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Studies on management model for wheat production based on key agronomic factors

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Abstract. Experiments of the pentagonal quadratic orthogonal combining design were conducted in the three major wheat ecological areas in Sichuan Province of China to study the effects of the five key agronomic factors (X_1: sowing date; X_2: seedling density; X_3: N application; X_4: P application and X_5: K application) on wheat yield to build up the production management models. The results indicated the differences in the importance of the respective factors to wheat yield between different ecological environments. The effects of the different agronomic factors in the west flat area, the middle area of small hills, and the south-west areas of Sichuan basin were respectively in the turns of $X_1 > X_3 > X_2 > X_4 > X_5$; $X_3 > X_1 > X_4 > X_5 > X_2$, and $X_4 > X_3 > X_1 > X_2 > X_5$. The way and impact for the different agronomic factors to affect the wheat yield were determined by the ecologic environment and the levels of other factors. So the setting up of the production management models was important to realize the potentials of wheat varieties according to the local conditions with minimal investment and was able to provide solutions to make decisions in a system of multiple factors, layers and purposes.

Keywords: key agronomic factors, wheat, production management, model

1 Introduction

Management model for wheat production is a knowledge-based computer software system which is a high-tech resulted from the application of specialist decision-making systems into agriculture[3,7,9].It is a complex system including several sub-systems involving the researches on weather, soil, production conditions, cropping systems, varieties and cultivation technology and other factors of different layers for multi-purposes[11,12]. The effects of the different factors on the system are not equaled because some key factors can affects the whole complex system much more significantly than others[13,16]. It is a solution for the decision-making in a complex system for multi-purposes involving a multitude of factors of multi-layers to find out key factors and then produce a management model based on the key factors after the experiments on the quantitative relationships between the different key factors[19,25].

The ability of crop simulation models to predict growth and yield as influenced by the environment, agronomic practices and crop traits suggests that such models can identify traits to increase yield potential[6,14,20,28]. Similarly, models seem ideal for studying variation in cultivation response to environment, the genotype x environment interaction[4,17,22]. Data on soils, weather and cultivars are not available in 'model-ready formats', notwithstanding efforts to establish standards for minimum data sets [10,18]. A logical starting point for such a wheat model is the simulation of phenology. Based on reviews of wheat phenology by Flood and Halloran(1986)[8] and Slafer and Rawson (1994)[23], field comparisons of cultivars of known genotypes in contrasting environments should be emphasized[1,2,5,30]. Previous studies have indicated that wheat

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varieties and several other agronomic factors out of the hundred of involved factors were determining in wheat production decision-making[20,21,24,26,27,31].

As an attempt to solve the complexities in the decision-making in wheat production, the authors selected five key agronomic factors affecting the wheat yield and quality as the basis for the building of the management models for wheat production by the methods of multi-location ecological experiments of the pentagonal quadratic orthogonal combining design and verification experiments in wheat production[15,29]. The resulted management models provide a possibility to solve the decision-making for multi-purposes involving multi-factors of multi-layers.

2 Methods and materials

Five key agronomic factors involving sowing date (X_1), seedling density (X_2), the amount of applied Nitrogen (X_3), calcium superphosphate$X_4$and Potassium Chloride (X_5) were selected as decisive variables and grain yield (Ya), ears/hm^2(Yb) and weight of 1000 grains (Yc) as dependent variables, of which the levels and codes were shown in Table 1. Experiments of the pentagonal quadratic orthogonal combining design $(Mc = 16, Mr = 10, Mo = 10)$ were made in three ecological areas in Sichuan basin of China: Guanghan City located in the west flat area, Zizhong County in the middle area of small hills, and Fushun County in south-west areas of Sichuan basin. Four controls were made (X_1=0, X_2=0 and no application of N, P, and K) in the experiments of 40 plots of the size 3.2m×2 m. Distance between rows and hills were respectively 20 cm and 10 cm. Plots were arranged in random within each block. Factors other than the treatments were the same as the requirement for the local high-yield cultivation. 70% of N and all of the P, K were applied as base fertilizer and the remaining 30% N were applied at the period of shooting.

