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Precise classification and regional delineation of maturity groups in soybean cultivars across China

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A R T I C L E I N F O

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A B S T R A C T

The maturity group (MG) system is a widely recognized and effective approach for assessing the photothermal sensitivity of soybean cultivars and determining their optimal adaptation zones. In China, soybean have been cultivated extensively for thousands of years, evolving into various ecotypes through natural and artificial selection. In this study, the relative maturity groups (RMGs) of a total of 766 soybean cultivars collected from the Northeast Spring Planting Sub-region (NE), Huang-Huai-Hai Summer Planting Region (HH), Northwest Spring Planting Sub-region (NW,), and South Multiple Cropping Region (SC) of China were evaluated using linear regression models at 36 sites nationwide. The results show that the RMGs of Chinese soybean cultivars range from MG m1.6 to MG 9.5. Among all the identified soybean cultivars, MG III cultivars account for the largest proportion of 22.19 %, followed by MG II (21.67 %) and MG I (18.54 %). Conversely, MG IX has the fewest number of cultivars, representing only 0.26 % of all cultivars. The MG ranges for spring- and summer-sowing cultivars are MG 000-V and MG II-IX, respectively. The adaptive soybean MG zones across China were mapped using the method of Kriging interpolation based on the soybean RMGs data from 816 sites of 29 soybean-producing provinces. Cultivars of MG 0 and earlier groups are primarily distributed in the NE, and MG III and MG IV are the major MGs in HH and NW. The cultivars in MG V and later groups mainly distribute in SC. This study realizes the unification and normalization of the MG system between China and other major soybean-producing countries worldwide. Such unification and standardization will facilitate global germplasm exchanges and assist soybean producers in making more informed decisions when selecting cultivars.

Abbreviations: MG, Maturity group; RMG, Relative maturity group; GIS, Geographic Information System; GRIN, Germplasm Resources Information Network; NE, Northeast Spring Planting Sub-region; HH, Huang-Huai-Hai Summer Planting Region; NW, Northwest Spring Planting Sub-region; SC, South Multiple Cropping Region; DPM, days to physiological maturity.

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1. Introduction

Soybean [*Glycine max* (L.) Merr.] is a typical short-day plant (Garner and Allard, 1920). Due to its sensitivity to photoperiod and temperature, a soybean cultivar usually adapts to grow within a relatively narrow latitude range (Zhang et al., 2007; Liu et al., 2021). Optimal growth and yield potential are only achieved when soybean is cultivated within its adaptation zone (Gupta et al., 2021a, 2021b; Rod et al., 2021). Changes in photoperiod and temperature conditions in other zones could affect the development stages of soybean cultivars (Boyer et al., 2015; Morris et al., 2021; Mohammed et al., 2022).

In the past, breeders determined the adaptation zone of a given soybean cultivar mainly based on limited field test data and their experiences, resulting in a somewhat subjective determination. Since the 1970s, a rating maturity group (MG) system was developed in the United States and Canada (Hartwig, 1970). This system became a common practice for categorizing soybeans based on their photothermal response characteristics and general area of adaptation in major soybean-producing countries (Alliprandini et al., 2009; Dardanelli et al., 2006; Sampaio et al., 2020). Soybean cultivars are categorized by maturity group (MG) based on the number of days from planting to maturity at a defined location under optimal environmental conditions (Edwards et al., 2005). Fourteen MGs have been defined so far, ranging from "0000″ for the earliest soybeans to "X" for the latest ones (Jia et al., 2014). Additionally, a digitized relative maturity group (RMG) is further defined as gradations within MGs formed by assigning a decimal number from 0 to 9 to each MG in North America (Boerma and Specht, 2004). This soybean RMG categorization system has been accepted in Brazil and China due to its effectiveness in accurately and quickly predicting the potential cropping zone for a new or introduced cultivar (Cavassim et al., 2013; Song et al., 2019). Based on the application of RMG, the MG adaptation map across north America was firstly drawn by Scott et al. using Geographic Information System (GIS) (Scott and Aldrich, 1970), and further modified according to 139 State Soybean Variety Trial data (Zhang et al., 2007). It was found that the adaptation zones of MG IV-VI were much broader compared with the first MG map delineated in the 1970 s. More recently, the map was re-drawn, taking into consideration the constantly changing climate, evolving management practices, and genetic improvements (Mourtzinis and Conley, 2017). The MG adaptation zones of Brazil, Argentina, Japan, and Europe were also roughly delineated and played pivotal roles in guiding soybean breeding strategies (Alliprandini et al., 2009; Langewisch et al., 2017; Shanmugasundaram, 1981).

