented for the ISI-MIP Fast-Track (Müller and Robertson, 2013; Rosenzweig et al., 2014). Table 11 shows the availability of crops in the crop calendar data sets and the crops used from LPJmL.

MIRCA2000 data supply up to five growing periods per pixel, each with a specific area. For each pixel, we choose the growing period with the largest area. SAGE data supplies median planting and harvest dates as well as beginning and end of

[1]Available for download at ftp://ftp.rz.uni-frankfurt.de/pub/uni-frankfurt/physische_geographie/hydrologie/public/data/MIRCA2000/growing_periods_listed/CELL_SPECIFIC_CROPPING_CALENDARS_30MN.TXT.gz

[2]Available for download at http://www.sage.wisc.edu/download/sacks/netCDF0.5degree.html

[3]Available for download at the ISI-MIP fast-track archive http://esg.pik-potsdam.de

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planting/harvest. We use the median dates. Because MIRCA2000 has monthly resolution only, assuming the first of the month for planting dates and the last of the month for harvest dates, we use SAGE data with daily resolution where available, and MIRCA2000 data only in regions where no SAGE data is available. We ignore MIRCA2000 data if growing seasons are longer than 330 days (e.g., wheat in large parts of Russia), except for sugarcane, which is recorded to grow all year round in MIRCA2000. Finally, we use LPJmL data to fill remaining areas globally with climate-driven rule-based estimates covering a large subset of priority 1 and 2 crops.

To estimate growing season length, we use harvest dates from the same data set selected for planting dates. In order to estimate the maturity date (which characterizes crop varieties) from the harvest date, we correct for crop-specific times between harvest and maturity, assuming that maturity in models refers to the development stage in which the green LAI is zero ("fully ripe"; BBCH code 89)[4]. Where no information on differences between harvest and maturity dates could be found, we assume no difference (Table 11 contains details by crop).

In regions where neither crop calendar supplies data, we use simulated phenology from LPJmL. Here, we mask planting dates as unreasonable if planting in cool regions occurs before day 90 or after day 274 in the Northern Hemisphere or between days 152 and 304 in the Southern Hemisphere. We define *cool regions* as those in which the annual mean of monthly maximum temperatures according to the WATCH data average for 1991–2000, is only 3 °C above the crop-specific base temperature. In these areas, GGCMI modelers can chose any planting date or skip the simulation as results will not be evaluated. Generally, all anticipated analyses will consider current cropland areas only, for which data is generally available from crop calendars. Data filling with rule-based algorithms is only meant to harmonize assumptions among models and to enable standard all-crops-everywhere simulations.

We also mask harvest dates as unreasonable where crops in regions filled with rule-based LPJmL data do not reach maturity within a prescribed crop-specific maximum

[4]http://en.wikipedia.org/wiki/BBCH-scale_(cereals)

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growing season length, where crops die after less than 60 days, or where planting dates are unreasonable.

If the LPJmL growing season occurs in very hot seasons (defined as those for which Tmax of WATCH data average for 1991–2000 in one of the growing season months is > 38 °C), we assume that the growing season of temperate cereals (barley, rye, wheat) is offset by 6, +3 or −3 months to avoid the heat. Offsets are tested in this sequence and the first that actually reduces maximum monthly temperatures to at least below 36 °C is selected. Avoidance of heat is not part of the rules implemented in LPJmL (Waha et al., 2012) and may imply that corrected sowing happens not during the wettest season. Since these areas are not currently cropped (otherwise there would be crop calendar data), it seems justifiable to correct sowing dates for cooler seasons for harmonized simulation data.

SAGE calendar data are uniform within administrative units. If the SAGE data set suggests that planting in currently unused grid cells would occur in autumn but mean monthly temperatures are already below 5 °C, we correct planting dates for planting of spring varieties. For this correction, we select the first month, starting in January for the Northern Hemisphere and in July for the Southern Hemisphere, in which average monthly temperatures (Tas of WATCH data average for 1991–2000) rise above 5 °C.

The R processing script that we used to generate these data is available in the appendix and in the GGCMI software repository at https://github.com/RDCEP/ggcmi/.

3.2.2 Implementation instructions for growing season dates

GGCMI modelers should implement planting dates per grid cell, per crop, and per irrigation system (purely rain-fed vs. irrigated) either directly or with a given flexibility within model-specific planting windows. In regions in which the harmonized planting dates as supplied here are masked as unreasonable, crop modelers may either set planting dates to any date or simply skip simulations, whatever is easier to implement. These data will not be considered in GGCMI analyses.

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Crop variety parameters (e.g., required growing degree days to reach maturity, vernalization requirements, photoperiodic sensitivity) should be adjusted as much as possible to roughly match reported maturity dates supplied here for the average of the period 1991–2000. In regions in which harvest dates are masked as unreasonable, modelers should parameterize their fastest maturing crop variety as these stand best chances to reach maturity at all.

3.3 Harmonized fertilizer inputs

We supply average annual nitrogen (N-equivalent), phosphorus (P_2O_5-equivalent), and potassium (K_2O-equivalent) application rates (kg ha^{-1} yr^{-1}) for 15 crops and all locations. We supply crop-specific fertilization rates for the Priority 1 crops (Table 1) as well as a broad set of Priority 2 crops (cassava, cotton, groundnut, millet, potato, rapeseed, sorghum, sugarbeet, sugarcane, sunflower) as well as for one perennial crop, coffee. Fertilizer data is based on published data on mineral fertilizers and manure applications (Mueller et al., 2012; Potter et al., 2010; Foley et al., 2011). These data are available for currently cropped areas and have been extrapolated in space to cover the entire land surface.

3.3.1 Methodology

We compiled and harmonized fertilizer data in a four-step procedure. First, we disaggregated manure data to crop-specific application rates. This was done by assigning a proportion of the manure nutrient production from Potter et al. (2010) to croplands as outlined in Foley et al. (2011). Of manure applied to croplands, crop-specific application was determined by dividing manure application in each grid cell between all crops present in the grid cell, in proportion to harvested area of each crop.

