Allocation of maize varieties according to temperature for use in mechanical kernel harvesting in Ningxia, China

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Abstract: The reasonable assessment of maize varieties in different ecological regions can allow temperature resources to be fully exploited and reach the goal of high yield and efficiency and is thus an important direction of modern maize development in China. In this study, a logistic power nonlinear growth model was used to simulate the accumulated temperature required for kernel dehydration to moisture contents of 25%, 20%, and 16% for various maize cultivar, which were divided into six types based on the accumulated temperature required for kernel dehydration to a moisture content of 25%. The relationship between the yield of maize cultivars and the accumulated temperature required for kernel dehydration to a moisture content of 25% was found to follow a unary function model. Changing the planted maize variety was found to increase economic returns by more than 7000 RMB/hm^2 in Ningxia, Northwest China. Under the conditions of mechanical grain harvesting, economic benefits can be further increased by means of selecting high yields and fast-dehydrating varieties, selling when the grain dehydration is below 16%. A better way to achieve grain dehydration to a moisture content below 16% is to postpone the harvest date as much as possible rather than drying after the harvest at physiological maturity. The areas of various types of maize varieties can be dehydrated to moisture contents of 25%, 20%, and 16% were marked. Based on the distribution of heat resources in different regions of Ningxia from the normal sowing date to October 31 before winter irrigation, the appropriate cultivars for various regions in the province were determined based on production benefits. Therefore, in different areas of Ningxia, selecting suitable maize varieties according to temperature resources can reach a high yield and mechanical kernel harvesting, and ultimately obtain higher economic benefits.

Keywords: maize, dehydration, grain yield, economic return, mechanical kernel harvesting
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1 Introduction

Technology for the mechanical harvesting of maize kernels is being rapidly promoted in China. The moisture content of maize kernels has an important effect on the benefits of mechanical kernel-harvesting[1,2]. The quality of maize kernels is inversely related to their moisture content. Additionally, kernels with a high moisture content have a low unit sale price, high drying costs[3], and are difficult to transport and store. Therefore, lowering the moisture content of maize kernels at harvest time is key for improving the benefits and quality of maize harvesting.

Compared to the United States, the grain moisture content of maize at harvest is high in China. Generally, Chinese maize is mechanically harvested at moisture contents of 20%-28%[4]. The broken rate is often less than the Chinese national standard of ≤5% (GB/T-21962-2008) when the kernel moisture content is 15%-25%; meanwhile, the broken rate is the lowest when the kernel moisture content is 20%[5]. According to a report on the quality of maize kernels by the US Grain Council, from 2011 to 2019, the moisture content of harvested maize kernels in the United States averaged 16.4%. Most farms in the United States reduce the cost of kernel drying by ventilating at low temperature in autumn and winter[6].

Maize variety and temperature are the key factors that influence maize kernel dehydration[7-12]. The change of kernel moisture content with accumulated temperature can be simulated by the Logistic Power nonlinear growth model[13]. In the mechanical harvesting of maize kernels, some early-maturing and fast-dehydrating varieties are being widely adopted in China. Early-maturing cultivars require less accumulated temperature between sowing and physiological maturity[14]. Additionally, the dehydration rate of early-maturing cultivars is faster than that of late-maturing cultivars. However, the yield of late-maturing cultivars is generally higher than that of early-maturing cultivars. Nevertheless, early-maturing cultivars require less dehydration

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time in the field after physiological maturity[15]. Therefore, maize varieties with high yield and a fast dehydration rate are suitable for mechanical kernel harvesting.

China has a large maize planting region with large differences in accumulated temperature, radiation, and precipitation. Therefore, the reasonable assessment of maize varieties to make full use of temperature resources and reach the goal of high yield and efficiency is an important direction of modern maize development in China. The Ningxia Hui Autonomous Region (NHAR) is located in the arid region of Northwest China. The low-altitude areas in the north and the middle of the region are irrigated agricultural areas where the accumulated temperature of ≥0°C from April to October is up to 4100°C·d; the high-altitude areas in the south are dry-farming regions with 2900°C·d minimum accumulated temperature of ≥0°C from April to October. Therefore, Ningxia can represent the temperature conditions of the main maize growing areas in China. The north and middle of Ningxia can represent the maize cropping pattern in the irrigated agricultural area of Northwest China.

Studies have shown that there are significant differences in the rate of grain dehydration for maize varieties with very similar growth periods. Therefore, in this study, the indicator of growth period was abandoned and used the accumulated temperature requirement of variety's dehydration to 25% as the criterion for the variety's dehydration type was used. This work aimed to answer the following rarely studied questions: (1) What is the relationship between the accumulated temperature demand for dehydration to 25% and the yield? (2) In production, how much do economic benefits differ between maize varieties with different dehydration types? and (3) How much does the economic benefit change between high-moisture grain harvest and low-moisture grain harvest?

In this study, a Logistic Power nonlinear growth model was used to simulate the accumulated temperature that is required to dehydrate the kernels of various maize cultivars to a moisture content of 25%. Additionally, the cultivars were classified by 200°C·d as the gradient in order to match the various types with accumulated temperature resources. The classification results reflect the dehydration characteristics of the studied cultivars. The economic benefits of various types of maize varieties were calculated based on total production investment and total grain sales value. A univariate function model was used to simulate the relationship between yield and the accumulated temperature demand for maize grain dehydration to a moisture content of 25% and calculated the difference in economic benefits between different varieties. Additionally, the economic benefits per hectare of high-moisture maize kernels after drying was calculated. Furthermore, the saved drying costs of maize kernels by naturally drying in the field after physiological maturity was calculated. Further, we determined the regions in Ningxia in which various types of maize varieties can be dehydrated to moisture contents of 25%, 20%, and 16% under normal sowing conditions. Based on the test results, we recommend varieties high yield and low lodging rate varieties to be planted in each region in Ningxia. These results will promote the development of mechanized maize-kernel harvesting technology in China. Additionally, they are of great significance for promoting the current transformation of Chinese maize from high moisture at harvest (≥25%) to low moisture at harvest (≥20%), which is important to increasing the economic benefits of maize grain harvesting technology. This study could be an important reference for other regions to achieve mechanical grain harvesting.