Table 1. Variable and coded levels

Agronomic factors (X)	ΔX	Coded levels				
		-2	-1	0	1	2
X_1 Sowing date, day/month	5	26/10	31/10	5/11	10/11	15/11
X_2 Seedling density, seedling/m^2	50	148	198	248	298	348
X_3 Nitrogen, kg/hm^2	60	0	60	120	180	240
X_4 Calcium superphosphate, kg/hm^2	225	0	225	450	675	900
X_5 Potassium Chloride, kg/hm2	37.5	0	37.5	75	112.5	150

Investigation at the determined locations inside each the plots were made to record the growth of wheat seedlings and efficient ears. Yield of biomass and wheat grain were harvested without the lateral rows. Grain number and weight were investigated on the basis of individual plants. Data were analyzed by statistic software DPS[15,29].

3 Result and analysis

3.1 Effects of key agronomic factors on wheat yield

Table 2 shows the regression models of the each decisive variable and dependent variable. The result of non-correlation tests the further significance tests of the regression models $(F_2 < F_{0.01}, F_1 < F_{0.05})$ indicated the satisfying simulation correlation degree to the results at each experiment location and the main factors affecting wheat yield had been tested. After the deletion of the insignificant items (α=0.05), the optimal regression equations for wheat yield (kg/hm^2) were as the followed:

$$Y = 5453.6 - 291.6X_1 - 127.7X_1^2 - 114.3X_3^2 - 93.9X_4^2 + 131.6X_1X_2 \quad \text{(for Guanghan);}$$

$$Y = 4346.1 + 441.3X_3 - 105.0X_1^2 - 168.9X_3^2 + 149.1X_1X_2 + 117.2X_4X_5 \quad \text{(for Zizhong);}$$

and $$Y = 3604.7 + 335.0X_3 + 139.5X_4 - 191.9X_1^2 - 215.9X_3^2 - 124.8X_4^2 + 139.1X_1X_2 \quad \text{(for Fushun).}$$

Table 2. Regression coefficients and result of the significance tests

Coef-ficient	Yield(kg/hm^2)			Ears/m^2			Grains/ear			1000-GW(g)		
	G	Z	F	G	Z	F	G	Z	F	G	Z	F
B_0	5453.6	4346.1	3604.7	368.9	294.3	268.1	37.34	30.58	39.83	39.57	48.62	46.01
B_1	-291.6^{**}	-55.504	-67.05	-22.4^{**}	-2.7	5.0	0.19	0.72	1.05	-0.52^{*}	-0.47^{*}	-0.21
B_2	64.05	29.25	-22.95	7.2^{**}	21.9^{*}	20.0^{**}	-0.52^{*}	-1.88^{*}	-2.53^{**}	0.23	-0.18	-0.35
B_3	85.05	441.30^{**}	334.95^{**}	9.6^{**}	12.5^{*}	14.0^{**}	0.26	2.39^{*}	1.15	-0.71^{*}	-0.72^{*}	-0.88^{**}
B_4	2.1	8.70	139.50^{*}	-0.6	5.4	1.5	-0.03	-0.28	1.30^{*}	-0.06	0.20	0.29
B_5	7.50	-24.75	-14.85	4.2	-3.8	-3.5	-0.08	0.26	-0.18	-0.08	0.07	0.52
B_1^2	121.65^{**}	-105.00^{*}	-191.85^{**}	-3.8	2.1	-6.2	0.10	-0.54	-0.18	-0.73^{*}	-0.02	-0.12
B_2^2	-38.10	-41.70	27.90	-2.3	4.5	3.8	0.28	-0.06	0.39	-0.02	-0.08	-0.31
B_3^2	-114.30^{**}	-168.90^{**}	215.85^{**}	2.6	-7.1^{*}	-6.8	-0.80^{*}	-0.29	-0.83	0.21	-0.00	-0.59^{*}
B_4^2	-93.90*	66.30	-124.80^{**}	-4.4	2.1	-0.5	-0.52^{*}	-0.15	-0.86	-0.02	-0.15	-0.08
B_5^2	-68.85	51.90	15.90	-3.8	5.1	2.7	-0.65^{**}	-0.32	0.24	0.57^{*}	-0.13	0.27
B_{12}	131.55^{*}	149.10^{*}	139.05^{*}	11.1^{**}	5.4	6.0	0.04	-0.27	0.49	-0.10	-0.03	-0.28
B_{13}	63.90	56.40	-40.80	-3.0	5.4	-1.2	0.30	0.45	-1.95^{*}	0.21	0.81	-0.43
B_{14}	2.10	27.45	23.85	1.7	1.8	-0.8	-0.10	0.04	-0.35	0.11	-0.28	-0.17
B_{15}	-7.35	22.05	22.20	-1.5	0.2	-3.8	0.01	-0.25	-0.66	0.15	0.09	0.21
B_{23}	30.30	16.05	-22.20	-4.7	-9.6^{*}	-10.7	0.34	0.02	2.11^{**}	0.10	0.38	-0.11
B_{24}	0.45	2.85	-13.80	5.0	2.9	-5.9	0.16	-0.28	1.04	-0.18	-0.03	-0.07
B_{25}	17.10	37.95	7.05	2.9	3.9	10.4	0.05	-0.19	0.85	-0.24	0.12	0.18
B_{34}	-17.40	-21.60	11.85	-4.4	4.1	7.7	-0.13	0.13	0.03	0.01	0.28	-0.34
B_{35}	-21.30	-33.90	-51.60	3.0	-2.6	-6.9	-0.09	0.33	1.49	-0.10	-0.32^{*}	0.51
B_{45}	1.35	-117.15^{*}	-107.40	3.2	-11.0^{*}	-1.4	-0.19	0.99	-1.24	-0.13	-0.36^{*}	-0.08