We aggregate data from the original five arcminute resolution to the GGCMI simulation grid of $0.5^\circ \times 0.5^\circ$. The political units in the original mineral fertilizer dataset differ for each crop type and cover current crop-specific growing area, up to 473 units for the maize nitrogen fertilizer data (Mueller et al., 2012). Therefore we harmonized the administrative boundary units across crop and nutrient types for the interpolation procedure here. Data on manure application (Potter et al., 2010) have resolution finer than political units, as they are based off a gridded livestock dataset. Thus, the manure nutrient maps were simply aggregated to each of the 372 administrative units as an area-weighted average.

In a third step, we harmonized the reference units between organic and inorganic fertilizers (manure). Original manure data is reported in terms of atomic nitrogen (N) and phosphorus (P) and assumed to contain no potassium (Potter et al., 2010) whereas inorganic fertilizer data is reported as N, phosphate (P_2O_5) and potassium oxide (K_2O). The conversion from P manure to P_2O_5 is based on atomic masses

$$P_2O_5\text{-eq.} = P/31 \cdot (31 \cdot 2 + 5 \cdot 16). \quad (1)$$

Nutrients from manure are generally less available to plants than mineral fertilizers. We assume 60 % of applied N-manure and 75 % of applied P-manure to be plant-available (Rosen and Bierman, 2005).

In the final step, we extrapolated fertilizer application rates to currently uncultivated land. The original data on mineral fertilizers (Mueller et al., 2012) cover only crop-specific harvested areas. First, we assigned the national average nutrient-specific fertilizer rate (area-weighted) to all administrative units that do not apply any mineral fertilizer or manure in the original data but are within a country actually reporting fertilizer application. Second, for all other countries that do not currently apply fertilizer to grow the specific crop, we attributed estimated nutrient-specific application rates by averaging fertilizer application rates over the corresponding income level group. We base income level groups on the World Bank's definition to classify countries by income level: economies are divided according to 2012 GNI per capita, calculated using the World Bank Atlas method (World Bank, 2013). The groups are: low income, USD 1035 or less; lower middle income, USD 1036–4085; upper middle income, USD 4086–12 615; and high income, USD 12 616 or more. We averaged fertilizer application rates for all countries with fertilizer application larger than zero within the income level group and applied those rates to all countries without fertilizer data within that group.

3.3.2 Implementation instructions

All fertilizer data supplied here should be treated as mineral fertilizer; organic fertilizer (manure) has been reduced to account for limited plant-availability and combined with data on inorganic fertilizer applications.

3.4 Data format conventions of input data

All input data is supplied in gridded form at $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution in a compressed NetCDF4 file format. Weather data is available at daily time steps and at 3 hourly values for WFDEI (which is required for some participating land-surface models). Management data is available for only one time period and are assumed to apply for all historic time periods since data is lacking on changes in management over time (all comparisons are done between detrended observation and simulation time-series, which greatly reduces, but certainly does not eliminate the effect of changes management practices and technology over time).

4 Validation datasets and procedures

4.1 Historical yield data

We will use three yield data products at multiple scales to validate our analysis, Iizumi (Iizumi et al., 2013), Ray (Ray et al., 2013), and FAOSTAT (FAOSTAT data, 2013). Iizumi (Fig. 4, left) provides a hybrid of national statistics and satellite derived Normalized Difference Vegetation Index (NDVI) at a nominal resolution of 1.125°, covering maize, soy, wheat, and rice, and spanning 1982–2006. Ray (Fig. 4, right) covers the same four crops using national, sub-national and sub-subnational statistics, spans 1961–2008,

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and is provided at a nominal resolution of five arcminutes by distributing yield statistics from administrative units to grid cells evenly based on the approximate distribution of crop areas in the unit, without any proxy measures of the relative distribution of attained yields. To fill in the gaps of crops and years that are not available in these first two datasets, we will compare aggregated simulation outputs at the national level directly with statistics from FAOSTAT.

4.2 Open-source processing and evaluation pipeline

In order to ensure consistency and encourage consensus in GGCMI products, we are developing all output processing software utilities within an open software repository available at https://github.com/RDCEP/ggcmi/. Additionally, we permanently archive the intermediate and final results of each step in the output processing pipeline on the GGCMI data servers. These data will be made available along with the data supplied by GGCMI modeling groups at the time of public release. The key stages of the pipeline are described in Sects. 4.2.1–4.2.4.

4.2.1 Aggregation

All simulated data is first aggregated up to administrative and environmental boundaries for the purpose of various planned evaluations and analyses, including state/province (GADM[5] level 1), country (GADM level 0), river basins and Food Producing Units (FPUs; river basins crossed with countries (Cai and Rosegrant, 2002)), Koeppen–Geiger climate regions (Peel et al., 2007) (example shown in Fig. 5), and large-scale continental or sub-continental regions.

[5] http://gadm.org/

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4.2.2 Detrending

In order to compare FAOSTAT observations with simulation results, we must remove trends from the statistics. As there are several methods to remove trend from observed data and no one method works best in all situations, we employ four distinct detrending methods: we take the linear or quadratic trends from a least-squares regression (Fig. 6, right), we take a 7 year moving mean trend, and we calculate the fraction first differences, $Y_t / Y_{t-1} - 1$, of the series and remove a linear trend (Fig. 6, right). All conclusions and results are then checked for robustness against all the detrending method used.

4.2.3 Multi-metric validation

GGCMI uses a varied approach to model validation over the evaluation period, comparing reference data and simulations using a number of metrics and methodologies. In preliminary analysis, metrics evaluated include the time-series correlation, root-means-square error, ratio of simulated and observed coefficients of variation, and the top and bottom hit-rates (number of years in the top and bottom quintile of the observation series that are reproduced in the simulated series). The metrics are formalized in the output processing pipeline in a set of multi-dimensional metric files, which are provided along with a plotting application that produces 2-dimensional cross-sections by selecting, averaging, or optimizing over any combination of dimensions (an example array is shown in Fig. 7).