2 Materials and methods

2.1 Experimental design

The experiment was conducted in 2017-2019. In 2017 and 2018, a total of 38 locally grown maize cultivars were planted in the Yongning test base of the Ningxia Academy of Agriculture and Forestry Sciences in the NHAR. A total of 19 cultivars were planted in 2017 and a total of 30 were planted in 2018, with 11 cultivars in common between the two years (Table 1). The row spacing was 60 cm and the planting density was 90 000 plants/hm^2. The method of field management was the same as the local production. Etoxazole and lambda-cyhalothrin were sprayed once during the period between silking and physiological maturity. A total of 250 single-ear plants of maize without pests were selected before the silking. The ears were bagged until the filaments had grown to 2-3 cm. Then, after the bags were removed, the plants were jiggled to achieve full pollination. The moisture content of the kernels in the middle of the ear was measured at intervals of 5-7 d beginning on the 10th day after pollination. The moisture content of the kernels was measured at an interval of 2-3 d when the plants were close to physiological maturity. The disappearance of the milk line and the formation of a black layer on the surface of the kernels were used as indicators of physiological maturity. The experiments were terminated on September 27 in 2017 and October 30 in 2018. In 2019, a total of three plots were added, one in Yingchuan City, one in Lingwu City, and one in Pingluo County, planting 3-5 cultivars of maize in each plot. Then, the kernel moisture content and broken rate of the harvested kernels were measured in Yingchuan, Lingwu and Pingluo (Table 1). The data of average air temperature during the growing season (from April 1 to October 31) in 2008-2018 in Yinchuan were obtained from the National Weather Service Network of China. The average air temperature during the 2017 and 2018 growing seasons is normal level (Figure 1).

Table 1 Maize cultivars investigated in this study

Year	Site	Cultivars	Plot area	Sowing date
2017	Yinchuan	Lianchuang 825 (LC825), MC670, Denghai 618 (DH618), Denghai 739 (DH739), Denghai 769 (DH769), Denghai 786 (DH786), M751, Denghai 105 (DH105), Lianchuang 808 (LC808), Liaodan 575 (LD575), Liaodan 585 (LD585), Liaodan 586 (LD586), Shaandan 628 (SD628), Zengyu 1572 (ZY1572), Zhengdan 528 (ZD528), Heyu 187 (HY187), Nonghua 213 (NH213), Zhengdan 1002 (ZD1002), Shandan 620 (SD620)	72.0 m^2	Apr. 20
2018	Yinchuan	M751, Dika 519 (DK519), Huamei 1 (HM 1), LC 825, NH213, Xianyu 335 (XY335), DH739, Dongdan 1331 (DD1331), Jidan 66 (JD66), LD575, Ruipu 909 (RP909), Yinyu 123 (YY123), DH769, Dongdan 6531 (DD6531), Jingnongke 728 (JNK728), LD585, SD620, Yinyu 274 (YY274), Dika 517 (DK517), Fuyou 968 (FY968), Lidan 295 (LD295), LD586, Xianyu 1321 (XY1321), Yinyu 439 (YY439), ZY1572, Zhengdan 958 (ZD958), KX9384, Demeiya 1 (DMY 1), Demeiya 2 (DMY 2), DH786	72.0 m^2	Apr. 28
2019	Lingwu	KX9384, DK517, YY274	5.0 hm^2	Apr. 14
	Pingluo	KX9384, DK517, YY274	5.0 hm^2	Apr. 24
	Yinchuan	KX9384, DK517, YY274, XY335, YY439	3.3 hm^2	Apr. 20

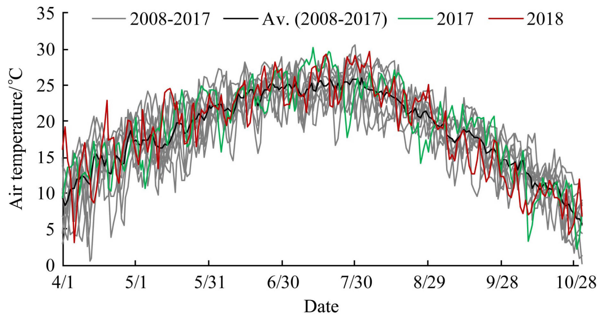


Figure 1 Average of air temperatures during the growing season in 2008-2018 in Yinchuan

2.2 Sampling and measurements

2.2.1 Kernel moisture content

Five ears were removed from each cultivar and the kernels in the middle of the ear were removed. A total of 100 fresh kernels were weighed before and after drying in an oven at 85°C in order to calculate their moisture content. Three replicates were performed for each cultivar. The kernel moisture content was calculated as follows:

$$MC=\frac{WF-WD}{WF}\times 100\% \tag{1}$$

where, MC is the kernel moisture content, %; WF is the fresh weight of kernel, g; WD is the dry weight of kernel, g.

2.2.2 Grain yield

At harvest, an area of 18 m^2 (10 m long × 3 rows) was harvested manually from the three middle rows. Kernel number per ear was measured using 20 randomly selected ears from each sampling area. Kernel weight was determined by counting 1000 kernels in triplicate. Grain yield was expressed at a grain water content of 14%. The grain yield was calculated as follows:

$$Y=\frac{WF_{ears}\times PK\times(1-MC)}{(1-14\%)} \tag{2}$$

where, Y is the grain yield, kg/hm^2; WF_{ears} is the fresh weight of ears per hectare, kg/hm^2; PK is the percentage of kernels, %.