Note *, **: Significant at $P < 0.05$ and $P < 0.01$ levels. G: Guanghan, Z: Zizhong, F: Fushun

The yield regression model resulted from the experiments in Guanghan showed that only the simple coefficient of X_1, instead of that of X_2, X_3, and X_4, was significant, indicating that sowing date X_1 had significant effects on wheat production. The significant but negative binomial coefficient of X_1, X_3 and X_4 in the regression indicated that the un-proper increase in the levels of the sowing date, N and P could resulted in the decrease of the wheat yield in Guanghan. The orthogonal coefficient other than that of X1 and X_3 were not significant. The wheat regression model for Zizhong only showed significance of positive simple coefficient of X_3, the negative binominal coefficient of X_1 and X_3, the positive orthogonal efficient of X_1X_2 and the negative orthogonal coefficient of X_4X_5. The result form the experiments at Fushun indicated that simple coefficient and the negative binominal coefficient of N and P amount, the negative binominal coefficient of sowing date as well as the orthogonal coefficient of sowing date and density were significant, indication that the increase in the N and P levels in certain ranges could significantly increase the wheat yield but could resulted in decrease in the yield above the proper levels whereas the postponing of the sowing date would decrease the wheat yield.

The calculation of the contribution of the individual factors to the wheat yield on the basis of F values can determine the importance of the key agronomic factors to the wheat yield in different ecological areas. The contribution of each factor at Guanghan, Zizhong and Fushun were respectively in the sequences of $X_1 > X_3 > X_2 > X_4 > X_5$, $X_3 > X_1 > X_4 > X_5 > X_2$ and $X_4 > X_3 > X_1 > X_2 > X_5$. The result indicated that the sowing date and then N application were the most important factors for wheat yield in the west flat of Sichuan basin whereas the in the small-hilled areas in the middle of the basin the most important factors were N application and then sowing date. For southeast areas of Sichuan, it could be concluded that the application of P and subsequently that of N were most important for wheat yield.

The significant effects of the different agronomic factors on the ear numbers were sequenced as sowing date (X_1) >density $(X_2) > N$ application (X_3) at Guanghan, $X_3 > X_2 > K$ application $(X_5) > X_4$ (P application) at Zizhong and $X_3 > X_2 > X_1 > X_4$ at Fushun. Sowing date has little effects on ear number at Zizhong and Fushun. For grain numbers pear ear at three experiment locations, the simple coefficient of density (X_2) were all significant (α =0.05 or 0.01) but negative, indicating the negative effects of the density to grain number. Among the other factors, all of the significant and negative binomial effects of N, P and K

application on the grain number at Guanghan showed the negative effects of the over-fertilization on the grain number pear ear of wheat. The significant simple effects and the negative but insignificant binomial effects of N application showed that high N provision is key to the obtaining of high grain number in Zizhong. The similar effects of N provision on grain number had been observed in Fushun where the factor had significant but negative interactive effects with sowing date and positive interactive effects with densities, K application. Similar to that of N application at Zizhong, the effects of P application were positive. The late sowing and increases in N levels were harmful to the grain weight increase while increase in K levels was observed to have positive effects on grain weight increase at Guanghan.

