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A high-yielding traits experiment for modeling potential production of wheat: field experiments and AgMIP-Wheat multi-model simulations

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Abstract: Grain production must increase by 60% in the next four decades to keep up with the expected population growth and food demand. A significant part of this increase must come from the improvement of staple crop grain yield potential. Crop growth simulation models combined with field experiments and crop physiology are powerful tools to quantify the impact of traits and trait combinations on grain yield potential which helps to guide breeding towards the most effective traits and trait combinations for future wheat crosses. The dataset reported here was created to analyze the value of physiological traits identified by the International Wheat Yield Partnership (IWYP) to improve wheat potential in high-yielding environments. This dataset consists of 11 growing seasons at three high-yielding locations in Buenos Aires (Argentina), Ciudad Obregon (Mexico), and Valdivia (Chile) with the spring wheat cultivar Bacanora and a high-yielding genotype selected from a doubled haploid (DH) population developed from the cross between the Bacanora and Weebil cultivars from the International Maize and Wheat Improvement Center (CIMMYT). This dataset was used in the Agricultural Model Intercomparison and Improvement Project (AgMIP) Wheat Phase 4 to evaluate crop model performance when simulating high-yielding physiological traits and to determine the potential production of wheat using an ensemble of 29 wheat crop models. The field trials were managed for non-stress conditions with full irrigation, fertilizer application, and without biotic stress. Data include local daily weather, soil characteristics and initial soil conditions, cultivar information, and crop measurements (anthesis and maturity dates, total above-ground biomass, final grain yield, yield components, and photosynthetically active radiation interception). Simulations include both daily in-season and end-of-season results for 25 crop variables simulated by 29 wheat crop models.

Keywords: Wheat, yield potential, field experimental data, crop model ensemble, simulations.

1 ORIGINAL PURPOSE: The original purpose of this dataset was to support a model inter-comparison (Guarin et al. 2022) as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP, https://agmip.org/) (Rosenzweig et al. 2013). The field experimental data were from high-yielding trait experiments to investigate and improve wheat yield potential in high-yielding environments using improved physiological traits (Bustos et al. 2013; Garcia et al. 2013; Garcia et al. 2014). This dataset contains field measurements of selectively bred high-yielding wheat cultivars, including the highest reported wheat grain yield in the literature – 16.6 t ha^{-1} dry weight (Bustos et al. 2013; Garcia et al. 2013), for benchmarking local and regional yield improvements and model improvement against an ensemble of 29 state-of-the-art wheat crop simulation models.

2 FIELD EXPERIMENTS: A full description of the experiment sites and treatments are available in Bustos et al. (2013) and Garcia et al. (2013). The critical information for the simulation of the high-yielding treatments used in the AgMIP-Wheat Phase 4 project is summarized below for crop model setup and analyses.

The experiment consisted of three sites located at the University of Buenos Aires Facultad de Agronomía experimental field, Buenos Aires, Argentina (34°35' S, 58°29' W, 26 m a.s.l.), the Norman E. Borlaug experimental station, Ciudad Obregon, Mexico (27°25' N, 109°54' W, 38 m a.s.l.), and the Austral University of Chile experimental station, Valdivia, Chile (39°47' S, 73°14' W, 19 m a.s.l.). The dataset includes two spring wheat genotypes, one check cultivar (Bacanora) from the International Maize and Wheat Improvement Center (CIMMYT) and one high-yielding doubled haploid (DH) line from the cross between Bacanora and Weebil with improved radiation use efficiency (RUE), light extinction coefficient (*K*), potential grain filling rate (GFR), and potential grain size (GWpot) and slightly decreased fruiting efficiency (FE) and grain filling duration (GFD) (Table 1). The entire experiment consisted of 105 spring wheat DH lines, but only the best-yielding DH lines for each location are reported here.