2.3 Determination of the dehydration equation of maize cultivars

According to the methods of Li et al.[13] and Daynard[16], a Logistic Power nonlinear growth model (hereinafter referred to as the dehydration model) was used to simulate the dehydration process of the maize kernels. The accumulated temperature after silking was the independent variable and the kernel moisture content was the dependent variable. Using the nonlinear curve-fitting function of the Curve Expert Professional 2.2 software, the optimal estimates of the b and c parameters for the regression models of different cultivars were obtained[13]. The coefficient of determination (R^2) was used to evaluate the performance of the models, and the dehydration equation (Equation (3)) of the maize kernels was determined[17]. The 11 cultivars which were used during both 2017 and 2018 were used to test the applicability of the dehydration model. The measured kernel moisture contents for 2017 were used to validate the 2018 kernel dehydration model. The dehydration model is as follows:

$$MC_d=\frac{a}{1+(\frac{T}{b})^c} \tag{3}$$

where, MC_d is the dynamic kernel moisture content, %; T is the accumulated temperature after pollination (≥0°C accumulated temperature), °C·d; and a, b, and c are model parameters; a was a model extreme value and was set to 90 in this study.

2.4 Calculation of economic return

The maize variety economic return is as follows:

$$y=Yi\times P-Ei \tag{4}$$

where, Yi is the variety yield at 14% moisture content, kg/hm^2; and P is the unit price of maize kernels with a moisture content of 14%, which has a value of 1.977 RMB/kg (2019); Ei is the extra investment which is required for fertilizers, irrigation pesticides, etc., and has a value of 14 175 RMB/hm^2 (based on 2019 data); Ei includes: machinery operating cost (4410 RMB/hm^2), irrigation equipment cost (1015 RMB/hm^2), pesticide cost (1015 RMB/hm^2), fertilizer cost (3225 RMB/hm^2), seed cost (1170 RMB/hm^2), labor cost (3270 RMB/hm^2), and drying cost (0-0.04 RMB/kg).

When the variety has changed the economic return was assessed using the following equation:

$$y=\Delta T\times a\times P-(Yi+\Delta T\times a)\times\Delta Dc-(Yi+\Delta T\times a)\times\Delta Pg-\Delta Ei \tag{5}$$

where, a is the increase in yield due to an increase in accumulated temperature of 1 °C·d, kg/(°C·d); ΔT is the change of accumulated temperature, °C·d; P is the unit price of maize kernel with a moisture content of 14%, RMB/kg; the range of P was set to 1.977 RMB/kg in the NHAR (based on 2019 data); Yi is the variety yield at 14% moisture content, kg/hm^2; ΔDc is the increase in drying cost due to the increase in kernel moisture content that is caused by changing from low-yield cultivars to high-yield cultivars, RMB/kg; the range of ΔDc was set to 0.01-0.04 RMB/kg (based on 2019 data); ΔPg is the decrease in the sales order price that is caused by a grade drop; the range of ΔPg was set to 0-1.0 RMB/kg (based on 2019 data); ΔEi is the change of Ei when the cultivar is changed.

2.5 Accumulated temperature calculation and variety recommendation

By combining T with the temperature data from 2008 to 2017, the locations were marked on a map of Ningxia, China various types of maize varieties can be dehydrated to moisture contents of 25%, 20%, and 16% under normal sowing conditions. Based on the test results, varieties with a high yield and low lodging rate were recommended to be planted in each area in Ningxia.

$$T=Ti+Ts \tag{6}$$

where, T is the accumulated temperature from the sowing date to kernel dehydration to a certain kernel moisture content; Ti is the required accumulated temperature from pollination to dehydration to achieve the target kernel moisture content simulated by the dehydration model; Ts is the required accumulated temperature from sowing to silking.

2.6 Data calculation and plot

The Microsoft Excel 2016 software was used to calculate the data of kernel dehydration, harvested kernel quality, etc.; the Sigmaplot 12.5 software (Systat Software Inc., San Jose, California, USA), Excel 2016, and ArcGIS software (Esri, Redlands, California, USA) were used to plot data; the SPSS 17.0 software (IBM, Armonk, New York, USA) was used to perform statistical analysis and significance tests; and the Curve Expert Professional 2.2 software was used to estimate the model parameters.

3 Results

3.1 Applicability test for kernel dehydration model

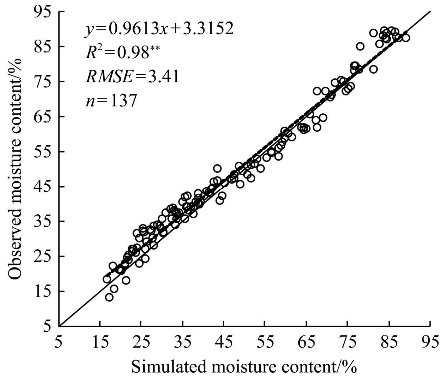
For the 38 tested cultivars, the minimum accumulated temperature requirement from seeding to physiological maturity was 2720.5°C·d (cultivar Demeiya 2), the highest accumulated temperature was 3542.7°C·d (cultivar Shaandan 628) and the average accumulated temperature was 3274.3°C·d (Table 2). The kernel moisture content at harvest was between 26.0% (cultivar Xianyu335) and 35.7% (cultivar Shaandan 628), with an average value of 30.1%. The value of b parameter in the dehydration equation was between 929.69 and 1259.35, with an average value of 1058.50. The value of c parameter of the dehydration equation was between 1.58 and 2.29, with an average value of 1.97.

Table 2 Maize cultivars accumulated temperature requirements during the seeding to physiological maturity and the parameters *b* and *c* of the kernel dehydration equation (Equation (3))

