Assessment of Genotypes and Management Strategies to Improve Resilience of Winter Wheat Production

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Received: 19 January 2020; Accepted: 4 February 2020; Published: 17 February 2020

Abstract: Climate is a main factor that influences the winter wheat production. Changing the crop cultivars and adjusting the sowing dates are used as strategies to adapt to climate change. First, we evaluated the simulation ability of the Decision Support System for Agro-technology Transfer (DSSAT) CERES wheat model based on the experimental data with varied sowing dates and cultivars. Second, we designed optimal cultivars in three different environmental conditions with the highest grain yield in the North China Plain (NCP) based on model sensitivity analysis. Furthermore, we optimized the sowing dates for three sites with the above-derived cultivar parameters. The results showed that the DSSAT–CERES wheat model was suitable for winter wheat simulation after calibration and validation with a Normalized Root Mean Square Error (NRMSE) between 0.9% and 9.5% for phenology, 6.8% and 17.8% for above ground biomass, and 4.6% and 9.7% for grain yield. The optimal cultivars significantly prolonged the wheat growth duration by 14.1, 27.5, and 24.4 days at the Shangzhuang (SZ), Xingtai (XT), and Zhumadian (ZMD) sites compared with current cultivars, respectively. The vegetative growth duration (from sowing to anthesis) was prolonged 18.4 and 12.2 days at the XT and ZMD sites significantly, while shortened 0.81 days at the SZ site. The grain yield could be potentially improved by 29.5%, 86.8%, and 34.6% at the SZ, XT, and ZMD sites using the optimal cultivars, respectively. Similarly, the improvement of aboveground biomass at three sites was 5.5%, 47.1%, and 12.7%, respectively. Based on the guaranteed rate and analysis of variance, we recommended a later sowing date (from 15 September to 20 October) at the SZ and ZMD sites, and 15 September to 15 October at the XT site. In addition, the methodology of this study could be expanded to other regions and possibly to other crops.

Keywords: climate change; winter wheat; adaption; virtual cultivar; North China Plain

1. Introduction

Winter wheat is one of the most vital crops around the globe [1]. Demand for wheat is growing at a rate of about 1.7% a year [2]. One of the most important challenges facing the world under climate change is to produce enough foodstuff for a continuously increasing population. However, the climate is a major factor, which greatly influences crop production and is regarded as one of the key factors contributing to production stagnation globally [3,4]. For example, in the past few decades, existing studies have identified that climate change has been affecting crop growth and yield in many countries [5–7]. There is existing evidence showing that climate change (temperature increment) since the 1980s has reduced crop yields, because the crop growth duration was shortened...
and heat/water stress-aggravated [8,9]. Furthermore, the negative impacts of climate change on the agricultural industry will continue to challenge food safety in the future [10,11]. The North China Plain (NCP) accounts for 60% of the nationwide wheat production [12], and the wheat production would be reduced by 0.9% and 1.9% for irrigated and rainfed conditions, respectively, under climate change [13]. Therefore, the maintenance of winter wheat security is crucial and urgent for both farmers and government.

Strategies for adaptation to climate change have mainly focused on genetic improvement and improved management practices. Changing cultivars, for example, with longer growing seasons instead of “old” cultivars or cultivars that have tolerance for abiotic stresses, has proven to be an efficient way to alleviate the negative effect of the climate [14–18]. Specifically, Parent et al. (2018) used experiments and a process-based model to analyze the results of climate change on European maize yields under the farmers who used the best current genetic variability. The results showed that if the crop cycle was adapted, the total maize yield increased by 4.5% and 7.0% for RCP (Representative Concentration Pathways) 4.5 and 8.5, respectively, under a moderate increase in transpiration efficiency (TE) [19]. Among many management practices, optimizing the sowing dates of crop was considered to be another efficient way to avoid heat/drought stress on phenology development or a reduction in crop yield. For example, Bassu et al. (2009) reported that a sowing date as early as in October could help to crop escape water shortage and heat stress, which would minimize the negative impact of climate change under Mediterranean climatic regions [20]. However, how these adaptations will work out in the North China Plain (NCP) have not been substantially studied.

Experiments may be useful to help us to breed and can interpret Genotype × Environment × Management interactions (G × E × M); however, it is not convenient to allow the testing of wide-range climatic conditions, which are extensive enough to represent the expected with climate change. Additionally, they are costly and time-consuming because of the need to reflect on the impact of long-term climate variability [21]. For the reasons mentioned above, the experiments are not suited for breeding for a large area such as the North China Plain (NCP) with different temperature, precipitation, and soil heterogeneity. The crop model offers an alternative and effective method for the evaluation of the probable impact of climate as they interact with edaphic condition and crop traits, as well as managements [21]. For example, Rötter et al. (2015) reviewed that using the crop simulation model helped the ideotype design to avoid extreme climate events or climate change and describe developments of cultivar traits in response to climate variability [22]. Luo et al. (2009) used the Agricultural Production Systems Simulator (APSIM) wheat model to change the parameters regarding phenology to derive later or earlier cultivars, and combined these “cultivars” with an earlier sowing date with different N application rate. The result showed that the wheat grain yield could not maintain the current production level of the southeast of South Australia in 2080 [23]. Gouache et al. (2017) did a study on the gene-based model of wheat phenology. It was illustrated that we need to link the optimal model parameters and the allelic at the gene levels as a key step of this approach in future work. It is a profitable way to use a crop model to design an ideotype of winter wheat, which could lead to a high grain yield to adapt to climate change [24].