3.2 Decision-making analysis

3.2.1 Major effects of individual agronomic factors

Analysis the binominal variable relationship between individual treatment factors and yield were conducted by lowering dimension method. It was indicated the sowing date had prominent effects on wheat yield. When density (X_2), N (X_3), P (X_4), and K (X_5) application were at the level -2 (basic seedling at 144/m^2, no N, P and K application), wheat yield was higher than in the former cases and decreased sharply at all experiment locations when sowing date were postponed. The wheat yield decreased less in according to the later sowing dates when X_2, X_3, X_4 and X_5 were at the level 0 (medial). At the high level of other factors of $+2$, the effects of the sowing date on wheat yields were different in different areas: the sowing date between the interval from -2 to 0 at Guanghan and Fushun increased in accordance to the later sowing but the postponing of the date over the level 0 resulted in the yield decrease, however, a increase in yield was obtained by postponing the dated from level -2 to$+2$ at Zizhong.

The increase in density resulted in the yield decrease when seed were sown on October 26 and without N, P and K application, and the result was more prominent at Fushun. When seeds were sown on November 5 and fertilizers were applied at medial levels, wheat yield at different density levels were higher and stable. At all locations, the increased brought about the higher yield at high fertilization level of $+2$ when sowing date was postponed to November 15.

Increases in N application in certain regions gave rise to yield increase whatever the levels of other factors but the increase magnitude was larger in the small-hilling areas where a higher threshold level for N application to resulted in decrease in wheat yield was also observed.

There was large difference in the effects of P application on wheat yield between different areas. The increase the P application from -2 to 0 brought about the yield increase in certain degrees while the higher level over 0 resulted in yield decrease at Guanghan. At Zizhong, the increase in P application from -2 to $+2$ was observed to increase the wheat yield when other factors were all at the level -2 and to reduce the yield when levels of other factors were enhanced, for instance, to $+2$. The increased P application resulted in the significant increase in wheat yield when the levels of other factors were also higher, especially at the level of $+2$.

The effects of the K application on wheat yield were similar to that of local P application at Guanghan and Zizhong but were different from the latter at Fushun where the increase in wheat yield in according to higher level of K application was observed when other factors were at the level of -2 but not at the level of 0. The increase in K application at Fushun resulted in a reduction in wheat yield at the level of $+2$ of the other factors.

From the extremum analysis in marginal yield models for individual factors after the calculation of partial differential coefficient, the optimal level of the individual factor for highest wheat yield when other factors at the level of 0 were obtained. The sowing date at Guanghan was at the level of -1.2 (October 30) when the density, N, calcium superphosphate and Potassium Chloride were respectively at the level of 248 seedling/m^2, N120, P450 and K75kg/hm^2. The optimal density was level of 0.84 (289seedling/m^2) when other factors were at the level 0 in Guanghan.

3.2.2 Interactive effects between different agronomic factors

The experimental results had indicated the significance of the interaction between the sowing date and density. At the 0 level of other factors, the models of effects on wheat yield were respectively:

$$Y = 5453.6 - 291.6X_1 + 64.1X_2 - 121.7X_1^2 - 38.1X_2^2 + 131.6X_1X_2 \quad \text{(for Guanghan);}$$

$$Y = 4346.1 - 55.5X_1 + 29.3X_2 - 105.0X_1^2 - 41.7X_2^2 + 149.1X_1X_2 \quad \text{(for Zizhong);}$$

$$\text{and} \quad Y = 3604.7 - 67.1X_1 - 23.0X_2 - 191.9X_1^2 + 27.9X_2^2 + 139.1X_1X_2 \quad \text{(for Fushun).}$$