Soybean cultivation in China has a history of more than 5000 years (Hymowitz and Newell, 1981; Dong et al., 2004). Through extensive periods of natural and artificial selection, a wealth of soybean germplasm adapted to diverse ecological conditions has been accumulated (Dong et al., 2004). To date, a significant body of research has been conducted to ecotype cultivars across diverse soybean-growing regions and farming systems in China (Pu and Pan, 1982; Wang and Gai, 2000). The concept of MG has gained acceptance among an increasing number of Chinese soybean researchers over the past two decades. Some soybean germplasms in China have been roughly classified into thirteen MGs (0000-IX) (Gai et al., 2001; Jia et al., 2014; Li et al., 2017; Liu et al., 2017; Wu et al., 2012; Wang et al., 2006). A systematic and quantifiable methodology, along with a list of standard cultivars for RMG identification in China, was subsequently provided, and RMGs of limited primary cultivated soybean cultivars were identified (Song et al., 2019). However, it is challenging to comprehend the distribution of soybean MGs throughout China relying solely on these cultivars. The RMGs of the major cultivars produced in China are not yet known. Moreover, the RMG identification system has not been adopted in the soybean production in China, partially due to the lack of accurate delineation and regionalization of MG adaption zones across the country.

The objective of this study is to characterize the RMG of current soybean cultivars and delineate soybean MG adaptation zones across China using GIS mapping techniques. This effort will assist soybean breeders in evaluating potential regions for new cultivars and will enable soybean producers to apply and introduce cultivars more effectively, thereby increasing their profitability. Furthermore, this study will contribute to the international exchange of germplasm resources.

2. Materials and methods

2.1. Soybean materials

A total of 185 MG standard cultivars, ranging from MG 0000 to MG IV, were selected as references. These references included 2 cultivars from MG 0000, 7 from MG 000, 14 from MG 00, 19 from MG, 17 from MG I, 20 from MG II, 20 from MG III, 37 from MG IV, 8 from MG V, 8 from MG VI, 28 from MG VII, and 5 from MG VIII. The RMGs of these cultivars were obtained from GRIN (Germplasm Resources Information Network, https://npgsweb.ars-grin.gov) or previous studies (Alliprandini et al., 2009; Jia et al., 2014; Song et al., 2019). Detailed information regarding the RMG and MG, as well as the origin and accession numbers of the reference cultivars, can be found in Supplementary Table 1. For RMG identification, a total of 766 representative cultivars were collected from 816 sites across 208 prominent soybean-producing counties in China. These 766 cultivars were distributed across various regions: 439 from the Northeast Spring Planting Sub-region (NE), 52 from the Northwest Spring Planting Sub-region (NW), 95 from the Huang-Huai-Hai Summer Planting Region (HH), and 180 from the South Multiple Cropping Region (SC). The complete list of cultivars is provided in Supplementary Table 2.

2.2. Field experiments

Field experiments were conducted annually at 36 sites across four soybean planting areas in China from 2011 to 2015. Among these sites, 14 were distributed in the NE region, 5 in the NW region, 9 in the HH region, and 8 in the SC region (Pu and Pan, 1982; Song et al., 2023). At each site, reference cultivars covering a range of 4–8 MGs and the major local cultivars were planted together in spring for precise MG classification according to the RMG classification method described in our previous report (Song et al., 2019). The MG range and sowing dates across the 36 sites over the years are presented in Table 1. For most of the trials, the annual sowing dates exhibited similarity (± 3–5 d on average).