The DSSAT model (DSSAT Foundation, Gainesville, FL, USA) is a process-oriented modeling framework, which simulates crop growth and development as a response to crop cultivar characteristics, environmental conditions, and agronomic managements [25,26]. The DSSAT–CERES wheat model was broadly used to simulate the effects of climate change and as a method to adapt to climate change globally. The model can simulate the interaction between cultivars, climate, and managements, as well as N and soil water dynamics in daily steps. There are seven crop cultivar genetic parameters to explain the phenology and yield. The meanings of the parameters and the range of each parameter derivative from all the wheat cultivars existing in the DSSAT–CERES wheat model are listed in Table 2. Detailed information of the DSSAT–CERES wheat model are available at Official Home of the DSSAT Crop Systems Model [27].
The objectives of the present study were: (1) to evaluate the ability of the DSSAT–CERES wheat model to simulate wheat growth, aboveground biomass and grain yield under different sowing dates with three cultivars; (2) to design ideotypes for three contrasting environmental sites; and (3) to optimize sowing date based on the ideotypes for three sites.

2. Materials and Methods

2.1. Experimental Design

We conducted field experiments from 2015 to 2018 at the Shang Zhuang experiment station of the China Agricultural University that is located in the North China Plain (40°08′12″ N, 116°10′45″ E; 50.21 m above sea level) and has a warm temperate monsoon climate.

The experiment included two factors (cultivar types and sowing dates) using a split-plot design with three replications. In each year, three or four sowing dates were conducted with a 10-day interval, and three different cultivars were sowed on each sowing date: weak-winter wheat YZ4110 (YZ), which is usually sowed in the southern NCP; semi-winter wheat HD 6172 (HD), which is typically sowed in the central NCP; winter wheat ND 211(ND), a typical cultivar sowed in the northern NCP—the three cultivars with increased freezing resistance from weak-winter wheat to winter wheat [28]. Specifically, winter wheat sowing dates were performed on October 1, 11, and 21 during the 2015/2016 growing season; September 23, and October 3, 13, and 23 during the 2016/2017 growing season; and October 3, 13, and 23 during the 2017/2018 growing season.

During the three winter wheat growing seasons, irrigations were applied (60 mm each time) three times, which were before winter, around the jointing stage, and at the flowing stage. Nitrogen fertilizer was applied before sowing (120 kg/ha N urea; in the 2015/2016 growing season of winter wheat, we applied an additional 60 kg/ha N urea around the jointing stage). The other managements were similar to the local practices [29]. The sowing depth was 4 cm, and each subplot was 5 m long and 4 m wide.

2.2. Data Acquisition and Analysis

2.2.1. Crop Phenology

Crop phenology was recorded using the Zadoks scale [30], including anthesis and maturity date. The corresponding dates were recorded when 50% of populations reached anthesis (Z61), and the grain is hard to divide by thumbnail (maturity, Z91).

2.2.2. Grain Yield and Aboveground Biomass

The spike number per m² was estimated in two 1 m inner rows, as well as the grain number per spike from 40 randomly selected plants in each plot. The grain yield and aboveground biomass were measured from an area of 1 m² in each plot at maturity. The 1000 grain weight was calculated with three replicates.

2.3. Obtaining Winter Wheat Cultivar Parameters

We used the experimental data to derive the parameters of the three cultivars by using a trial-and-error method. The parameters are presented in Table 2. The observed values for winter wheat in terms of the phenology, aboveground biomass, and grain yield of the 2015/2016 growing season and the first two sowing dates of the 2016/2017 growing season were used for calibration; the rest of the values were used for validation.
2.4. Scenario Analysis

2.4.1. Wheat Cultivar Optimization for Different Environmental Conditions

In this study, we optimized the parameters of the cultivars by the DSSAT–CERES wheat model to identify the high-yield cultivars with genetic traits. The optimization trials involved two steps. First, we conducted a sensitivity test to determine the sensitivity of each of the seven cultivar parameters to the winter wheat grain yield for three sites. That is, every parameter was +20% based on the calibrated and validated cultivar of ND, HD, and YZ, and the other parameter was kept constant to see the grain yield change (%) compared with the calibrated and validated cultivar of ND, HD, and YZ:

\[ \text{Yield}_c = \frac{\text{Yield}_{i(j+20\%)} - \text{Yield}_{i(j)}}{\text{Yield}_{i(j)}} \]  

(1)

where \( \text{Yield}_{i(j+20\%)} \) is the grain yield of parameter \( j +20\% \) based on the three cultivars (i), that is, ND, HD, and YZ at the SZ, XT, and ZMD sites, respectively. \( \text{Yield}_{i(j)} \) is the grain yield of parameter \( j \) for the three cultivars (i), \( \text{Yield}_c \) is the yield change (%). All the grain yields were averaged from the 1987–2016 growing seasons of winter wheat at the SZ, XT, and ZMD sites.