When paired code value were imputed the theoretical wheat yield were obtained as in Table 3. It is obvious that variation in the yield at different densities were different according to the sowing dates. The variation coefficient was 2.3 when X_1=-1 ∼1.0, it increased sharply when X_1=-2 or $+2$, especially in the latter case at Guanghan. When sown early (at level of $-2 \sim -1$), wheat yield increased in accordance to the increases in the density. The situation was the opposite when sowing was postponed to level $+1 \sim +2$. The variations in the yield decreases between the different sowing dates decreased from 18.4% to 4.7% in according to the density level increase from -2 to $+2$ at Guanghan. The variation in wheat yield was relatively less when sowing from $-1 \sim +1$ and increased when X_1=-2 or $+2$ at Zizhong where the yield variation between different sowing dates was less at the density levels from $0 \sim +1$ and became largest when density was at the level of -2. At Fushun, the yield variation between different densities was large at each sowing dates and that between different sowing dates was relatively less between at the density levels from $-1 \sim +1$.

Among the different ecological areas, the yield variation between the different density levels were sequenced as Fushun>Zizhong>Guanghan whereas that between different sowing dates were Guanghan>Fushun>Zizhong.

The analysis of the interactive effects between X_4 and X_5 in Zizhong indicated that wheat yield was the highest at levels of low P and K application or at that of low K or high P. The concomitant high or low levels of P and K application could result in the decrease in wheat yield. When P (or K) application was leveled at 0, the yield variation between different K (or P) was the least.

3.2.3 Yield potential and optimal integrated agronomic methodology

The differences in the soil fertility and climate conditions between different ecological areas were indicated in Table 4. Wheat yield without fertilizer application in Guanghan, Zizhong and Fushun was respectively 5.195, 2.225 and 2.189ton/hm^2. The average yield after the 36 treatments at the three locations was respectively 5.454, 4.436, and 3.605ton/hm^2. Compared to the non-fertilization controls, the increase magnitude at the three locations were respectively 5.0%, 95.3% and 64.7%. When other factors at the level 0, the early sowing at Guanghan gave rise to a yield of 5.862ton/hm^2 which were 18.7% higher that that resulted from late sowing. At Zizhong and Fushun, the yield in both cases of early and late sowing was similar and was$7.0 - 9.0\%$lower than the respective averages of all the treatments. The high densities resulted in an increase around 11.0% in wheat yield compared to the low densities at Guanghan and Zizhong but no variations were observed at Fushun. The high Napplication at Guanghan gave rise to a yield increase of 5.6% than without N application whereas the increase in wheat yields by high$N$ treatment at Zizhong and Fushun was as high as 90.6%. The high application of P resulted in an increase in the yield of 42.1% and high potassium application was harmful to high yield at Fushun but not at other locations.

The distribution frequencies of different agronomic factor levels at different wheat yield levels were also indicative. At Guanghan, the agronomic levels of the highest frequencies over the yield level of 5.7225ton/hm^2 were sowing date and density coded from $-2 \sim +2$, Nitrogen and calcium superphosphate application coded from $-1 \sim +1$ and the frequency of Potassium Chloride were the same for each levels, which indicated that the sowing from October 26 to 31, densities at 148 ∼198 seedling/m^2, Nitrogen, calcium super phosphate application respectively 120 and 450kg/hm^2 as well as small amount of Potassium Chloride were the optimal agronomic methodology for Guanghan. For the wheat yield over 4.4775ton/hm^2 at Zizhong, the agronomic factor levels of the highest frequencies were respectively sowing date coded from $-1 \sim +1$(at the frequency

Table 3. Interaction of yield (kg/hm^2) between sowing date (x_1) and seedling density (x_2)

X_2 Coding value	Guanghan							
	X_1 Coding value					Y	S	CV %
	-2	-1	0	1	2			
-2	5796	5606	5172	4497	3577	4930	906	18.4
-1	5711	5653	5351	4807	4013	5107	709	13.9
0	5550	5618	5454	5040	4384	5209	513	9.9
1	5313	5518	5480	5198	4673	5236	340	6.5
2	5000	5336	5429	5355	4886	5201	242	4.7
Y	5474	5546	5377	4979	4306			
S	323	128	124	338	523			
CV	5.9	2.3	2.3	6.8	12.1			