Each growing year consisted of one to three replicates where the wheat crops were grown with ample N supply, full irrigation, and agronomic practices to reach potential yield for the local soil and weather conditions. All other crop factors including weed, disease and pest control, and potassium, phosphate, and sulphur fertilizers, were applied at levels to prevent yield limitation. The soil at Buenos Aires was a silty clay loam, classified as Vertic Argiudoll, and each replicate was sown in flat plots with five rows 2.1 m long by 0.9 m wide and 0.175 m between rows. The soil at Ciudad Obregon was a sandy clay, classified as Typic Caliciorthid, and each replicate was sown in a 2.5 m long by 0.8 m wide plot consisting of one raised bed with two rows per bed and 0.25 m between rows. The soil at Valdivia was a volcanic ash, classified as a Typic Hapludand, and each replicate was sown in either a continuous plot of three rows 1.5 m long with 0.15 m between rows (2008 and 2009) or split plots 2 m long by 1.5 m wide with 0.15 m between rows (2010). At each site, the temperature and solar radiation data were provided from a weather station located < 2 km from the experimental field and the rainfall, wind speed, and relative humidity data were obtained using the NASA POWER database (https://power.larc.nasa.gov) (Kratz et al. 2014; White et al. 2011). The average grain yield of each treatment for the three high-yielding locations is shown in Figure 1.

3 SIMULATION OF FIELD EXPERIMENTS: The treatments described above were simulated by 29 wheat crop models (Guarin et al. (2022); see CIM_AgMIP_model_names.txt). Simulations were carried out using standard AgMIP protocols (Rosenzweig et al. 2013; Asseng et al. 2015) in two steps, one step for model calibration for the check cultivar Bacanora, and the second step for 'blind' simulations of the high-yielding DH line. The simulation results reported here are for both steps.

For step one modelers had access to all the experimental data for the check cultivar, Bacanora, for the five growing seasons at Valdivia, Chile (2008-2009, 2009-2010, 2012-2013, 2013-2014 and 2014-2015), one growing season at Buenos Aires, Argentina (2009-2010) and four growing seasons at Ciudad Obregon, Mexico (2009-2010, 1990-1991, 2015-2016 and 2016-2017) for a total of 10 site-year-treatment combinations. The data at Ciudad Obregon, Mexico in 1990-1991 were obtained from a previous AgMIP study (Asseng et al. 2015; Martre et al. 2017). The soil profile at Buenos Aires was from in situ measurements (Garcia et al. 2013).The soil profile at Ciudad Obregon was from Hernandez-Ochoa et al. (2018). The soil profile at Valdivia was based on the Natural Resources Conservation Service (NRCS) volcanic ash profile and Asseng et al. (2017). Detailed initial soil conditions were not available for each location. Therefore, as water and nitrogen (N) were managed to limit any stress, total initial soil mineral N (NO_3^- and NH_4^+) content was assumed to be equal to 140 kg N ha^{-1}. To ensure no water stress, supplementary irrigation was provided. For each experiment, the dates and rates of irrigation were calculated using the DSSAT-NWheat model (Kassie et al. 2016) automatic irrigation routine. Modelers used either the irrigation dates and rates provided by DSSAT-NWheat or their model-integrated unlimited water and N routine to prevent any simulated water or N stress.