Second, a sensitivity analysis was conducted by the DSSAT–CERES wheat model by means of a “direction-set” algorithm optimization [31] to design and evaluate the wheat ideotypes for three different climate conditions (SZ, XT, ZMD); each site was suited for sowing ND, HD, and YZ, respectively. The three locations were representative of different climate conditions in the region (Figure 1). Some specifications of the three sites were illustrated in Table 1. Sensitivity analysis was conducted in order by initially changing the parameter that controls the wheat phenology. The value that had the highest average grain yield was chosen to represent the best value for that particular trait parameter and was selected for the next step of the sensitivity analysis, while keeping the values of the other cultivar parameters unchanged. Then, a sensitivity analysis was conducted in order on the growth parameters based on the same method. The combination of the parameters, which resulted in the highest simulated grain yield over 30 years (1987–2016), represented the ideotypes for the three sites (ND sowed at SZ, HD sowed at XT, YZ sowed at ZMD). The range values of the parameters and their incremental steps can be found in Table 2.

![Figure 1](image_url)

**Figure 1.** Three study sites were selected based on different temperatures, precipitation, and radiation values through the North China Plain (NCP).
Table 1. Details of the location and climate for each site during the winter wheat growth season (from October to June); values were the average from 1987 to 2016.

| Site | Location | Tmax (°C) a | Tmin (°C) b | AP (mm) c | AR (MJ) d |
|------|----------|-------------|-------------|-----------|-----------|
| SZ   | 40°08’12” N, 116°10’45” E | 14.7 | 4.3 | 191.7 | 3670.1 |
| XT   | 37°02’24” N, 114°18’00” E | 16.3 | 6.4 | 184.6 | 3381.9 |
| ZMD  | 33°00’00” N, 114°36’00” E | 17.4 | 7.6 | 475.6 | 4469.4 |

a annual average of maximum temperature. b annual average of minimum temperature. c Annual Precipitation. d Annual Radiation. SZ: Shangzhuang; XT: Xingtai; ZMD: Zhumadian.

2.4.2. Sowing Date Optimization

We considered the sowing dates as the key adaptation approach to climate change. For the three sites, we used the validated DSSAT–CERES wheat model with optimization ideotypes to simulate wheat grain yields during 1987–2016 with different sowing dates from 15 September to 10 November every 5 days. The seeding density of winter wheat was set to 300 plants per m\(^{-2}\), and there was no nitrogen stress. We then compared the simulated wheat grain yield at 50% and 80% of the guaranteed rate [32] and performed an analysis of variance to find a reasonable sowing window with optimization ideotypes for the three sites.

2.5. Data Source

The weather data from 1987 to 2016 for SZ, XT, and ZMD, including the daily maximum and minimum temperature (°C), precipitation (mm), and sunshine hours (h), were obtained from the China Meteorological Data Service Center [33]. Solar radiation was calculated from the sunshine hours, based on the Angström formula [34,35].

The basic soil physical parameter data included the soil bulk density, saturated moisture content, field moisture capacity, and wilting coefficient of each layer [36]. The proportion of clay sand, clay, and silt in the soil parameters was obtained from the China Soil Science Database [37].

2.6. Statistical Analysis

The influence of the sowing date on crop yield was tested using R (version 3.6.1) (R Foundation for Statistical Computing, Vienna, Austria.), while grain yield average values were considered significantly different at a least significance difference (LSD) of 5% probability level. A linear regression was used to analyze the relationships between simulated values and measured values.

Validation is a vital step to prove the model performance [38], and it includes a comparison between field observations and the output simulated by the model. Different statistical indices, for instance, coefficients of determination (R\(^2\)), D-index [39,40], root mean square error (RMSE), and normalized root mean square error (NRMSE) [41] were used to check the agreement between the observed and simulated values:

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - X_i)^2}{n}}
\]

\[
\text{NRMSE} = \frac{1}{X} \sqrt{\frac{\sum_{i=1}^{n} (Y_i - X_i)^2}{n}} \times 100
\]

\[
D = 1 - \frac{\sum_{i=1}^{n} (Y_i - X_i)^2}{\sum_{i=1}^{n} (|Y_i - \bar{Y}| + |X_i - \bar{X}|)^2}
\]
where $X_i$ and $Y_i$ are the observed and simulated values, respectively, $\bar{X}$ and $\bar{Y}$ are the average of the observed and simulated values (including phenoology, aboveground biomass, and grain yield), and $n$ is the number of observations.

