Winter Wheat Experiments to Optimize Sowing Dates and Densities in a High-Yielding Environment in New Zealand: Field Experiments and AgMIP-Wheat Multi-Model Simulations

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Abstract: This paper describes the data set that was used to test the accuracy of twenty-nine crop models in simulating the effect of changing sowing dates and sowing densities on wheat productivity for a high-yielding environment in New Zealand. The data includes one winter wheat cultivar (Wakanui) grown during six consecutive years, from 2012-2013 to 2017-2018, at two farms located in Leeston and Wakanui in Canterbury, New Zealand. The simulations were carried out in the framework of the Agricultural Model Intercomparison and Improvement Project for wheat (AgMIP-Wheat). Data include local daily weather data, soil profile characteristics and initial conditions, crop measurements at maturity (grain, stem, chaff and leaf dry weight, ear number and grain number, grain unit dry weight) and at stem elongation and anthesis (total above ground dry biomass, leaf number per stem and leaf area index). Several in-season measurements of the normalized difference vegetation index (NDVI) and the fraction of intercepted photosynthetically active radiation (FIPAR) are also available. The crop model simulations include both daily in-season and end-of-season results from twenty-nine wheat models.

Keywords: Field experimental data, multi-crop model ensemble, sowing date, sowing density, winter wheat, yield potential.

1 BACKGROUND To meet the growing demand for wheat under increasingly challenging environmental conditions, cropping systems must increase production and one promising avenue is optimizing seeding dates and seeding rates (Bai and Tao 2017, Xin and Tao 2019, Sun et al. 2013, Padovan et al. 2020). Adapting sowing conditions requires an understanding of how crop growth, development and yield are affected by sowing dates and densities, including interactions between canopy development, radiation interception and biomass production.

The original purpose of the experiments was to investigate if there is a yield advantage from earlier sowing of winter wheat and to determine the optimum plant population for the different sowing dates. Data were collected to quantify the effects of sowing date and plant population on tiller number, leaf area, dry matter accumulation, lodging, head number and final harvest components. The field trials were conducted by the New Zealand Institute for Plant and Food Research and The Foundation for Arable Research at two farms located in the Canterbury Region of the South Island of New Zealand (Craigie *et al.*, 2015). In this region, winter wheat is usually sown between early April to mid-May, with some farmers sowing in late March in recent years (Craigie *et al.*, 2015). The objective of the trials was to test if sowing earlier (February or early March) and therefore increasing the canopy duration and the intercepted radiation, would increase grain yield.

As part of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al. 2013: https://agmip.org/wheat/) twenty-nine process-based wheat crop models were provided with the data from these field experiments, with the goal of evaluating the accuracy of the models in simulating the effect of varying seeding dates and densities on wheat growth and yield in a high yielding environment.

2 FIELD EXPERIMENTS The data were collected at two farms located in a high yielding environment at Leeston (43° 45’ S, 172° 15’ E) and Wakanui (43° 58’ S,171° 48’ E). In the field experiments reported here, the local winter wheat cultivar Wakanui was grown under non-stress conditions for six consecutive years, first at Leeston (from 2012-2013 to 2014-2015) and then at Wakanui (from 2015-2016 to 2017-2018). Wakanui cultivar is a soft winter wheat with very high yield potential associated with a long grain-filling period.

Four sowing dates were tested: mid-February, early-March, late-March and mid-April (Table 1). At Leeston, the effect of sowing dates was studied in combination with four sowing densities (50, 100, 150 and 200 seeds m^{-2}), while at Wakanui, only the locally recommended sowing density was used (150 seeds m^{-2}). The experiments consisted of a split-plot design with sowing dates as the main plots and sowing rates as the subplots, with four replicates. The Wakanui trials investigated different cultivars, sowing dates and the use of plant growth regulators (2015-2016) or defoliation (2016-2017 and 2017-2018), at different sowing dates. The experiments were designed as randomized blocks with sowing dates as the main plots and cultivar by plant growth regulation or defoliation as the subplots, replicated four times. In our data set, we considered only the data of the 'Wakanui' cultivar grown under standard growth regulation and without defoliation. In the data set the crop measurements are given for each of the four repetitions and as the mean value of the repetitions.