Cultivar	Accumulated temperature/°C·d		Kernel moisture content at physiological maturity/%	Parameters		
	Sowing to silking	Sowing to physiological maturity		b	c	R^2
Dongdan 1331	1747.6	3290.6	34.9	1152.34	2.14	0.98**
Lidan 295	1747.6	3276.2	30.7	1056.31	2.08	0.98**
Xianyu 1321	1802.1	3435.8	30.9	1031.71	1.75	0.96**
Denghai 739	1626.7	3315.7	31.3	1158.03	1.85	0.98**
Lianchuang 825	1755.9	3406.4	31.4	1084.38	1.91	0.96**
Liaodan 585	1756.4	3445.0	31.5	1105.63	1.99	0.96**
Zengyu 1572	1741.5	3385.6	31.6	1121.54	1.78	0.98**
Shandan 620	1686.8	3295.2	31.7	1033.18	1.80	0.96**
Zhengdan 958	1747.6	3360.6	32.0	1069.31	1.88	0.99**
Zhengdan 528	1707.1	3450.1	33.6	1139.29	1.71	0.96**
Liaodan 586	1741.5	3414.9	33.6	1112.54	1.86	0.97**
Denghai 105	1735.9	3309.1	33.7	1068.99	1.68	0.98**
Shaandan 628	1765.1	3542.7	35.7	1259.35	1.58	0.98**
Heyu 187	1656.0	3194.7	31.8	1073.01	2.12	0.98**
Denghai 786	1503.7	3025.9	31.7	1015.00	1.96	0.98**
MC670	1679.0	3237.6	30.3	1115.97	2.29	0.98**
Dongdan 6531	1718.7	3138.2	29.5	992.16	2.00	0.98**
Jidan 66	1620.0	3235.3	26.6	1005.61	2.01	0.98**
Demeiya 1	1372.8	2861.6	26.7	939.03	2.10	0.98**
KX9384	1450.9	3107.0	27.7	1031.86	2.19	0.98**
Huamei 1	1548.1	3079.9	28.9	1036.87	2.29	0.98**
Nonghua 213	1713.3	3273.6	28.9	1004.03	2.02	0.96**
Yinyu 274	1644.4	3100.6	29.1	1005.47	2.20	0.99**
Jingnongke 728	1666.4	3034.9	29.2	937.71	2.11	0.99**
Ruipu 909	1666.4	3230.3	29.3	1027.65	2.00	0.97**
Demeiya 2	1344.6	2720.5	29.5	929.69	2.07	0.99**
Fuyou 968	1747.6	3277.4	28.0	999.13	2.10	0.97**
Xianyu 335	1644.4	3309.7	26.0	1006.10	2.00	0.96**
Zhengdan 1002	1679.0	3456.6	27.3	1146.80	1.81	0.99**
Dika 519	1747.6	3345.4	27.6	977.00	1.97	0.97**
Yinyu 439	1691.1	3440.6	27.9	1069.55	1.81	0.97**
Yinyu 123	1718.7	3371.0	28.6	1041.34	2.00	0.98**
M751	1699.1	3413.8	28.8	1099.74	2.01	0.97**
Dika 517	1691.1	3299.0	28.8	999.33	2.07	0.97**
Lianchuang 808	1735.9	3441.4	29.4	1115.85	1.70	0.99**
Liaodan 575	1699.1	3290.4	29.5	1024.51	2.01	0.97**
Denghai 769	1638.0	3285.6	30.0	1105.61	2.10	0.98**
Denghai 618	1655.9	3323.7	30.0	1131.19	2.05	0.99**
Maximum	1802.1	3542.7	35.7	1259.35	2.29	0.99
Minimum	1344.6	2720.5	26.0	929.69	1.58	0.96
Average	1670.9	3274.3	30.1	1058.50	1.97	0.98

Note: ** indicates significance at the p<0.01 level.

The results of the test of the applicability of the dehydration model show that R^2=0.98 (n=137) and the root-mean-square error ($RMSE$) =3.41. Therefore, the applicability of the dehydration model was proven (Figure 2).



Note: y is the observed moisture content, %; x is simulated moisture content, %. ** indicates significance at the p<0.01 level. R^2: coefficient of determination; $RMSE$: root-mean-square error.

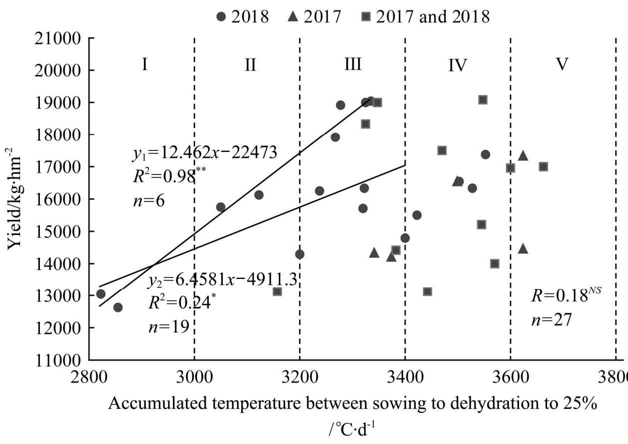
Figure 2 Difference between the measured and predicted maize kernel moisture content

3.2 Classification of maize cultivars

The yield of the 38 studied maize cultivars ranged from 12 635 kg/hm^2 to 19 091 kg/hm^2, with an average value of 16 147 kg/hm^2 (Table 3). The accumulated temperature required for kernel dehydration to a moisture content of 25% was between 2820.2°C·d and 4068.6°C·d, and was below 3800°C·d for 37 of the 38 cultivars. Starting at 2800°C·d, the maize cultivars were divided into six types—namely types I, II, III, IV, V, and VI—based on the gradient of the accumulated temperature of 200°C·d. The cultivars required accumulated temperatures of between 3048.3°C·d and 4544.6°C·d for kernel dehydration to 20% and between 3294.1°C·d and 5080.0°C·d for dehydration to 16%. The accumulated temperature required for kernel dehydration to a moisture content of 20% was below 4000°C·d for cultivars of types I–IV, and that required for dehydration to a moisture content of 16% was below 4000°C·d for cultivars of types I–III.

3.3 Relationship between yield and dehydration to 25% accumulated temperature

The fitted relationship between the yield (kg/hm^2) and the accumulated temperature (°C·d) required between sowing and kernel dehydration to a moisture content of 25% for cultivars of types I–III is y_2=6.4581x−4911.3 (R^2=0.24**, n=19), where y is the yield and x is the accumulated temperature required for kernel dehydration to a moisture content of 25% (Figure 3). Among



Note: I, II, III, IV, V are types I, II, III, IV and V maize cultivars, respectively. * and ** represent significance at the p<0.05 and p<0.01, respectively. NS: not significant at the p<0.05.