3. Results and Analysis

3.1. Performance of DSSAT–CERES Wheat Model

The model showed good simulations for major phenological phases from sowing to anthesis and maturity date. The results for simulated anthesis and maturity date were satisfying, with a RMSE of 3.2 days and 4.3 days for ND211 (3.8 days and 3.4 days for HD6172, 2.3 days and 3.4 days for YZ4110) in calibration (Figure 2a,c,e). The NRMSE were lower than 10% for the three cultivars, and the index of agreement (D) was higher than 0.8, which indicated that the model could reproduce the wheat development well. The validation of the model proved the reliability of the above-derived genetic parameters, as most of the simulation data matched the observed data, and all the statistic indicators showed satisfying results (Figure 2b,d,f). For three cultivars at both calibration and validation, the $R^2$ value was close to 1, which confirmed the ability of the DSSAT–CERES wheat model to simulate the duration of the phenological phases of cultivars sowed at various dates in the North China Plain.

![Figure 2](image_url). Evaluation between measured and simulated phenology (days after sowing) for three cultivars. The single circle in blue and the blue line indicate anthesis; the single circle in orange and the orange line indicate maturity. (a,b) is winter wheat ND 211 (ND); (c,d) is semi-winter wheat HD 6172 (HD); (e,f) is weak-winter wheat YZ 4110 (YZ). (a,c,e), for calibration; (b,d,f) for validation.
The model simulated wheat grain yield well for cultivars during different sowing dates with good statistical indices (Figure 3a,b). Simulation results for grain yield were satisfying with root mean square errors (RMSE) of 272.6, 316.8, and 423.9 kg ha\(^{-1}\) for ND211, HD6172, and YZ4110, respectively, in calibration (Figure 3a). The NRMSE were lower than 10% for the three varieties, and the index of agreement (D) was higher than 0.7, indicating that the model could reproduce the wheat grain yield well (Figure 3a). The validation for the simulated and measured values was in reasonable control (Figure 3b).

The model evaluation of the aboveground biomass performed well with good statistical indices during growing seasons for cultivars at different sowing dates. Simulation results for aboveground biomass were satisfying, with root mean square errors (RMSE) of 829.3, 492.9, and 664.6 kg ha\(^{-1}\) for ND211, HD6172, and YZ4110, respectively, in calibration (Figure 3c). The NRMSE were lower than 10% for the three cultivars, and the index of agreement (D) was higher than 0.6, which indicated that the model could reproduce the wheat aboveground biomass well (Figure 3c). The validation of the model proved the trustworthiness of the above-derived genetic parameters, with most of the simulation data matching the observed ones and all the statistic indicators showing satisfying results (Figure 3d).

Taking the errors in the field experiment into account as well as observations, the agreement showed that the DSSAT–CERES model could get the changes of phenology, aboveground biomass, and grain yield in response to different cultivars under different sowing dates in the North China Plain.
Table 2. Main genetic parameters used in the DSSAT–CERES wheat model and optimal values for each of the cultivar parameters for the three sites.

| Parameter | Calibrated Value | Incremental Step | Range in the Default | Optimum Cultivar Value at Three Sites |
|-----------|------------------|------------------|----------------------|----------------------------------------|
|           | ND211            | HD6172           | YZ4110               |                                        |
| P1V       | 44               | 36               | 29                   | 5                                      |
|           | 0–60             | 55               | 55                   | 55                                     |
| P1D       | 85               | 80               | 87                   | 20                                     |
|           | 0–200            | 80               | 120                  | 100                                    |
| P5        | 575              | 585              | 560                  | 50                                     |
|           | 100–999          | 950              | 950                  | 950                                    |
| G1        | 25               | 27               | 31                   | 5                                      |
|           | 10–50            | 45               | 45                   | 40                                     |
| G2        | 35               | 36               | 31                   | 5                                      |
|           | 10–80            | 35               | 35                   | 35                                     |
| G3        | 3.0              | 2.7              | 3.1                  | 1                                      |
|           | 0.5–8.0          | 7                | 1                    | 1                                      |
| PHINT     | 110              | 75               | 85                   | 15                                     |
|           | 30–150           | 135              | 135                  | 90                                     |

*a* Days, optimum vernalizing temperature, required for vernalization; *b* Percentage reduction in development rate in a photoperiod 10 h shorter than the optimum relative to optimum; *c* Grain-filling (excluding lag) period duration (GDD); *d* Kernel number per unit canopy weight at anthesis (g$^{-1}$); *e* Standard kernel size under optimum condition (mg); *f* Standard non-stressed dry weight (total, including grain) of a single tiller at maturity; *g* Interval between successive leaf tip appearances (GDD).
3.2. Wheat Cultivar Optimization for the Three Sites

Sensitivity analysis was performed to evaluate how the simulation results changed because of the seven major parameters, which were changed in the DSSAT–CERES wheat model compared to the calibrated three cultivars. We used the grain yield as the target variable for the sensitivity analysis.