4.2.4 Multi-model ensembles

In a final processing step, we aim to produce multi-model ensemble versions of the output to evaluate, for example, how well the ensemble performs relative to individual models, highlighting individual model skill and deficiencies vs. model community skills and deficiencies. This step uses the multi-metrics files to produce versions of the simulated

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variables that aggregate all the models into various combinations. Ensembles range in complexity from simple averages (all models weighted equally) to weighted averages using one or more evaluation metric, and from all models included in the average to the inclusion of only the top-performing model. Finally, we produce evaluation multi-metric files for the ensemble combinations to easily facilitate comparison of the ensemble measures with individual models. This will be the basis for identifying central processes in models that are responsible for differences in model performance as well as general model deficiencies that require improvements in all models and in understanding. This phase will likely require additional simulations with modified models.

5 GGCMI data archive and crediting

GGCMI computing and data services are housed at the University of Chicago Research Computing Center (RCC) and the German Climate Computing Center (DKRZ). GGCMI will host an archive of all project inputs and outputs and will work continuously with research and stakeholder communities to improve archive access and usability. During each phase of the project (i.e. before public launch of the resulting archive), all inputs and outputs generated belong to the GGCMI as a team (i.e., all GGCMI modelers) and must not be used, distributed, presented, or published in any individual or selected study without the consent of the group of contributing GGCMI modelers. During this time, presentations and publications will be led by GGCMI team members and will be coordinated through the GGCMI coordinators. The publications must acknowledge each individual contribution, including providers of not publicly available input or reference data, via co-authorship or other agreed acknowledgement.

Because GGCMI acts as the sectoral coordinator for crop modeling in phase 2 of the ISI-MIP project (ISI-MIP2), we have designed the GGCMI protocols to overlap with (planned) ISI-MIP2 simulations as closely as possible. Upon the data submission deadline as defined by ISI-MIP2, GGCMI data will automatically be transferred to ISI-MIP2, unless otherwise specified by participating modelers. At this time, GGCMI modelers

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become ISI-MIP2 participants and additional restrictions or specifications for data availability, as negotiated between ISI-MIP2 and GGCMI coordinators and modelers, may apply at this time.

6 Discussion

The core outcome of GGCMI is the creation and maintenance of an international community of modelers focusing on climate impacts and relationships to food security, resources, economics, land-use change, and climate feedbacks at continental and global scales. As has been amply demonstrated in processes like CMIP (Taylor et al., 2012), the Energy Modeling Forum (Weyant et al., 2006), AgMIP projects such as the wheat pilot (Asseng et al., 2013), and the ISI-MIP fast-track recently completed (Warszawski et al., 2014; Rosenzweig et al., 2014; Elliott et al., 2014a; Nelson et al., 2014), the bringing together of modelers working independently on complex dynamic phenomena to compare and synthesize outputs can generate substantive insights and innovations that are not generally possible otherwise. A key observation from the AgMIP/ISI-MIP Fast-Track and other recent model intercomparisons (Rosenzweig et al., 2014; Nelson et al., 2014; Challinor et al., 2014), and a key motivation for GGCMI, is the importance of harmonization on input data and assumptions.

We intend that during GGCMI's three year duration, the community will create a new standard for research on global change vulnerabilities, impacts, and potential adaptations. Data products, analyses and insights are to be published in peer-reviewed scientific journals and will thus be accessible to the scientific community. Due to the open and accessible structure of the project and its data distribution architecture, we expect important scientific outcomes and deliverables to evolve and develop during and well beyond the planned project lifetime. GGCMI leverages, and relies on, the contributions of many partners that typically lack funding for this project. However, the tremendous enthusiasm that this project has generated among participants and user communities makes us confident that GGCMI will succeed in its stated goals – and, with high

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likelihood, greatly surpass those goals. In addition, close partnership with the AgMIP and ISI-MIP networks, and the active participation of leaders from those groups, will help ensure that GGCMI is highly visible within and beyond the scientific community. The GGCMI team will also work with potential end-users to facilitate usage of GGCMI results downstream in economic models and global and regional integrated assessments. For this purpose we are developing several use cases for the existing fast-track archive (Nelson et al., 2014) and working with economic modeling communities such as EMF and GTAP[6] and actively seek funding for GGCMI activities and cooperation with other groups.

The standardized, protocol-based model intercomparison described here will be the basis for a clear analysis of model skills and deficiencies, identification and reduction of crop model uncertainties, and identification of future development paths to improve models and assessments. Clearly, more work than is envisioned here is needed in analyzing and improving crop modeling skills for gridded large-scale applications. Still, the first phase of GGCMI will provide a solid basis for future work by providing not only standardized inputs and reference data but also open-access data processing and analysis tools. During this first part of the project, we expect that key conditions for the next phase of analysis will take shape, by identifying the main sources of uncertainty and model-disagreement. We hope to support all large-scale crop modeling efforts with the insights and analysis tools that are produced in GGCMI, and we invite all agricultural scientists to contribute to the development and framing of the next phases of the project and protocols.

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[6]https://www.gtap.agecon.purdue.edu/

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Table 1. Models and groups engaged thus far for GGCMI.