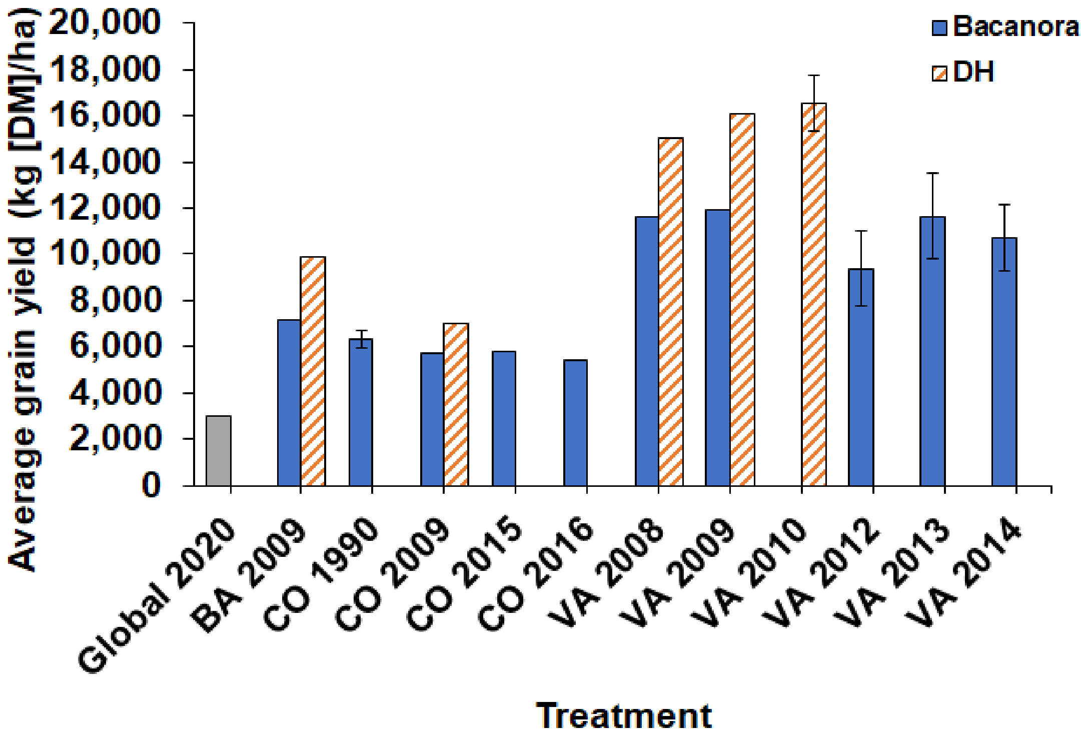

Figure 1. Observed average grain yield of cv. Bacanora (solid blue bars) and the high-yielding DH line (dashed orange bars) for the 11 treatments at Buenos Aires, Argentina (BA), Ciudad Obregon, Mexico (CO), and Valdivia, Chile (VA) from the experimental data (Bustos et al. 2013; Garcia et al. 2013; Garcia et al. 2014). Global average yield (solid gray bar) based on the latest reported global statistics for 2020 (FAOSTAT 2022) included for comparison to high-yielding observations. Error bars indicate standard deviation of the observed replicates. Bacanora data at Valdivia in 2010 was not available. All yields shown are with 0% moisture content.

For step two, a 'blind' simulation study was conducted for the best-yielding DH lines at each location using the same initial growing and management conditions from the calibration, but the measured data were not provided. One additional season at Valdivia, Chile was included (2010-2011). Only calculated trait percent changes (Table 1 final column) and instructions describing how to modify the calibrated cv. Bacanora traits for the high-yielding DH line (Guarin et al. 2022) were provided to simulate growth for the seasons that the DH line was grown, i.e., three seasons at Valdivia, Chile (2008-2009, 2009-2010, and 2010-2011), one season at Buenos Aires, Argentina (2009-2010), and one season at Ciudad Obregon, Mexico (2009-2010). The RUE and *K* of the DH line were calculated using the average of the two best-yielding DH lines from Chile because detailed light interception data was only measured in Chile. The FE, GWpot, GFD, and GFR were calculated using the mean percent change between the best-yielding DH line and Bacanora from each of the three locations (Table 1). In addition to the five 'blind' DH line treatments, the five Bacanora treatments corresponding to these treatments were re-simulated in step two for comparison to step one to ensure model consistency.

Table 1. Physiological trait description and measurements of Bacanora and the best-yielding doubled haploid (DH) line for each treatment used in the AgMIP high-yielding step 2 simulations. Average values are calculated for both Bacanora and the DH line across the three locations in the observed field experiment data (Bustos et al. 2013; Garcia et al. 2013; Garcia et al. 2014). The percent change (%) between Bacanora and the DH line is shown for each treatment and the average across all treatments. Bacanora data at Valdivia in 2010 was not available. DM, dry matter; GS, growth stage; PAR, photosynthetically active radiation; LAI, leaf area index; BA, Buenos Aires, Argentina; CO, Ciudad Obregon, Mexico; VA, Valdivia, Chile. To simulate the best-yielding DH line, modelers were provided with the average of the percent change of each treatment. Modified after: Guarin et al. (2022).

			BA 2009			CO 2009			VA 2008			VA 2009			VA 2010	Average			Average of % change of each
Trait	**Units**	**Calculation**	**Bac.**	**DH93**	**%**	**Bac.**	**DH34**	**%**	**Bac.**	**DH18**	**%**	**Bac.**	**DH28**	**%**	**DH[a]**	**Bac.**	**DH**	**%**	**treatment**
Radiation use efficiency (RUE)	g MJ^{-1}	Slope of above-ground biomass DM (GS10 to GS89) vs. cumulative intercepted PAR	2.89												3.86	2.89	3.86	34	34
Light extinction coefficient at GS31 (*K*)	m^2 m^{-2}	Exponential coefficient of cumulative PAR (pre-anthesis) vs LAI at stem elongation													0.46	0.42[b]	0.46	10	10
Fruiting efficiency (FEspike)	grain g^{-1} DM	Grain number divided by DM of spike at anthesis	143	114	-20	66	72	9								105	93	-11	-5
Potential grain size (GWpot)	mg DM $grain^{-1}$	Average single grain DM under potential growth conditions	29	38	33	39	40	2	39	42	7	39	48	23		36	42	15	16
Potential grain filling duration (GFD)	°Cd	Thermal time (base temperature 0°C) between anthesis and physiological maturity	654	698	7	779	674	-14	674	634	-6	799	764	-4		727	693	-5	-4
Potential grain filling rate (GFR)	mg DM $°Cd^{-1}$	Grain DM divided by thermal time (base temperature 0°C) between anthesis and physiological maturity under potential growth conditions	0.044	0.055	24	0.050	0.059	19	0.058	0.066	14	0.048	0.062	29		0.050	0.061	21	21