According to the physiological characteristics of winter wheat and the sensitivity analysis, the results showed that the sensitivity of each parameter for the three sites was different (Figures 4h, 5h and 6h).

At the SZ site, the result of the model sensitivity analysis showed that, with the parameter P1V increased, the wheat grain yield increased (Figure 4). Therefore, we selected the P1V value at the highest grain yield as the optimal parameter. Then, we changed the parameter P1D based on the incremental step in Table 2, and selected the value of P1D at the highest grain yield. The grain yield increased with the increase of P5, because the grain-filling duration was prolonged and the grain-filling stage is essential for winter wheat to set up grain, and it is very important for winter wheat to stabilize grain yield. The grain yield increased with the increase of G1. The sensitivity of parameter G2 was similar to parameter G1 (Figure 4h), but when G2 was greater than 35, the grain yield decreased. Parameter G3 changed the grain yield little (Figure 4g, h).

**Figure 4.** The sensitivity of wheat grain yield to each genetic parameter at the SZ (Shangzhuang) site with a cultivar of ND (ND211). The black line indicates the average grain yield; and the grey shade indicates the 95% confidence interval. The horizontal lines in the boxplot show the maximum and minimum values; the white square in the boxplot shows the average value; the upper and lower boundaries of boxes show 75th and 25th percentiles. (a–g) represent the sensitivity of P1V, P1D, P5, PHINT, G1, G2 and G3 based on incremental step, respectively at SZ (Shangzhuang) site; (h) represent the sensitivity of each parameter +20% based on calibrated ND (ND211) at SZ (Shangzhuang) site.
We optimized cultivars for the XT and ZMD sites (Figures 5 and 6) with the same method as the SZ site. The differences between the optimal cultivar parameters and the calibrated parameters were shown in Table 2. In terms of parameter P1V, the optimal cultivar parameters were the same for all three sites. The P1D parameter was lower in the SZ site than the other two sites, and was greatest in the XT site (Table 2). The sensitivity of P5 was similar for all three sites, and we selected parameter P5 at highest grain yield, which could prolong the duration of grain-filling (Figure 7). At the ZMD site, the optimal cultivar had the lowest phyllochron interval (PHINT) compared with the other two sites. Parameter G3 was larger in the SZ site compared with the other two sites. At the SZ site, the cultivars with high yield were characterized by a lower P1D and larger P1V, PHINT, P5, G1, G3 compared with the current cultivar (Table 2). At the XT and ZMD sites, the cultivars with high yield were characterized by higher P1V, P1D, P5, G1, PHINT, and lower G3 value compared with the current cultivar (Table 2). Meanwhile, regarding G2, the optimal cultivars with suitable G2 values could increase the grain yield at the three sites.

**Figure 5.** The sensitivity of wheat grain yield to each genetic parameter at the XT (Xingtai) site with cultivar HD (HD6172). The black line indicates the average grain yield; the grey shade indicates the 95% confidence interval. The horizontal lines in each boxplot from the bottom up represent the minimum, 25th percentile, 75th percentile, and maximum values; the white circle in the boxplot shows the average value. (a–g) represent the sensitivity of P1V, P1D, P5, PHINT, G1, G2 and G3 based on incremental step, respectively at XT (Xingtai) site; (h) represent the sensitivity of each parameter +20% based on calibrated HD (HD6172) at XT (Xingtai) site.
Figure 6. The sensitivity of wheat grain yield to each specific parameter at the ZMD (Zhumadian) site with cultivar YZ (YZ4110). The black line indicates the average grain yield; the grey shade indicates the 95% confidence interval. The horizontal lines in each boxplot from the bottom up represent the minimum, 25th percentile, 75th percentile, and maximum values; the white circle in the boxplot shows the average value. (a–g) represent the sensitivity of P1V, P1D, P5, PHINT, G1, G2 and G3 based on incremental step, respectively at ZMD (Zhumadian) site; (h) represent the sensitivity of each parameter +20% based on calibrated YZ (YZ4110) at ZMD (Zhumadian) site.