Model	Lead Institution	Contact(s)	Model type and notes
pDSSAT[a,c,d]	U of Chicago, USA	jelliott@ci.uchicago.edu	Site-based process (Elliott et al., 2014b) (DSSAT v4.5, Jones et al., 2003)
EPIC-Boku[b,c,d]	Boku, Austria	erwin.schmid@boku.ac.at	Site-based process (EPIC v0810) (Balkoviè et al., 2013)
GEPIC[b,c,d]	EAWAG, Switzerland	folberth@iiasa.ac.at	Site-based process (EPIC v0810) (Liu et al., 2007)
pAPSIM [a,d]	U of Chicago, USA	jelliott@ci.uchicago.edu	Site-based process (APSIM v7.5) (Elliott et al., 2014b; Keating et al., 2003)
EPIC-IIASA[b,d]	IIASA, Austria	khabarov@iiasa.ac.at	Site-based process (EPIC v0810) (Balkoviè et al., 2013)
EPIC-TAMU[b,d]	TAMU and UMD, USA	cizaurra@umd.edu	Site-based process (EPIC v1102) (Izaurralde et al., 2006)
CropSyst[e]	WSU, USA	stockle@wsu.edu	Site-based process (Stöckle et al., 2003)
DAYCENT[e]	Colorado State, USA	dennis.ojima@colostate.edu	Site-based process (Stehfest et al., 2007)
LPJmL[c]	PIK, Germany	cmueller@pik-potsdam.de	DGVM (Bondeau et al., 2007; Müller and Robertson, 2014)
ORCHIDEE	IPSL, France	nathalie.de-noblet@lsce.ipsl.fr	DGVM (de Noblet-Ducoudre et al., 2004)
LPJ-GUESS[c]	KIT, Germany	almut.arneth@kit.edu	DGVM (Lindeskog et al., 2013; Smith et al., 2001)
JULES-crop[e]	Met Office, UK	pete.falloon@metoffice.gov.uk	DGVM (Van den Hoof et al., 2011)
CLM-Crop	LBNL, USA	adjones@lbl.gov	DGVM (Levis et al., 2012; Drewniak et al., 2013)
PEGASUS[c]	Tyndall, UEA, UK	d.deryng@uea.ac.uk	Empirical/process (Deryng et al., 2011, 2014)
GLAM[e]	SEE, Leeds, UK	a.j.challinor@leeds.ac.uk	Empirical/process (Challinor et al., 2004)
CGMS	WUR, NL	allard.dewit@wur.nl	Empirical/process (WOFOST) (van Diepen et al., 1989; Supit et al., 1994)
PRYSBI-2	NIAES, Japan	iizumit@affrc.go.jp	Empirical/process (Okada et al., 2011)
MCWLA [e]	IGSNRR, China	taofl@igsnrr.ac.cn	Empirical/process (Tao and Zhang, 2012)

[a] pDSSAT and pAPSIM are both part of the pSIMS framework, using inputs and assumptions as closely harmonized as is possible, allowing for a more direct comparison of inter-model differences.
[b] Four contributing GGCMs are built from the field-scale EPIC model and will be used for detailed explorations of the effects of different assumptions and configurations even within the same model.
[c] Model participating in the 2012/2013 AgMIP/ISI-MIP Fast-Track.
[d] EPIC, DSSAT, and APSIM-based models will perform additional scenarios using alternative methods to model evapotranspiration in order to better understand the effect this important model choice has on assessments.
[e] Models expected to participate starting in Phase 2.

Table 2. Priority 1 and 2 crops in phase 1.

Priority	Crops	Labels	# models	Notes
1	Wheat, maize, soy, rice	whe, mai, soy, ric	15–20	Required for all objectives
2	All others: managed grass[a], sugarcane, sorghum, millet, rapeseed, sugar beet, barley, cassava, field peas, sunflower, groundnuts, drybean, cotton, potato	mgr, sug, sor, mil, rap, sgb, bar, cas, pea, sun, nut, ben, cot, pot	Based on availability (> 2)	Priority 2 crops will be considered case-by-case (require at least 3 model submissions)

[a] We consider only managed grassland productivity, not unmanaged pasture.

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Table 3. General simulation configurations for phase 1.

Config	Long name	Description
Default	Default configuration	Simulations using default "best guess" choices for all inputs.
fullharm	Fully harmonized configuration	Simulations using harmonized inputs and assumptions.
harmnon	Harmonized with no nitrogen	Harmonized inputs with no nitrogen stress.

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Table 4. Output variables to be collected during GGCMI Phase 1. The first two variables are to be provided by every model; other variables are to be provided as possible by each model.

Variable	Variable name[a]	Units (and notes)
Mandatory variables to be provided for all simulations		
Crop yields	yield_< crop >	$\mathrm{t\,ha^{-1}\,yr^{-1}}$ (dry matter)
Applied irrigation water	pirrww_< crop >	$\mathrm{mm\,yr^{-1}}$ (firr only, assume loss-free conveyance/application)
Additional variables below are to be provided as possible by each model		
Total Above ground biomass yield	biom_< crop >	$\mathrm{t\,ha^{-1}\,yr^{-1}}$
Actual growing season evapotranspiration	aet_< crop >	$\mathrm{mm\,yr^{-1}}$ (season only)
Actual planting date	plant-day_< crop >	day of year
Days from planting to anthesis	anth-day_< crop >	days from planting
Days from planting to maturity	maty-day_< crop >	days from planting
Nitrogen appl. Rate	initr_< crop >	$\mathrm{kg\,ha^{-1}\,yr^{-1}}$
Nitrogen leached	leach_< crop >	$\mathrm{kg\,ha^{-1}\,yr^{-1}}$
Nitrous oxide emissions	sn2o_< crop >	$\mathrm{kg\,N_2O-N\,ha^{-1}}$
Accumulated precip, plant to harvest	gsprcp_< crop >	$\mathrm{mm\,ha^{-1}\,yr^{-1}}$ (season only)
Growing season incoming solar	gsrsds_< crop >	$\mathrm{W\,m^{-2}\,yr^{-1}}$ (season only)
Sum of daily mean temps, planting to harvest	sumt_< crop >	$\mathrm{^{\circ}C\,days\,yr^{-1}}$ (season only)

[a] < crop > refers to the three-letter variable codes (whe, mai, ric, etc.) from Table 2.

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Table 5. Simulation priorities for phase 1. For climate product descriptions see Table 9.