Table 1: Summary of the trials set up for the six growing seasons: sowing dates and sowing densities, for the experimental locations and years. Sowing dates with * were removed from the dataset because of significant lodging.

		Sowing dates				**Sowing densities (seeds m^{-2})**			
Location	**Growing season**	**Mid-February**	**Early-March**	**Late-March**	**April**	**Low**	**Intermediate**	**Locally recommended**	**High**
Leeston	2012-2013	21 Feb.	-	26 Mar.	-	50	100	150	200
	2013-2014	20 Feb.	-	26 Mar.	16 Apr.	50	100	150	200
	2014-2015	20 Feb.	10 Mar.	26 Mar.	23. Apr	50	100	150	200
Wakanui	2015-2016	20 Feb.	10 Mar.	20 Mar.	09 Apr.	-	-	150	-
	2016-2017	24 Feb.*	08 Mar.	29 Mar.	14 Apr.	-	-	150	-
	2017-2018	-	09 Mar.	30 Mar.	19 Apr.	-	-	150	-

The field management was adapted each year to obtain potential yield growth conditions. Individual plots (12 × 1.65 m) were drilled into a top worked seedbed. At both sites, the soil type was a Temuka clay loam (Fluventic Endoaquents in USDA classification), a deep, low permeability soil with high water storage capacity (Kear *et al.*, 1967; Craigie *et al.*, 2015). The Leeston site was characterized by a shallow water table at about 1 m below the soil surface. Weather data were collected at a weather station located within 2 km from the experimental fields and provided daily minimum and maximum temperature, rainfall, solar radiation, wind speed and relative humidity. Wind and relative humidity were measured at 2 m height.

In all experiments the grain, stem, chaff and leaf dry weight at maturity, ear number and grain number, grain unit dry weight and dry mass harvest index were determined (Table 2). The total above ground dry biomass, leaf number per stem and leaf area index (LAI) were measured at Zadoks growth stage (Zadoks *et al.*, 1974) 32 (stem elongation) and 65 (anthesis), except for the first two growing seasons of the trial. Except for the first growing season, several in-season measurements were conducted, including the normalized difference vegetation index (NDVI, from Trimble Greenseeker [Trimble Agriculture Division CO, USA] measurements) and FIPAR from Sunscan [Delta-T devices, Cambridge, UK] measurements), the dates of the 32, 65 and 90 Zadoks growth stages as well as the number of leaf tips, ligules, green leaves, senescing leaves and dead leaves. In addition, for the growing season 2013-2014 there was detailed information on individual final leaf dry mass, surface area, specific leaf area of the flag leaf and the last four leaves (culm leaves).

2.1 SIMULATION OF FIELD EXPERIMENTS Twenty-nine process-based wheat crop models participated in this study and contributed to the multi-model ensembles (MME) output (Dueri et al., 2022). Modelling groups were provided with daily weather data and soil physico-chemical characteristics (soil water lower limit, drained upper limit, saturation, apparent bulk density, organic C and organic N concentration and soil pH). Initial soil inorganic N amount was estimated for the upper 150 cm for each growing season, based on mineral nitrogen values measured in 2013 and 2014 in the upper 60 cm and 75 cm of soil, respectively. The soil was represented by three layers of equal thickness (50 cm) and the distribution of the total initial amount of inorganic N in each layer was estimated at 55%, 30% and 15%, from the top layer to the bottom layer. Initial soil water content was estimated at field capacity. The same initial values of soil inorganic N and soil water content were used to initialize the simulations, regardless of sowing dates.

Table 2. Summary of crop measurements for different growing seasons. Numerical values correspond to growth stages: 32, stem elongation; 65, anthesis; 90, harvest maturity.