3.3. The Change of Winter Wheat Growth Duration, Aboveground Biomass and Grain Yield Under Optimal Cultivar Parameters

We also observed the change of phenology, aboveground biomass and grain yield of the three optimal cultivars compared with the current cultivars at the three sites (Figure 7). The grain yield could be significantly improved by 29.6%, 86.9%, and 34.6% at the SZ, XT, and ZMD sites by using the optimal cultivars, respectively. The aboveground biomass could be significantly improved by 47.2% and 12.7% at the XT and ZMD sites. However, the aboveground biomass at the SZ site was improved by 5.4%, which was not significant compared to the current cultivar. The whole growth duration (from sowing to maturity) was significantly prolonged 14.0, 27.5, and 24.4 days at the SZ, XT, and ZMD sites by using the optimal cultivars, respectively. The vegetative growth duration (from sowing to anthesis) was significantly prolonged 18.4 and 12.2 days at the XT and ZMD sites, respectively, while shortened 0.83 days at the SZ site. The optimal cultivars obtained a high yield by prolonging the vegetative growth duration and the reproductive growth duration, except for the SZ site, which prolonged the reproductive growth duration.
3.4. Optimizing Sowing Date for the Three Sites

We performed an analysis of the sowing dates based on 30 years (1987–2016) for the three sites with the optimal cultivars (Figure 8). The optimal cultivar at the SZ site achieved a maximum average grain yield (6764.6 kg ha\(^{-1}\)) when sowed on 30 September. The average grain yield decreased 71.4% once the sowing date was delayed from 30 September to 10 November. There were no significant differences from the sowing dates of 15 September to 20 October, and the grain yield on these sowing dates was significantly higher than the sowing dates of 5 November and 10 November (Table 3). When considered, the guaranteed rates were 50% and 80%, and the grain yields of the last two sowing dates were lower than the others (Figure 9). In addition, in certain years, there was no grain yield, because the winter wheat had not reached maturity at the last two sowing dates (Figure 9). The grain yield of the optimal cultivar at the XT site decreased with the sowing dates delayed. The maximum average grain yield was 6732.7 kg ha\(^{-1}\) when sowed on 15 September, and the grain yield on the first seven sowing dates was significantly higher than the last two sowing dates (Table 3). When considered, the guaranteed rates were 50% and 80%, and the grain yield of the first seven sowing dates was higher than the last two sowing dates (Figure 9). The grain yield at the first sowing date (15 September) was the highest (10893.7 kg ha\(^{-1}\)) at the ZMD site. The grain yield decreased with a delayed sowing date. There were no significant differences from the sowing dates of 15 September to 20 October (Table 3). On the other hand, the grain yield at the ZMD site showed narrow differentials in yield between the different sowing dates when the guaranteed rate was over 50% (Figure 9).
Figure 8. Simulated winter wheat grain yield of optimal cultivars at different sowing dates for the SZ, XT, and ZMD sites. The horizontal lines in each boxplot from the bottom up represent the minimum, 25th percentile, median, 75th percentile, and maximum values; the white circle in the boxplot shows the average value.

Figure 9. Guaranteed rate of simulated winter wheat grain yield for optimal cultivars at different sowing dates at the SZ, XT, and ZMD sites.
Table 3. Average grain yield and coefficient of variation (CV) of 12 sowing dates during 1987–2016.

| Sowing Date   | Optimal ND |       | Optimal HD |       | Optimal YZ |       |
|---------------|------------|-------|------------|-------|------------|-------|
|               | Grain Yield (kg ha\(^{-1}\)) | CV   | Grain Yield (kg ha\(^{-1}\)) | CV   | Grain Yield (kg ha\(^{-1}\)) | CV   |
| 15 September  | 6436.97 abc | 0.27 | 6732.67 a  | 0.28 | 10,893.67 a | 0.28 |
| 20 September  | 6528.67 abc | 0.26 | 6692.67 a  | 0.27 | 10,868.47 a | 0.27 |
| 25 September  | 6657.00 ab  | 0.25 | 6652.33 ab | 0.27 | 10,810.50 a | 0.27 |
| 30 September  | 6764.60 a   | 0.24 | 6467.07 ab | 0.27 | 10,642.77 a | 0.27 |
| 5 October    | 6719.40 ab  | 0.23 | 6297.63 abc | 0.27 | 10,369.47 ab | 0.27 |
| 10 October   | 6564.87 ab  | 0.23 | 6055.23 abcd| 0.27 | 10,079.47 ab | 0.27 |
| 15 October   | 6380.36 abc | 0.23 | 5853.87 bcd| 0.27 | 9898.53 abc | 0.26 |
| 20 October   | 6175.40 abc | 0.22 | 5623.77 cde| 0.27 | 9647.83 abc | 0.25 |
| 25 October   | 5922.13 bc  | 0.21 | 5385.60 def| 0.26 | 9307.53 bcd | 0.24 |
| 30 October   | 5734.56 c   | 0.20 | 5260.27 def| 0.27 | 9059.47 bcd | 0.24 |
| 5 November   | 4852.63 d   | 0.37 | 4959.57 ef | 0.27 | 8647.20 cd  | 0.23 |
| 10 November  | 3945.90 e   | 0.53 | 4578.67 f  | 0.27 | 8292.10 d   | 0.23 |

a–f represent significant difference at \(P\) value < 0.05. Among the grain yield of sowing date with the same letter are not significantly different (\(P \geq 0.05\)) according to Least-significant difference (LSD).
4. Discussion