Priority	Crops	Climate product	Scenarios	Goal
Priority1	P1	WFDEI.GPCC, AgMERRA	*Default*, *fullharm*, *harmnon*	Establish key minimal yield estimates and comparisons
Priority 2	P1	WATCH.GPCC, PGF, GRASP, AgCFSR	*fullharm*	Extend range of years and characterize uncertainty due to multiple forcing products.
2.1 Climate track	P1	WFDEI.CRU, ERA-I and CFSR	*fullharm*	Evaluate the effects of different drivers (pure reanalysis, GPCC vs. CRU target for bias-correction, etc.)
2.2 Crop Track	P2	WFDEI.GPCC, AgMERRA	*fullharm*	Evaluate other crops that have a sufficient number of models and interest.

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Table 6. Filename conventions for standardized model outputs.

Filename tag [ ]	Values
[model]	pdssat, epic-iiasa, lpjml, etc. (see Table 1)
[climate]	watch, wfdei.gpcc, wfdei.cru, grasp, agmerra, agcfsr, Princeton (see Table 9)
[clim.scenario]	Hist
[sim.scenario]	default_firr, fullharm_noirr, etc. (see Table 3)
[variable]	yield, pirrww, plant-day, anth-day, etc. (see Table 4)
[crop]	mai, soy, whe, ric, mil, sor, etc. (see Table 2)
[timestep]	annual
[start-year]_[end-year]	1958_2001, 1980_2009, 1980_2010, etc. (see Table 9)

Table 7. NetCDF file dimension, variable, and attribute info.

Dimension/variable	Fill value	# type	Units	Range
lon	NA	double	degrees east,	−179.75 ... 179.75
lat	NA	double	degrees north	89.75 ... −89.75
time	NA	double	"growing seasons since 1 Jan YYYY 00:00:00" (YYYY varies, see Table 9)	1 ... T (T varies, see Table 9).
[variable]_[crop]	1.e+20f	Float	Varies (see Tables 2 and 4).	Varies

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Table 8. Harmonized input variable sources for *fullharm* and *harmnon* configurations in Phase 1.

Variable	Source	Units	Notes
Planting window	(Sacks et al., 2010; Portmann et al., 2008, 2010) & environment-based extrapolations	Julian days (1 Jan = 1,...)	Crop calendar data (planting and maturity) for primary seasons.
Approximate maturity	(Sacks et al., 2010; Portmann et al., 2008, 2010) & environment-based extrapolations	Days/GDD from sowing	Growing season length provided in number of days.
Fertilizers and manure	(Mueller et al., 2012; Potter et al., 2010; Foley et al., 2011)	$kg\,ha^{-1}\,yr^{-1}$	Average nitrogen, phosphorus, and potassium application rates in each grid cell.
Historical [CO_2]	Mauna Loa/RCP historical	ppm	Annual and monthly [CO_2] values from 1900–2013.
Definition of time variable	Protocol choice	"growing seasons since 1 Jan YYYY"	YYYY is just the first year in the file. For a run 1958–2001, YYYY = 1958. Values of time are independent of how to map growing season to calendar.
Season Definition	Protocol choice	Definition	AET and PirrWW defined as accumulated over the growing season, not over the calendar year.
Automatic irrigation	Guidance for parameter choices	Definition	Management depth = 40 cm/Efficiency = 100 % Lower event trigger threshold = 90 % Max single AND annual volume = Unlimited
Automatic planting	Guidance for parameters choices	Definition	Min/max soil H_2O at planting (40 cm) = 40/100 % Min/max soil temp at planting (10 cm) = 10/40 °C

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Table 9. Historical climate forcing datasets for Phase 1.

Dataset	Reanalysis	Years	Resolution*	Bias correction target	Notes
WATCH	ERA-40	1958–2001	2.5° (0.5°)	GPCC	WATCH forcing data v1 (Weedon et al., 2011)
WFDEI	ERA-Interim	1979–2009	0.75° (0.5°)	GPCC and CRU as separate versions	Versions with different bias target are denoted WFDEI.GPCC and WFDEI.CRU (Weedon et al., 2011)
GRASP	JRA-25 & ERA-40	1961-2010	1.125° (1.125°)	CRU-TS3.10, CL1.0 wind, SRB solar	Mean/max/min 2 m temp, precip, solar, vap pres., 10 m wind (Iizumi et al., 2014)
AgMERRA	MERRA	1980–2010	0.5° × 0.66° (0.5°/0.25°)	CRU/GPCC/UDel/ SRB/Satellite precip	Precip: CMORPH, PERSIANN, TRMM. Out: Tmax/min, precip, solar, RHS@Tmax, wind (Ruane et al., 2014)
AgCFSR	CFSR	1980-2010	0.3°(0.5°/0.25°)	Same as AgMERRA	Same target as AgMERRA (Ruane et al., in review)
Princeton GF	NCAR Reanalysis1	1948–2008	2.8° (0.5°)	CRU/GPCC/SRB/ TMPA	TMPA: TRMM Multi-satellite Precipitation Analysis (Sheffield et al., 2006)
Pure reanalysis products (for evaluation of the effects of bias-correction)					
CFSR	CFSR	1979–2012	0.3° (N/A)	N/A	Pure reanalysis (Saha et al., 2010)
ERA-I	ERA-I	1979–2012	0.75° (N/A)	N/A	Pure reanalysis (Dee et al., 2011)

* This denotes the resolution of the underlying reanalysis dataset (and in parentheses the typical resolution of the key target data, temp and precipitation, used in the bias correction). All datasets will be standardized to a 0.5 x 0.5 degree spatial resolution in the GGCMI archives.

Table 10. Weather variables supplied per data set.