Figure 3 Relationship between the yield and the accumulated temperature required for dehydration to a kernel moisture content of 25% for various maize cultivars these cultivars, the two cultivars with the highest yields of each type were selected. For these cultivars, the fitted equation for the same relationship as above was $y_1 = 12.462x - 22473$ ($R^2 = 0.98$, $n=6$). No significant correlation was found between the yield and the accumulated temperature required for kernel dehydration to a moisture content of 25% for cultivars of types III–V.

Table 3 Accumulated temperature required for various degrees of kernel dehydration and yields for different maize cultivars

Type and at range/°C·d	Cultivar	Yield /kg·hm^{-2}	Predicted AT/°C·d		
			Dehydration to MC of 25%	Dehydration to MC of 20%	Dehydration to MC of 16%
I (2800-3000)	Demeiya 2	13051.0	2820.2	3048.3	3294.1
	Demeiya 1	12635.2	2852.3	3077.1	3318.9
	Average	12843.1	2836.3	3062.7	3306.5
II (3000-3200)	KX9384	15764.3	3048.1	3280.5	3529.2
	Huamei 1	16156.7	3121.7	3339.7	3571.6
	Jingnonek 728	—	3140.5	3363.2	3602.6
	Denghai 786	13109.9	3156.4	3427.7	3721.0
	Yinyu 274	14299.1	3197.4	3422.3	3662.7
	Average	14832.5	3132.8	3366.6	3617.4
III (3200-3400)	Jidan 66	16288.7	3236.2	3493.3	3771.4
	Xianyu 335	17928.5	3265.1	3524.2	3804.7
	Dika 517	18924.4	3276.4	3521.1	3784.7
	Dongdan 6531	15739.0	3317.3	3573.0	3849.8
	Fuyou 968	16351.2	3320.8	3559.3	3815.8
	Nonghua 213	18325.7	3324.3	35779.6	3855.5
	Ruipu 909	19018.6	3323.7	3589.3	3876.9
	Dika 519	19066.8	3333.2	3591.0	3870.6
	Heyu 187	14340.0	3341.1	3595.1	3868.0
	Liaodan 575	18984.1	3346.9	3609.5	3893.6
	MC670	14242.5	3374.3	3609.8	3860.3
	Denghai 769	14410.6	3380.9	3646.0	3931.2
	Yinyu 123	14799.9	3398.8	3668.4	3960.4
	Average	16801.5	3326.1	3581.5	3857.1
IV (3400-3600)	Lidan 295	15507.4	3420.1	3677.2	3954.0
	Shandan 620	13142.4	3442.0	3756.5	4102.5
	M751	17483.1	3469.2	3751.8	4057.5
	Yinyu 439	16562.4	3501.9	3824.2	4178.3
	Denghai 618	16569.0	3498.3	3785.1	4094.3
	Zhengdan 958	16357.9	3524.5	3828.5	4160.8
	Liaodan 585	15188.7	3545.1	3833.9	4146.8
	Dongdan 1331	17394.4	3550.3	3819.5	4108.3
	Denghai 739	13989.4	3569.2	3908.4	4280.0
	Xianyu 1321	—	3581.3	3910.0	4273.1
	Liaodan 586	16955.9	3599.3	3920.5	4272.1
	Lianchuang 825	19091.5	3546.2	3848.4	4177.9
	Average	16203.8	3520.6	3822.0	4150.5
V (3600-3800)	Denghai 105	14469.0	3622.6	3987.3	4393.1
	Zhengdan 1002	17343.0	3624.0	3971.4	4353.3
	Zengyu 1572	16983.5	3660.9	4010.1	4395.1
	Lianchuang 808	—	3695.1	4070.1	4486.6
	Zhengdan 528	—	3698.7	4076.5	4495.6
	Average	16265.2	3660.3	4023.1	4424.7
VI (≥4000)	Shaandan 628	—	4068.6	4544.6	5079.9
Total	Average	16147.3	3399.8	3685.3	3996.1

Note: "—" means quantity not measured; AT: Accumulated temperature; MC: Moisture content.

3.4 Cultivar types and economic returns

It was found that the increase in production caused by a 1°C·d rise in the accumulated temperature required for kernel dehydration to a moisture content of 25% led to an increase in economic return of 12.74 RMB/hm^2 ($a = 6.4581$, $P = 1.977$ RMB/kg, $\Delta Dc = 0$, $\Delta Pg=0$, $\Delta Ei=0$, based on Equation (5)). The results of this study suggest that, if the maize in the Yellow River irrigation area in the northern NHAR was harvested at the end of October, the kernel moisture content of type I cultivars would be about 14%, and the kernels could therefore be directly stored in warehouses. Meanwhile, the kernel moisture content of type III cultivars would be about 16%-18%. The maximum rise in economic return caused by an increase of 1°C·d in the accumulated temperature required for kernel dehydration to a moisture content of 25% is 24.30 RMB/hm^2 (a=12.462, P=1.977 RMB/kg, ΔDc=0, ΔPg=0, ΔEi=0).

Furthermore, the results suggested that replacing type I cultivars with type III cultivars could increase the economic benefits by 7553 RMB/hm^2 (based on Equation (4), Table 4). The economic benefits were approximately equal between type III and type V. Therefore, maize cultivars with accumulated temperatures required for dehydration to a kernel moisture content of 25% of less than 3400°C·d can be mechanically harvested.

Table 4 Economic returns of different maize cultivar types in different planting regions (RMB/hm^2)

Cultivar type	Huinong	Yinchuan	Zhongning	Taole	Zhongwei	Tongxin	Yanchi	Haiyuan	Guyuan	Xiji
I	11 216	11 216	11 216	11 216	11 216	11 216	11 216	10 985	10 985	—
II	16 969	16 969	16 969	16 969	16 969	16 941	16 941	—	—	—
III	18 739	18 739	18 739	18 739	18 739	18 739	18 588	—	—	—
IV	17 003	16 859	17 003	16 859	16 859	16 859	—	—	—	—
V	18 920	18 920	18 920	18 920	—	—	—	—	—	—
VI	—	—	—	—	—	—	—	—	—	—

Note: "—" means that mechanical harvesting is unsuitable in this region. Economic returns are calculated based on Equation (7).