4.1. Model Evaluation

The DSSAT–CERES wheat model was calibrated and validated by the experimental data, which had high-enough quality standards to run the model. The model evaluation showed that the DSSAT–CERES wheat model could simulate winter wheat growth and development with the three cultivars at different sowing dates. The NRMSE values for phenology, aboveground biomass, and grain yield were below 10% (Figures 2 and 3), which was a value below 13.5% that was indicated in agricultural experiments represented by the standard deviation of replicates [42]. The statistical indexes of calibration and validation for aboveground biomass and grain yield of winter wheat showed satisfying verification results. The genetic parameters of the three cultivars (Table 2) represented cultivar traits. The capability of the DSSAT–CERES model to simulate the phenology, aboveground biomass, and grain yield were verified in the North China Plain by previous studies [43,44]. The assessment of the DSSAT–CERES wheat model for phenology, aboveground biomass and grain yield indicated the reasonable predictive ability of the model around the globe under the no-abiotic-stress condition [45,46]. We concluded that the DSSAT–CERES wheat model could be accurately calibrated and validated for our conditions and was suitable for further use.

4.2. DSSAT–CERES Wheat Model Genetic Parameters Sensitivity Analysis

The DSSAT–CERES wheat model is a useful tool to optimize the interactions between genotypes, environments, and managements. The optimal cultivars are based on a sensitivity analysis of cultivar parameters, which affect the phenology and grain yield. The temperature and day length are the key environmental variables that influence winter wheat anthesis and can further influence grain yield components and grain yield. The parameters of P1V, P1D, P5, and PHINT influence the anthesis and maturity of winter wheat. Winter wheat cultivar usually needs relatively low temperatures to finish the vernalization. For all three sites, for the optimization of cultivars with high-yielding traits, the parameter P1V was higher than the current cultivar (Table 2), which meant that all sites required a winter-type cultivar [47]. The higher P1V meant that the optimal cultivars had a longer vegetative growth duration for all sites except the SZ site. From the results of the P1D sensitivity analysis, at the SZ site, we observed that the interaction between a higher P1V and a lower sensitivity of P1D resulted in shorter vegetative growth duration (Figure 7). A shorter photoperiod at the SZ site—caused by the lower sensitivity of P1D—generated a longer stem-elongation duration. The prolonged stem-elongation duration resulted in higher grain numbers [48,49] at the SZ site. For all three sites, the optimal cultivars had a higher P5, which extended the grain-filling period, and could capture more solar radiation, which was transferred to biomass. In recent studies, it was indicated that prolonging the winter wheat growth duration, especially the grain-filling duration, could decrease the impact of climate change on winter wheat [50,51]. In summary, the vernalization days and photoperiod were used to modify the accumulation of thermal time between emergence to terminal spikelet initiation. All three sites had high-yielding cultivars with higher P1V, P5 and G1 values. At the SZ site, the optimization cultivar had a lower P1D, and the XT site had the highest P1D. An earlier development in a dryer growth season environment such as the SZ site could allow winter wheat to avoid water stress.

The multiplication of the grain yield components generated grain yield. The cultivar parameters G1, G2, and G3 influenced the grain yield. All three sites with high-yielding traits had a higher G1 and similar G2 compared with the current cultivar, because G1 and G2 have a compensation effect on grain yield [52]; in this study, improving G1 could increase the grain yield for all three sites. At the SZ site, G3 was higher than the other two sites, due to the colder and dryer environment, needing more tillers to maintain grain yield. Potential compensation effects among grain yield components must be considered while considering grain yield improvement, due to the above parameters.

For all three sites, the optimal cultivars had the character of a longer growth period, more spikelet numbers, and greater grain weight. The vegetative and reproductive growth duration must be
optimized for different environments. These desired traits are aims for picking cultivars to grow at a contemporaneous time and which are suitable for breeding future cultivars.