X_2 Coding value	Zizhong							
	X_1 Coding value					Y	S	CV %
	-2	-1	0	1	2			
-2	4408	4370	4121	3662	2994	3911	593	15.2
-1	4265	4376	4275	3966	3446	4065	378	9.3
0	4037	4296	4346	4185	3815	4136	215	5.2
1	3726	4136	4334	4323	4101	4124	246	6.0
2	3333	3890	4238	4376	4304	4028	431	10.7
Y	3954	4214	4263	4103	3732			
S	432	206	92	293	524			
CV	10.9	4.9	2.1	7.1	14.0			

X_2 Coding value	Fushun							
	X_1 Coding value					Y	S	CV %
	-2	-1	0	1	2			
-2	3685	3300	2971	2698	2425	3016	495	16.4
-1	3915	3670	3480	3346	3267	3536	261	7.4
0	3762	3656	3605	3610	3670	3660	64	1.7
1	3225	3258	3346	3490	3670	3402	191	5.6
2	2304	2476	2703	2986	3325	2759	407	14.7
Y	3378	3272	3221	3226	3276			
S	653	485	374	377	513			
CV	19.3	14.8	11.6	11.7	15.7			

Table 4. Potential yield of wheat in different ecological zone (kg/hm^2)

Ecological location	No fertilization	Mean of all treatments	Early sowing	Late sowing	High density	Low density	High N	No N	High P	No P	High K	No K
Guanghan	5195	5454	5826	4910	6014	5391	5544	5250	5541	5417	5625	5534
Zizhong	2225	4346	4034	4077	4538	4080	3986	2616	4763	4719	4707	4659
Fushun	2189	3605	3129	3059	3920	4026	3780	2216	3947	2778	3410	3990

of 80%), N application from $+1 \sim +2$, density at -2 or $+2$ where as the frequencies of P and K application were similar between different levels. The frequencies of sowing dated coded as 0, -1 and $+1$ were respectively 50%, 25% and 25% when wheat yield was over the level of 3.675ton/hm^2 while that of N, P application respectively coded by $+1$, $0 \sim +1$ were as high as 80% and 100%. However, the frequencies of density and K application were similar at different levels.

4 Discussion and conclusions

The experimental results indicated the differences in the determining factors affecting the wheat yield between the different areas in Sichuan basin due to the differences in the soil fertility and climate conditions. The agronomic factors of primary and subsequent importance to affecting the wheat yield at Guanghan in west flat, Zizhong of middle small-hills, and Fushun in south east of Sichuan basin were respectively sowing date(X_1) $>$ N application(X_3) $>$density(X_2), N application(X_3) $>$sowing date(X_1) $>$ P application(X_4) and P application(X_4) $>$ N application(X_3) $>$sowing date(X_1). The building-up of the management models for wheat production based on key agronomic factors after experiments is important to make rational cultivation methodologies in accordance to local conditions and to realize of the variety potentials for the achievement of the high yield of wheat.

There was significant difference in the wheat yield between flat and hilling areas in Sichuan basin which could be minified but not eliminated by fertilization or adjusting in the sowing date and densities due to the more instinct differences in soil, climate and other environmental factors.

It was generally perceived that the ear number of primary importance for the wheat yield composition in the hilling areas with relatively lower production rates and hence the higher seedling density was pursued to ensure the ear number[14,30,31] But this researches concluded that ear number failed to increase in accordance to the increases in seedling densities because it tended to be adjusted by N application and sowing dates then seedling density was only of secondary importance to realize ear number. In contrast, the effect of the seedling density on wheat yield in flat areas was larger than that in hilling areas. When other factors were at the level 0 (sowing date on November 5, moderate fertilization), the seedling density around 285/m^2 was required for the high output of wheat.

The results indicated the differences in the importance of the respective factors to wheat yield between different ecological environments. The way and impact for the different agronomic factors to affect the wheat yield were determined by the ecologic environment and the levels of other factors. So the setting up of the production management models was important to realize the potentials of wheat varieties according to the local conditions with minimal investment and was able to provide solutions to make decisions in a system of multiple factors, layers and purposes.

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