Variable	long name	Unit	WATCH	WFDEI	GRASP	AgMERRA	AgCFSR	PGF	CFSR	ERA-I	Notes
tas	daily mean temperature	°C	x	x	x	x	x	x	x	x	
tasmin	daily min temperature	°C	x	x	x	x	x	x	x	x	
tasmax	daily max temperature	°C	x	x	x	x	x	x	x	x	
pr	daily avg precip flux rate	$Kg\,m^{-2}\,s^{-1}$	x	gpcc (2010) cru (2012)	x	x	x	x	x	x	(incl. snow)
rsds	short wave downward	$W\,m^{-2}$	x	x	x	x	x	x	x	x	
rlds	long wave downward	$W\,m^{-2}$	x	x	NA	NA	NA	x	x	x	
wind	wind speed	$m\,s^{-1}$	x	x	x	x	x	x	x	x	
hur	relative humidity	%	x	x	x	at Tmax & Tavg	at Tmax & Tavg	*	x	*	
hus	specific humidity	$kg\,kg^{-1}$	x	x	NA	NA	NA	x	NA	x	
vap	vapor pressure	Pa	*	*	x	*	*	*	*	*	
ps	surface pressure	Pa	x	x	NA	NA	NA	x	NA	x	

x These variables are directly provided by the climate data provider.
* These variables are not directly provided but can be calculated using standard relationships (Bolton, 1980) which we implement in GGCMI.
NA These variables are not available from the given dataset.

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Table 11. Combination of crop calendar data in GGCMI data sets.

GGCMI crop	MIRCA2000	SAGE	LPJmL	Days maturity to harvest
Barley	Barley	Barley standard + winter	Wheat	7[a]
Cassava	Cassava	Cassava	Cassava	assuming 0[b]
Groundnuts	Groundnuts	Groundnuts	Groundnuts	0[c]
Maize	Maize	Maize	Maize	1–28[d] here 21
Millet	Millet	Millet	Millet	assuming 0
Potatoes	Potatoes	Potatoes	Sugarbeet	assuming 0
Pulses	Pulses	Pulses	Pulses	assuming 0
Rapeseed	Rapeseed	Rapeseed, winter	Rapeseed	same as wheat = 7
Rice	Rice	Rice	Rice	0[e] or 8–12[f], here 7[a]
Rye	Rye	Rye, winter	Wheat	7[a]
Sorghum	Sorghum	Sorghum	Millet	0[g]
Soybean	Soybean	Soybean	Soybean	7–21[h] here 21
Sugarbeet	Sugarbeet	Sugarbeet	Sugarbeet	assuming 0
Sugarcane	Sugarcane	NA	Sugarcane	assuming 0
Sunflower	Sunflower	Sunflower	Sunflower	0[i]
Wheat	Wheat	Wheat, standard + winter	Wheat	3[j] to 8[k] here 7

[a] Assuming quick harvests for barley, rice, rye and wheat as they are all threatened by pre-harvest sprouting, see e.g., http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/445636/farrer_oration_1981_nf_derera.pdf but allowing some time to dry after full maturity.
[b] Can be anything from 0 days to up to 6 months, harvest on demand.
[c] http://www.interaide.org/pratiques_old/pages/agro/3cultures/Phalombe_Mlwi_crop_management_2010.pdf, p. 8;
[d] http://www.smartgardener.com/plants/4159-corn-cherokee-white-flour/harvesting;
[e] http://agris.fao.org/agris-search/search/display.do?f=1990%2FPH%2FPH90013.xml%3BPH8811720;
[f] http://www.interaide.org/pratiques_old/pages/agro/3cultures/Phalombe_Mlwi_crop_management_2010.pdf, p. 13;
[g] http://www.interaide.org/pratiques_old/pages/agro/3cultures/Phalombe_Mlwi_crop_management_2010.pdf, p. 14;
[h] http://agris.fao.org/agris-search/search/display.do?f=2009%2FJP%2FJP0932.xml%3BJP2009005739;
[i] http://www.interaide.org/pratiques_old/pages/agro/3cultures/Phalombe_Mlwi_crop_management_2010.pdf, p. 12;
[j] http://agris.fao.org/agris-search/search/display.do?f=2009%2FJP%2FJP0938.xml%3BJP2009007527;
[k] http://www.dwd.de/bvbw/appmanager/bvbw/dwdwwwDesktop?_nfpb=true&_windowLabel=T94008&_urlType=action&_pageLabel=_dwdwww_klima_umwelt_phaenologie shows that there is 16 days between "hard dough" stage (BBCH87) and harvest in Germany, and http://www.dwd.de/bvbw/generator/DWDWWW/Content/Landwirtschaft/Dokumentation/AgroProg/Kornfeuchte,templateId=raw,property=publicationFile.pdf/Kornfeuchte.pdf shows that there are about 8 days between "hard dough" and "fully ripe" (BBCH89) stages, so that the difference between "fully ripe" and harvest is 8 days as well.