4.3. Incorporating Crop Model-Based Physiology Breeding Practices and Optimizing Sowing Dates

Climate change is threatening the ability to grow winter wheat in the North China Plain. Strategies such as changing cultivars and optimizing managements could lessen the effect of climate change on crop growth. In this work, we optimized cultivars based on the validated parameters of ND211, HD6172, and YZ4110. Although the DSSAT–CERES wheat model is a mechanism model, we changed each parameter of the calibrated current cultivar, and it was arbitrary. Combining crop model and genetic analysis for breeding or to adapt to climate change is needed. For example, Guitton et al. (2018) integrated genetic analysis and crop model, and proposed an eco-physiological model, which provided a new idea for the flowering time of Quantitative Trait Locus (QTL) and its application in plant breeding programs [53]. They also identified a key QTL that affected the critical photoperiod and provided critical information to support the development of photoperiod-sensitive genotypes specially adapted to climate change faced in the Sudano–Sahelian zone. Zheng et al. (2013) used a gene-based model to integrate gene effects into the estimate heading time. They showed that the gene-based model was an appropriate method to consider how to target a gene integrated to current and future production environments with parameters determined from the phenotyping treatments. The ideotypes should yield potential or resilience traits [54]. Reynolds et al. (2010) found that, if the genetic improvement of radiation use efficiency (RUE) paralleled with attaining managements impacts, wheat yield potential could be increased by about 50%. In the same way, the wheat crop improved its grain yield when it had a heavier grain; the crop should have suitably strong stems and roots to avoid lodging [55]. Overall, integrating crop model physiology breeding with genes should consider the environment, the management, and genetic interactions (G × E × M). Furthermore, in this work, the method we used showed that the optimal parameters improved the grain yield and could be taken as an example or a simple method for breeding.

The optimization of sowing dates is one of the common strategies to cope with climate change. In this work, for all three sites, with delayed sowing dates, the grain yield was reduced. Especially during the several late sowing dates, due to the colder temperature, the grain yields were significantly lower than the other grain yields (Figure 8, Table 3). We also took the guaranteed rate at the levels of 50% and 80% to see the difference among the sowing dates. In our study, the optimal sowing dates improved the grain yield in comparison with other sowing dates. Some studies showed that optimal sowing dates could increase the grain yield, water use efficiency (WUE), and reduce evapotranspiration at the Loess Plateau [56]. The cultivars with high-yield traits and optimal sowing dates for the three sites could improve winter wheat’s resilience to the current climate change in the North China Plain.

4.4. Limitations of the Study

We considered sowing dates and optimal cultivars as strategies to adapt to current climate change at three sites. Compared with the current cultivar’s grain yield, the optimal cultivars’ grain yield was significantly increased. Therefore, to keep grain yield stable and to improve grain yield, changing the cultivar was one of the important strategies for the North China Plain to apply to adapt to climate change. In this study, there are some limitations to be considered. First, it was assumed that the soil moisture initial conditions were suitable for winter wheat to emerge. The optimal sowing dates of winter wheat have effects on anthesis that can avoid heat/drought stress on winter wheat. Second, in this study, drought stress and heat stress were not taken as the targets for optimizing winter wheat cultivar. We took the SZ, XT, and ZMD sites as examples to suppose strategies to adapt to climate. Third, in a future study, we should take different regions as study areas and use different climate conditions and potential disasters (such as frost, drought, and heat stress) as prime targets for “breeding.” In some studies, it has been shown that the use of multimodel ensembles is a possible method to reduce model uncertainty and attain accurate results [42,57], along with the use of
multimodel ensembles as a method to design future ideotypes (virtual cultivar) [58]. In the future, we should consider winter wheat–maize as a whole system for further study.

5. Conclusions

This study aimed at assessing approaches to cope with climate change. The statistical indexes indicated that the DSSAT model could achieve the changes of phenology, aboveground biomass, and grain yield in response to different cultivar and sowing dates in the North China Plain. The most sensitive parameters were P1D, PHINT, G1, and G2. The cultivars with longer growth duration and more spikelet numbers and grain weights were promising for the three sites. The growth duration of the optimal cultivars winter wheat were significantly prolonged by 14.0, 27.5, and 24.4 days, and the grain yield were significantly improved by 29.6%, 86.9%, and 34.6% compared with the current cultivar at the SZ, XT, and ZMD sites, respectively. We also selected 12 sowing dates as strategies to improve the grain yield. Based on guaranteed rates and an analysis of variance, we recommended a later sowing date at all three sites with grain yield having no significant difference between the early sowing dates. Our findings are useful for “breeding” climate-resilient cultivars and optimizing sowing dates as a management practice for location-specific environments to improve winter wheat grain yield. The suitable sowing dates were between 15 September and 20 October for the SZ and ZMD sites, and between 15 September and 15 October for the XT site. The optimal cultivars improved the winter wheat grain yield and made the simulated grain yield more stable. In addition, the methodology of this study could be expanded to other regions and possibly to other crops.

Author Contributions: Conceptualization, C.W. and L.F.; Methodology, C.W., L.W., and L.F.; Software, C.W. and Y.L.; Validation, C.W., L.F., and C.C.; Formal analysis, C.W.; Investigation, C.W. and L.F.; Data curation, C.W.; Writing—original draft preparation, C.W.; Writing—review and editing, C.W., L.P., L.W., and Y.L.; Visualization, J.Y. and J.G.; Supervision, L.F.; Project administration, L.F. and F.C.; Funding acquisition, L.F. and F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China, grant number 2016YFD0300201.

Conflicts of Interest: The authors declare no conflict of interest.

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