3.5 Matching of cultivars in the condition of the mechanical kernels harvesting

The sowing date and accumulated temperature from sowing to 31 October were surveyed in 10 sites of the NHAR to assess the appropriateness of the maize cultivars for mechanical kernel harvesting (Table 5). At these sites, the sowing date was from April 8 to 12 and the accumulated temperature of sowing to October 31 was between 2851.0°C·d and 3943.5°C·d.

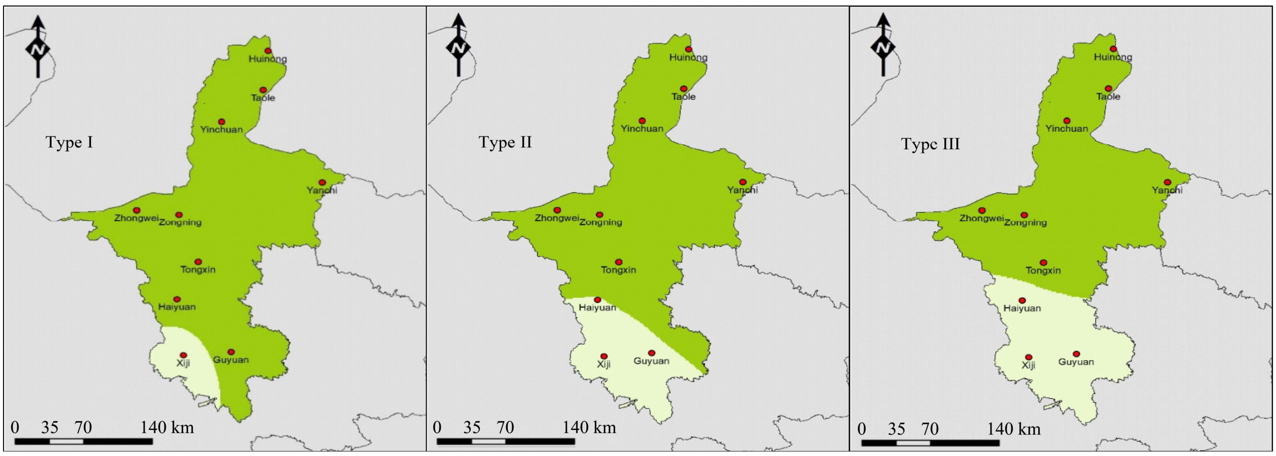
Table 5 Sowing dates and effective accumulated temperature of sowing to October 31 for the experimental sites in the Ningxia Hui Autonomous Region

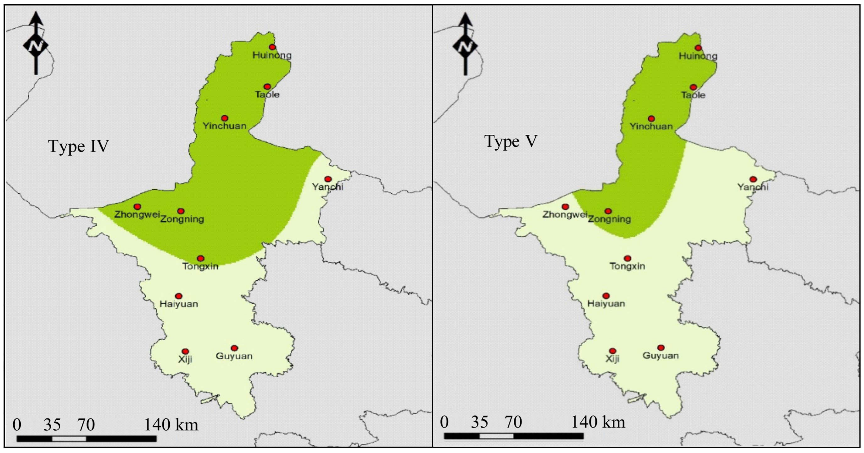
Site	Sowing date	Accumulated temperature/°C·d
Huinong	April 8	3943.5
Yinchuan	April 8	3918.7
Zhongning	April 12	3924.4
Taole	April 8	3804.6
Zhongwei	April 12	3727.6
Tongxin	April 12	3702.2
Yanchi	April 12	3529.8
Haiyuan	April 10	3173.0
Guyuan	April 8	3127.2
Xiji	April 8	2851.0

In general, in the Huinong, Taole, Yinchuan, Zhongning, Zhongwei, and Tongxin sites of the Yellow River irrigation area, cultivars of type I-IV (i.e., a total of 32 cultivars) could be dehydrated to a kernel moisture content of 25% by the end of October. Of these, 27 cultivars were investigated for lodging rate and yield. Of these 27, five cultivars-namely M751, Dika 517, Dika 519, Dongdan 1331, and Liaodan 586-are recommended for planting. In this region, cultivars of types I-III (i.e., a total of 20 cultivars) could be dehydrated to a kernel moisture content of below 20% before the end of October; among them, 17 cultivars were investigated for lodging rate and yield, and, based on this, cultivars Dika 517 and Dika 519 are recommended for planting. Cultivars of types I and II could be dehydrated to kernel moisture content of below 16%. Cultivar KX9384 was recommended among the six cultivars which were investigated for lodging rate and yield in type I and type II. In Yanchi County, the planting of type I cultivars could allow dehydration to kernel moisture contents of below 16%, the planting of type II cultivars could allow dehydration to below 20%, and the planting of type III cultivars could allow dehydration to below 25%. Moreover, the results suggest that in southern Haiyuan County and Guyuan City the planting of type I cultivars could allow dehydration to a kernel moisture content of below 20%, which would facilitate mechanical kernel harvesting. Therefore, we recommend the planting of cultivars Dika 517 and Dika 519 in Yanchi County and the planting of cultivars Demeiya 1 and Demeiya 2 in southern Haiyuan County and Guyuan City (Figure 4).