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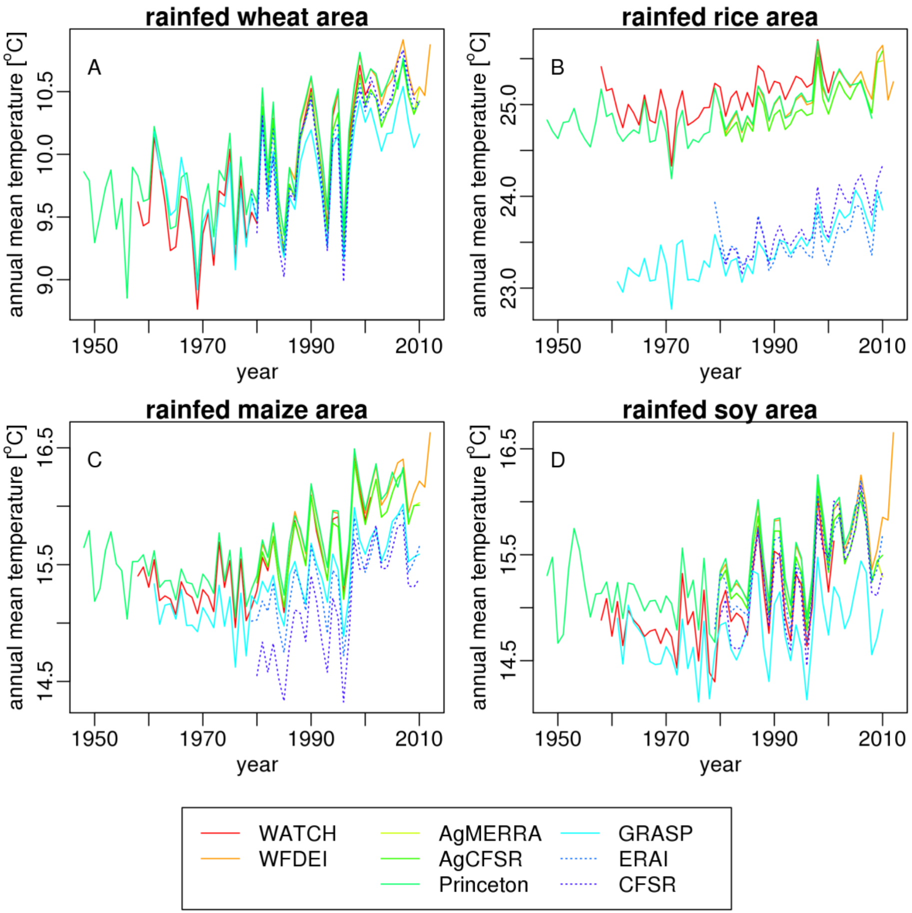

Figure 1. Area-weighted mean of annual temperatures [°C] for cropping areas for rain-fed wheat **(A)**, rice **(B)**, maize **(C)**, and soy **(D)**.

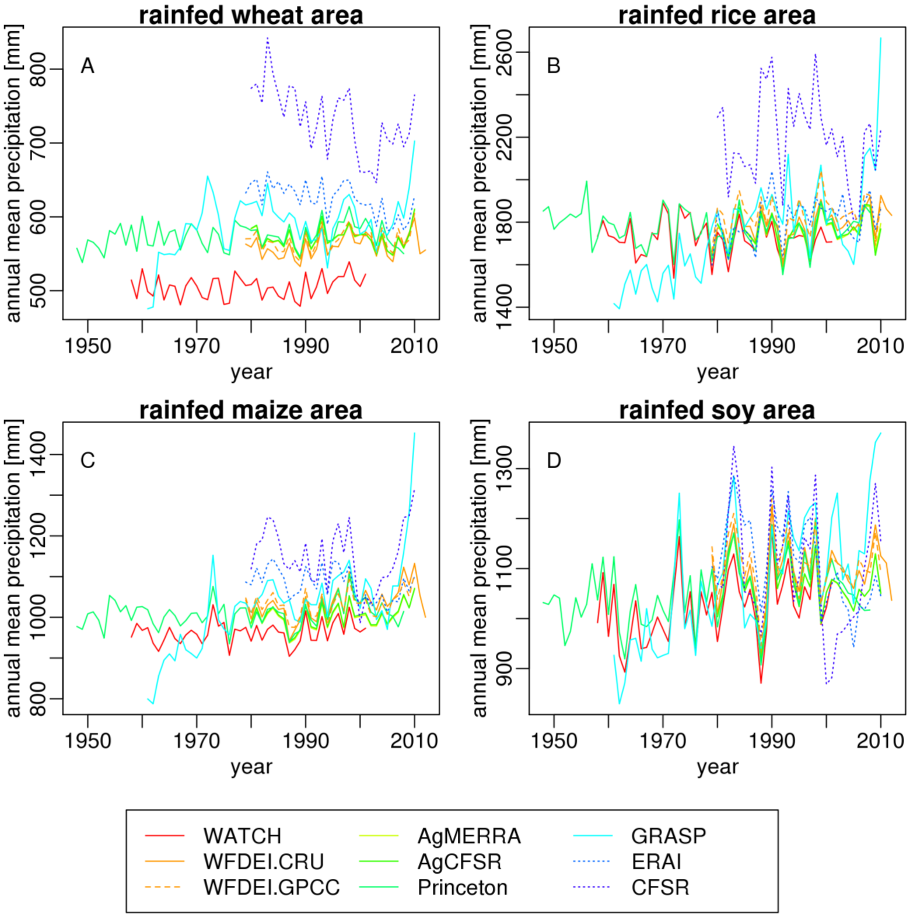

Figure 2. Area-weighted mean of annual precipitation [°C] for cropping areas for rain-fed wheat **(A)**, rice **(B)**, maize **(C)**, and soy **(D)**.

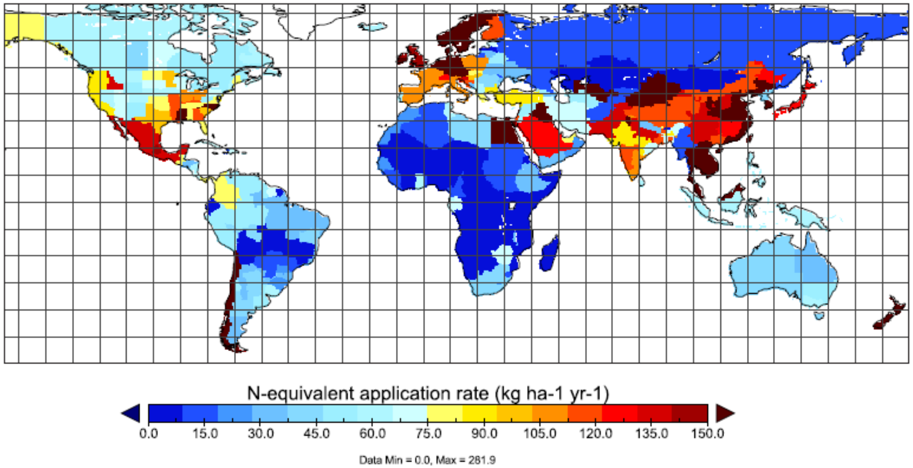

Figure 3. N-equivalent application rate of nitrogen fertilizers for the production of wheat.