			Growing season					
Measured variable	**Unit**	**Comments**	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**
Number of leaf tips		<		in season	in season	in season	in season	in season
Number of leaf ligules				in season	in season	in season	in season	in season
Average individual leaf surface area	cm^2			65	in season			
Average individual leaf dry mass	g DM $leaf^{-1}$			65				
Average specific leaf area	mm^2 g^{-1} DM			65				
Leaf senescence	% of total leaf area			65				
Number of mainstem green leaves	Leaf main $stem^{-1}$				in season	in season	in season	in season
Number of mainstem senescing leaves	Leaf main $stem^{-1}$				in season	in season	in season	in season
Number of mainstem dead leaves	Leaf main $stem^{-1}$				in season	in season	in season	in season
Total above ground dry mass	kg DM ha^{-1}		90	65,90	32,65,90	32,65,90	32,65,90	32,65,90
Grain yield (0% moisture)	kg DM ha^{-1}	at %0 moisture	90	90	90	90	90	90
Grain yield (14% moisture)	kg ha^{-1}	at %14 moisture	90	90	90	90	90	90
Straw dry mass	kg DM ha^{-1}		90	90	90	90	90	90
Stem dry mass	kg DM ha^{-1}		90	65,90	32,65,90	32,65,90	32,65,90	32,65,90
Ear dry mass	kg DM ha^{-1}			65,90	65,90	65,90	65,90	65,90
Chaff dry mass	kg DM ha^{-1}		90	90	90	90	90	90
Total leaf dry mass	kg DM ha^{-1}		90	65,90	90	90	90	32,65,90
Green leaf dry mass	kg DM ha^{-1}			65,90	32,65	32,65	32,65	32,65
Dead leaf dry mass	kg DM ha^{-1}			65,90	32,65	32,65	32,65	32,65,90
Green leaf to stem ratio					32,65	32,65	32,65	32,65
Average stem length	Cm				90	90	90	
Average stem dry mass	g DM $stem^{-1}$	Excluding ears		65,90				
Stem density	stem m^{-2}		90	90	90	90	90	90
Ear density	ear m^{-2}			65,90	90	90	90	90
Grain density	grain m^{-2}		90	90	90	90	90	90
Grains number per ear	grain ear^{-1}		90	90	90	90	90	90
Dry mass harvest index	-		90	90	90	90	90	90
Grain moisture	g water 100 g^{-1} DM		90	90	90	90	90	90
Grain fresh mass	g FW $grain^{-1}$	At harvest moisture	90	90	90	90	90	90
Grain specific weight	kg FW hl^{-1}	At harvest moisture		90	90	90	90	90
Average single grain mass	g $grain^{-1}$	At 14% moisture	90	90	90	90	90	90
Leaf area index	m^2 m^{-2}	Calculated from measured leaf area			32,65	32,65	32,65	32,65

Table 2. Continued

Measured variable	Unit	Comments	Growing season					
			2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018
Fraction of intercepted PAR	-	Corrected values from Sunscan		in season	in season	in season	in season	
Sunscan leaf area index	$m^2\ m^{-2}$	Corrected values from Sunscan		in season	in season	in season	in season	
RED	-	Reflectance from Greenseeker			in season	in season	in season	in season
NIR	-	Reflectance from Greenseeker			in season	in season	in season	in season
NDVI	-	Normalised Difference Vegetation Index		in season	in season	in season	in season	in season
WDVI	-	Weighted Difference Vegetation Index			in season	in season	in season	in season
NDVISC	-	Scaled Normalised Difference Vegetation Index		in season	in season	in season	in season	in season
Zadock growth stage	Date			in season	in season	32,65,90	32,65,90	32,65,90

The simulations were conducted using a standardized protocol and one step of calibration. The models were calibrated with data measured during the 2014-2015 growing season, including a combination of four sowing dates and four sowing densities, for a total 16 different treatments. Supplied data were the mean of the four replicates. For each experiment, modellers were provided with phenological records: the date of beginning of stem extension (Zadoks 31) anthesis (Zadoks 65) and physiological maturity (Zadoks 87). In addition, the grain, stem, chaff and leaf dry weight at maturity, ear number and grain number, grain unit dry mass and harvest index were provided. Also, time series of measurements of total above ground dry biomass, leaf number per main stem, leaf area index (LAI), normalized difference vegetation index and fraction of intercepted photosynthetic active radiation (FIPAR) were provided.
After calibration, simulations were conducted by each model for all combinations of sowing date, sowing density and growing season (Table 1), for a total of 50 simulations (treatment / year combinations). All twenty-nine models reported total above ground biomass at anthesis and maturity, grain yield, and harvest index, while LAI was missing for one model, grain unit dry mass and grain number was reported by 15 models and FIPAR by 13 models (Table 3). Variables not simulated are indicated by “NA”. Simulation results are reported for each individual model.