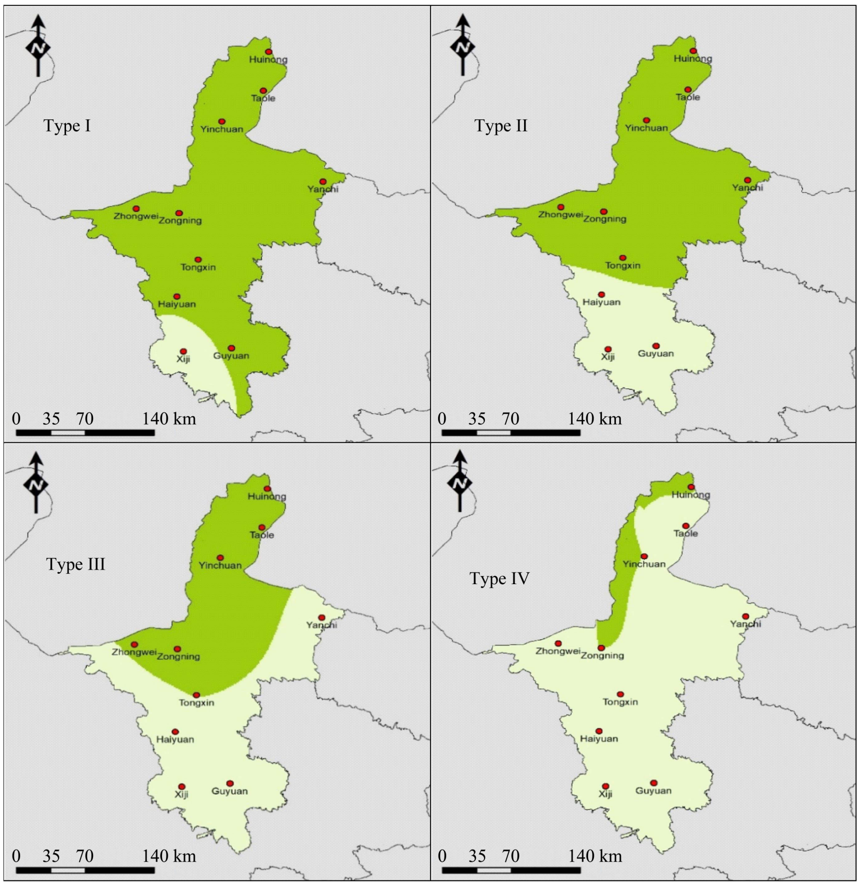
3.6 Moisture content and broken rate of harvested kernels

The moisture content and broken rate of the mechanically harvested maize kernels were investigated at the end of October in Lingwu City, Pingluo County, and Yinchuan City. For the three experimental sites, cultivars of types II, III and IV could be dehydrated to 14.6%-24.2% (Table 6). Among the 11 sets of data, 8 sets of data have a grain crushing rate lower than 5%, and 3 sets of data have a crushing rate higher than 5%. Therefore, postpone the harvest period with reducing grain moisture content for mechanical harvesting is advantageous.

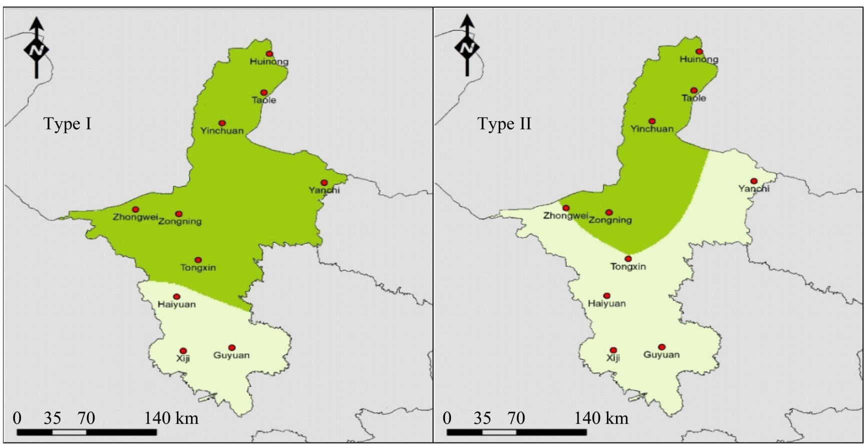




a. Distribution map of different types cultivars maize kernels dehydration to 25% in the Ningxia Hui Autonomous Region, China



b. Distribution map of different types cultivars maize kernels dehydration to 20% in the Ningxia Hui Autonomous Region, China



c. Distribution map of different types cultivars maize kernels dehydration to 16% in the Ningxia Hui Autonomous Region, China

Figure 4 Distribution map of different types cultivars maize kernels dehydration to 25%, 20%, and 16% in the Ningxia Hui Autonomous Region, China

Table 6 Moisture content and broken rate of kernels harvested at the end of October in Lingwu City, Pingluo County, and Yinchuan City

		KX9384 (II)	Yinyu 274 (II)	Dika 517 (III)	Xianyu 335 (III)	Yinyu 439 (IV)
Kernel moisture content/%	Pingluo	16.8±0.0	22.5±0.4	18.4±0.3	22.0±0.4	24.2±0.2
	Yinchuan	16.9±0.2	22.2±0.1	20.2±0.1		
	Lingwu	14.6±0.1	18.6±0.2	16.6±0.3		
Kernel broken rate/%	Pingluo	3.1±0.4	4.1±0.1	2.5±0.3	8.8±1.0	6.3±0.7
	Yinchuan	4.6±0.4	3.8±0.6	4.4±0.1		
	Lingwu	5.5±0.7	4.1±0.4	3.1±0.2		

4 Discussion

4.1 Relationship between the yield and required accumulated temperature for dehydration to a kernel moisture content of 25% for different maize cultivars

Studies have shown that the yield of maize cultivars is positively correlated with the accumulated temperature during the whole growing period[15]. Gong et al.[18] studied six maize cultivars at early maturity, middle maturity, and late maturity, and found that the required accumulated temperature from sowing to maturity was directly proportional to the yield. It has been found that, compared to early-maturing cultivars, late-maturing cultivars require more accumulated temperature during the growing period, have longer filling stages, and have a significantly higher yield. In the present study, the relationship between the yield and the required accumulated temperature of the 33 cultivars which were investigated for yield during the whole growth period was found to be $y = 6.3765x - 4700.5$ ($R = 0.54$, significant at $p < 0.05$). Additionally, for cultivars of types I–III, a significant positive correlation was observed between the yield and the accumulated temperature required for kernel dehydration to a moisture content of 25%.