[a] Valdivia 2010 treatment is the average of the two best yielding DH lines (DH18 and DH28).
[b] Bacanora average *K* was calculated from the Valdivia 2012 treatment (data not shown in table but included in data files).

Model outputs include emergence date, anthesis date, maturity date, grain dry mass yields, total above-ground biomass, leaf area index, number of grains per square meter, grain dry weight, harvest index, crop N dynamics, crop transpiration and evapotranspiration, soil water and N dynamics, and intercepted photosynthetically active radiation (PAR). Not all models simulated all variables. Variables not simulated are indicated by "NA". Simulation results are reported for each individual model and for the multi-model ensemble median (e.median).

4 DATA FORMAT, STRUCTURE, AND AVAILABILITY: An overview of the main tables and files from the data is given in Table 2. Experimental (means of crop measurements) and simulation (model output) data, model input (cultivar information and crop management), soil description, initial conditions, and daily weather data (incoming solar radiation, maximum and minimum air temperature, rainfall, wind speed, dew point temperature, vapor pressure, and relative humidity) for simulation setup are provided in a Microsoft Excel (version 2019) and a JavaScript Object Notation (JSON) file. These files follow the AgMIP Crop Experiment (ACE) data schema. The ACE JSON file was created from the Microsoft Excel file by using the data translator available at https://github.com/agmip/translator-excel-python. The ACE JSON can be used to create model input files using QuadUI desktop utility for ACE input and output data translation (http://tools.agmip.org) or model-integrated translators (Porter et al. 2014). Data are also provided in tab-delimited text format. All text files are UTF-8 encoded. The names, descriptions, and units of the variables (key) are provided in the Microsoft Excel file and in text files with their correspondence and conversion factors in the International Consortium for Agricultural Systems Applications (ICASA) standard (White et al. 2013). Data available at https://doi.org/10.7910/DVN/VKWKUP.

Table 2. Overview of the main dataset files. All files are provided in space- (weather data) or tab- (all others) delimited text format. Site description, soil, weather, initial conditions, crop management, cultivar description, and measurement data are provided in the Microsoft Excel (.xlsx) and JavaScript Object Notation (.json) format used in the AgMIP experiment and tab-delimited format. These *.xlsx, .json, and tab-delimited files all contain exactly the same information - for ease of use.

File name	Content
CIMXXXYYYYDDDYYYYDDD.wth	Space-delimited file of weather data. XXX is the three-character code for the site followed by a four-digit code for the starting year (YYYY), a three-digit code for the starting day of the year (DDD), a four-digit code for the ending year (YYYY), and a three-digit code for the ending day of the year (DDD).
CIM_AgMIP_weather_key.txt	Tab-delimited file with names, definitions, and units of measured weather variables in ICASA format.
CIM_AgMIP_measurement_key.txt	Tab-delimited file with names, definitions, and units of measured variables in ICASA format.
CIM_AgMIP_measurements_summary.txt	Tab-delimited file of summary means of all available crop measurements.
CIM_AgMIP.xlsx; CIM_AgMIP.json; CIM_AgMIP_tab_delimited	Microsoft Excel file, JavaScript Object Notation file, and tab-delimited files with site description, soil, weather, initial conditions, crop management, cultivar description, and measurements.
CIM_AgMIP_model_names.txt	Tab-delimited file with the name, version, and two-letter code of the 29 wheat crop models.
CIM_AgMIP_simulation_key.txt	Tab-delimited file with the name, definition, and units of the simulated variables in ICASA format.
CIM_AgMIP_summary_simulations_stepX.txt	Tab-delimited file of the summary model outputs. X indicates experiment step (1 or 2).
CIM_AgMIP_daily_simulations_stepX.txt	Tab-delimited file of the daily model outputs. X indicates experiment step (1 or 2).

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