Table 3. Availability of simulated variables by model.

		Model code																												
	Model Variable	AE	AQ	AW	CS	D1	D3	D4	DN	DR	DS	HE	L5	L6	LI	MC	MO	NC	NG	NP	NS	PG	S2	SA	SP	SQ	SS	WG	WO	WU
Summary	Crop emergence (DC10) date	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Anthesis (DC65) date	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Physiological maturity (DC89) date	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Final grain yield (at 0% moisture content)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Grain number at maturity	✓	–	✓	–	✓	✓	✓	✓	✓	–	–	–	–	✓	–	–	✓	✓	✓	✓	✓	✓	–	–	✓	–	–	–	–
Daily	Leaf area index	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Total above ground biomass	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Grain dry mass	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Total above ground N	✓	–	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	–
	Grain N	✓	–	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	–
	Water drainage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–
	Available soil water in the soil profile	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–
	Runoff	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	–	✓	✓	✓	✓	✓	–	–	✓	✓	–	✓	–	–	–
	Transpiration	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	✓
	Evapo-transpiration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	✓
	N leaching	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓	–	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	–	–	–
	N mineralization	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	–	–	✓	✓	–	–	–
	N volatilization	–	–	–	✓	–	✓	✓	✓	✓	✓	✓	–	–	–	–	–	✓	✓	✓	✓	✓	–	–	–	–	✓	–	–	–
	N immobilization	–	–	✓	✓	–	✓	✓	✓	✓	✓	–	–	✓	–	–	–	✓	✓	✓	✓	–	–	–	–	–	–	–	–	–
	Available soil mineral N	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	–	–	–
	N denitrification	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	–	–	✓	✓	–	–	–
	Cumulative franction of intercepted PAR	✓	–	–	✓	–	✓	✓	–	–	–	✓	✓	✓	✓	✓	–	–	–	–	–	✓	✓	–	✓	✓	–	–	–	–

3. DATA FORMAT, STRUCTURE AND AVAILABILITY An overview of the structure of the dataset and the content of the main tables is given in Table 4. Experimental and simulation (model output) data are provided in tab delimited text files, Excel and JSON (JavaScript Object Notation) format. The names of the variables (key) are explained in companion text files with their correspondence and conversion factors in the International Consortium for Agricultural Systems Applications (ICASA) standard (White et al., 2013): https://vest.agrisemantics.org/content/agmip-icasa-master-variable-list. Daily weather data (global solar radiation, daily maximum and minimum air temperature, rainfall, wind run, dew point temperature, vapor pressure and relative humidity) are provided in the ICASA format in tab delimited text files.

All data are available in the Harvard Dataverse data repository (https://dataverse.harvard.edu/) with the digital object identifier or doi: 10.7910/DVN/XA4VA2.
The experimental data is of high quality and does not contain outliers. The simulated results of some of the models may be outside the 25-75% quantile range in some situation, which can be considered as simulated outliers.

Table 4: Overview of the organization of the dataset. Files are provided in tabulation delimited text format, Excel or JSON format.

Folder name	File (or Folder) name	Content
Weather	FARLEE20110012015182.wth	Tab delimited file of weather data for Leeston
	FARWAK20150012018134.wth	Tab delimited file of weather data for Wakanui
Experimental_observation-Model_input	NZ_AgMIP_dataset.xlsx	Excel file containing of the data set of the experiment, including crop management, soil description, weather conditions and crop measurements
	NZ_AgMIP_dataset.json	JSON file, equivalent to the Excel file
	NZ_AgMIP_tab_delimited	Folder containing 27 tab delimited files, equivalent to the Excel file
	NZ_AgMIP_Measurement_key.txt	Tab delimited file of the keys of the field experiment dataset (ICASA standards)
	NZ_AgMIP_Measurement_summary.txt	Tab delimited file of crop measurements
Simulation_results-Model-output	NZ_AgMIP_model_names.txt	Tab delimited file with the full name, version and two-letter code of the 29 wheat models
	NZ_AgMIP_simulation_key.txt	Tab delimited file of the keys of the simulated variables
	NZ_AgMIP_simulation_summary.txt	Tab delimited file of the summary model output
	NZ_AgMIP_simulations_daily.txt	Tab delimited file of the daily model output

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