4.2 Effect of kernel moisture content on economic return

Excessive moisture content in maize kernels not only affects the quality of mechanical harvesting but also greatly increases the risk of mildew and kernel breakage during later storage and transportation, increases drying costs, and reduces maize quality[19,20]. It had been reported that, in Canada, when the kernel moisture content exceeds 25%, the drying cost is 24 Canadian dollars per ton of maize[3]. In parts of China, such as Gansu Province, the Xinjiang Uyghur Autonomous Region (XUAR), and the NHAR, the cost of drying maize kernels with a moisture content greater than 28% to moisture contents of 14%-16% is about 20-40 RMB/t. Therefore, there is a large difference in the sale price of maize kernels with high moisture content (25%-30%) compared to those with low moisture content (14%-16%). In the XUAR, the unit sale price of maize kernels with high moisture content is about 1.25-1.30 RMB/kg, while that for maize kernels with low moisture content is about 1.5-1.6 RMB/kg. After deducting about 0.02 RMB/kg for drying costs, drying 1 kg of maize kernels (14% moisture content) can increase profit by about 0.062 RMB/kg. In the NHAR, the unit sale price of maize kernels with high moisture content is about 1.5-1.6 RMB/kg, while that of maize with a low moisture content can exceed 1.9 RMB/kg. In the NHAR, assuming a unit price of RMB 1.977/kg and a drying cost of RMB 0.027/kg, after maize kernels are dried, the economic benefit will increase by about RMB 0.115/kg. The results of this study suggest that, in the NHAR, after maize kernels are dried, per hectare profits will increase by RMB 1453-2196. If the maize is dehydrated from a kernel moisture content of 28% to a kernel moisture content of 14% in the field after physiological maturity, a drying cost per hectare of RMB 341 to 515 will be saved, which can reduce carbon dioxide emissions by about 1.08 t. It is calculated that an accumulated temperature of 1°C·d can save a drying cost of about RMB 0.63/hm^2 during the air-drying of maize in the field in Ningxia.

The results of this study indicated that the following method can further increase economic benefits under mechanical grain harvesting (with grain dehydration to a moisture content of below 28%): (1) The selection of high-yield (e.g., type III varieties in this study) and fast-dehydrating varieties. Of these two properties, high yield is of chief importance. (2) Selling when the grain has been dehydrated to a moisture content of below 16%. A better way of achieving such grain dehydration is to postpone the harvest date as much as possible rather than drying after the harvest at physiological maturity since this can save some drying costs.

4.3 Adaptability of maize varieties

In Ningxia, the accumulated temperature was between 2851.0°C·d and 3943.5°C·d from normal sowing date to the end of October in 10 sites. In this study, the accumulated temperature requirements from sowing to physiological maturity were between 2720°C·d to 3543°C·d of 38 maize varieties. Therefore, suitable cultivars can be selected to mature and achieve low water harvest of the kernel. In Huinong, Taole, Yinchuan, Zhongning, Zhongwei, and Tongxin site of the Yellow River irrigation area, cultivars of type I–IV (i.e., a total of 32 cultivars) could be dehydrated to a kernel moisture content of 25% by the end of October. Cultivars of types I and II could be dehydrated to a moisture content of below 16%. In Yanchi, the planting of type I-III cultivars could achieve dehydration to a moisture content of below 25% (i.e., a total of 20 cultivars). In Haiyuan and Guyuan, the planting of type I cultivars could achieve dehydration to a moisture content of below 20% (i.e., a total of two cultivars). On October 28, 2018, the lodging rate is less than 10% in the 65% of varieties. Therefore, some of the varieties analyzed in this study can be planted in Ningxia in order to popularize mechanical maize grain harvesting technology in this region.

4.4 Main uncertainties in this study

Based on an analysis of the yield and lodging rate of 33 maize cultivars in Ningxia, the planting of cultivars with a low lodging rate and high yield was recommended to facilitate the mechanical harvesting of maize kernels. Maize dehydration, plant lodging risk, and yield are affected by many factors, among which maize variety is the key factor, and each factor has a different degree of influence in different regions[7,18,21-25]. According to the environmental characteristics of the study region, the cultivars with high yield, low lodging rate, and fast dehydration was chosen for mechanical kernel harvesting.

The average accumulated temperature in Yinchuan City from April 1to October 31 in 2008-2017 was 4001°C·d, while the maximum and minimum accumulated temperatures were 4091°C·d and 3883°C·d, respectively. The accumulated temperature in Yinchuan City from April 1 to October 31 in 2017 was 4091°C·d. The accumulated temperature in Yinchuan City from April 1 to October 31 in 2018 was 4036°C·d. The accumulated temperature from April 1 to October 31 in 2017 and 2018 was higher than the average accumulated temperature in 2008-2017 by 90°C·d and 35°C·d, respectively. Therefore, in colder years and places, the growth and dehydration of maize will slow. The work of our research group shows that accumulated temperature of silking-dehydration to a certain moisture content was very consistent with Equation (3); however, not all ≥0°C temperatures are effective for maize growth and development, and when the temperature is very high or low, the mature period of maize varieties should be paid attention.

5 Conclusions

In this study, it was found that, in 33 maize cultivars, the relationship between the yield and the accumulated temperature required for kernel dehydration to a moisture content of 25% followed: $y = 6.4581x - 4911.3$, where y is the yield and x is the required accumulated temperature, and where 2800°C·d < x < 3400°C·d. Planting cultivars that dehydrate extremely quickly can save on drying costs, however, the yield and overall profits are low. Very low yields lead to very low economic returns. Therefore, high-yield cultivars should be planted among cultivars that can dehydrate to a kernel moisture content of less than 25%, and the maize kernel dehydration time in the field should be extended to save costs.

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