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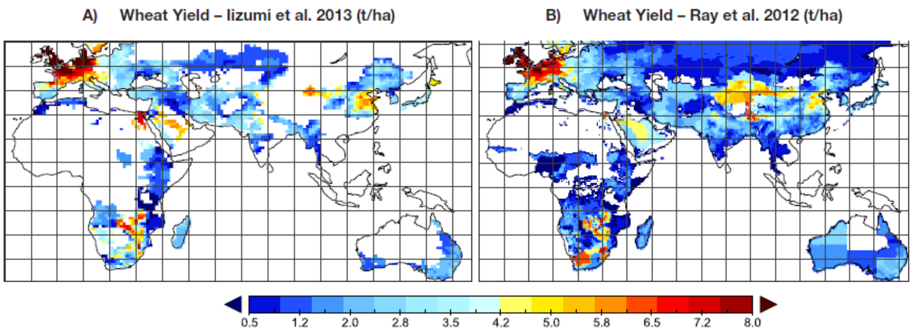

Figure 4. Example of historical validation data for year 2000 wheat yields from **(A)** Iizumi et al. (2013) (at 1.125° spatial resolution) and **(B)** Ray et al., 2012 (aggregated from 5 arcmin to 0.5°).

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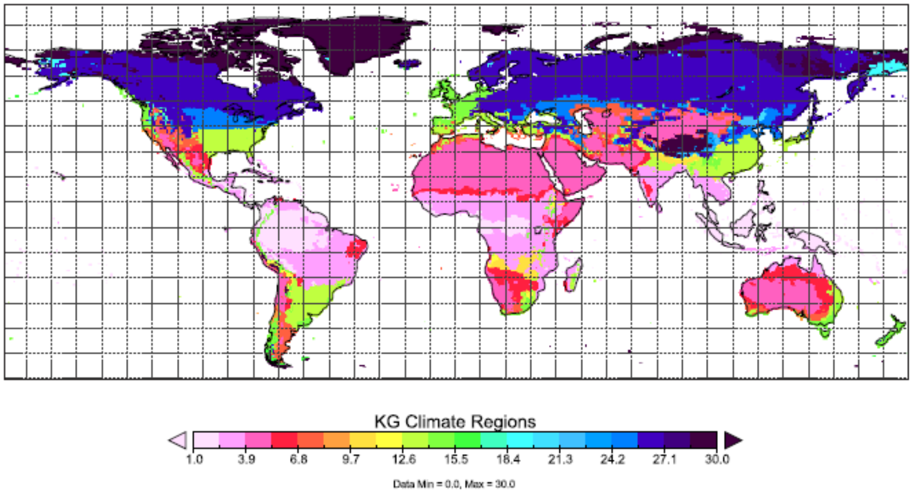

Figure 5. Example of a global Koeppen–Geiger climate classification.

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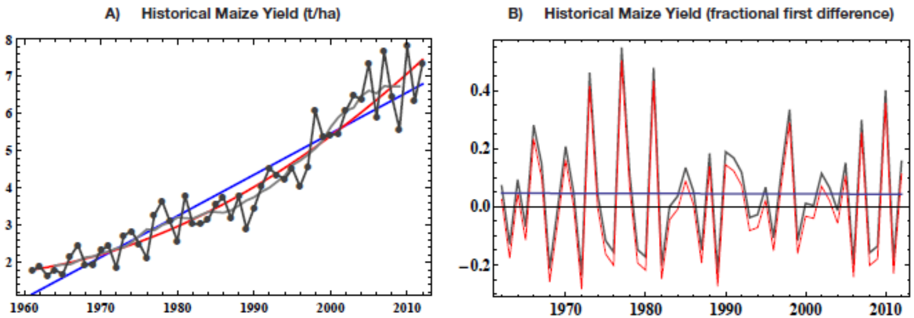

Figure 6. (A) FAOSTAT yield for maize in Argentina (solid line and points) with the linear (blue) and quadratic (red) best-fits and 7 year moving average (gray). **(B)** Fractional first difference of maize yields in Argentina (gray), the linear trend (blue line) and the fractional first difference with the trend removed (red).

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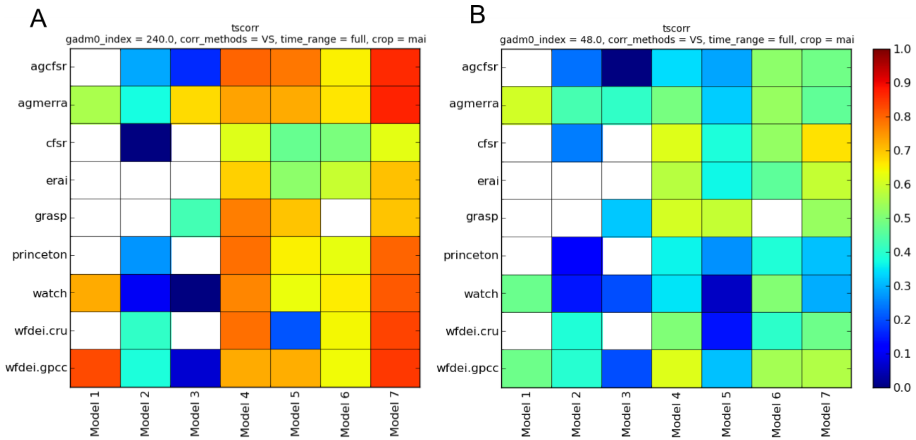

Figure 7. Examples of cross-sections of the multi-metric validation array for the top two maize-producing countries – the United States **(A)** and China **(B)**. Plot shows time-series correlations for 7 different crop models run (x axis) with 9 different climate forcing datasets (y axis). For each model/climate combination the best metric value among the scenarios (default, fullharm, and harmnon) and detrending methods (linear, quadratic, moving mean, and trend-removed fraction first difference) are shown.

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