All field experiments were conducted using a complete randomized block design with three replications. The management of the field experiments was performed according to recommended agronomic practices. Soybeans were planted in single-row plots, 1.5 m long, spaced 0.3 m apart, with 50 seeds sown in each row. After emergence, plants were thinned to a uniform standard of 15 plants per row, and ultimately, 5 plants were selected from each row for data collection. The number of days to reach maturity was measured by counting the days from emergence (VE) to physiological maturity (R7, Fehr and Caviness, 1977).

2.3. Statistical and spatial analysis

The phenotypic data were individually analyzed for each trial. A regression of days to physiological maturity (DPM) on assumed RMG was performed according to the performances of the reference cultivars in each environment (Alliprandini et al., 2009; Song et al., 2019). In cases where there were multi-year or multi-point test results for the same cultivar, the mean RMG value was used. To digitally quantify the MGs, values of MG 0-X were defined from 0.0 to 10.9, while values for MG0000, MG000, and MG00 were specifically designated as ranging from − 3.0 to − 2.1, − 2.0 to − 1.1, and − 1.0 to − 0.1, respectively. These were labeled as MG m3.0 to MG m2.1, MG m2.0 to MG m1.1, and MG m1.0 to MG m0.1 in the text, following the conventions outlined in our previous study (Song et al., 2019). The linear regression model was

Table 1
Soybean MG range and sowing dates in different years at 36 trial sites.

Ecological region	Site	Longitude	Latitude	MG range	Sowing date (m/d)				
					2011	2012	2013	2014	2015
NE	Heihe	127.46	50.26	0000-I	5/18	5/8	5/24	5/9	5/18
	Jiusan	125.29	48.88	000-I	5/2	5/7	5/14		
	Zhalantun	122.73	48.07	0000-II	5/13	5/17	5/13	5/11	5/15
	Hailun	126.93	47.45	000-I	5/11	5/7	5/18	5/11	
	Tsitsihar	123.92	47.37	000-II	5/9	5/5	5/11	5/6	
	Kiamusze	130.41	46.79	0-III	5/2	5/3	5/19		
	Suihua	126.88	46.61	00-III	5/3	5/5	5/8	5/3	5/10
	Daqing	125.15	46.58	00-III	5/6	5/14	5/14		
	Harbin	126.61	45.68	0-III	5/4	5/4	5/4		
	Changchun	125.24	43.95	00-III	4/29	4/30		4/24	4/28
	Gongzhuling	124.8	43.51	00-III	4/28	4/30	5/7	4/24	
	Chifeng	118.87	42.30	00-III	5/14	5/24	5/18		
	Tieling	123.8	42.25	00-III		4/30	5/18		
	Shenyang	123.55	41.86	0-IV	5/4	5/4	5/5	5/7	
NW	Shihezi	86.00	44.31	00-IV	4/20	4/27	4/24	4/25	
	Yan'an	109.47	36.57	II-V	5/4	5/9	5/17		
	Zhenyuan	107.49	35.50	I-V	4/17	4/13	4/10		
	Yinchuan	106.24	38.25	II-V	5/2	4/18	5/2	4/22	
	Fenyang	111.78	37.26	II-V	5/7	4/26	4/27	4/30	
HH	Beijing	116.33	39.97	II-V	5/7	5/14	5/13	4/30	5/4
	Cangzhou	116.82	38.28	II-V	5/16	5/16	5/14	5/12	
	Jinan	117.07	36.71	II-V	5/19		5/10		
	Jining	116.58	35.46	II-V	5/5		5/3	5/8	
	Zhengzhou	113.68	34.79	II-V			6/10	5/31	
	Shangqiu	115.68	34.45	II-V	5/24	5/15	5/7		
	Xuzhou	117.28	34.28	II-V	4/27	4/23	4/27	5/6	5/9
	Suzhou	116.98	33.63	II-V		5/9	5/15		
	Fuyang	115.8	32.93	II-V	5/13	5/15	6/6		
SC	Nanjing	118.84	32.04	I-VIII	5/6		5/20	5/23	
	Nanchong	106.07	30.8	I-VIII	4/21	4/17	4/12	4/16	4/16
	Wuhan	114.34	30.58	I-VIII	4/29	4/7	4/3	4/9	4/11
	Nanchang	115.94	28.56	I-VIII	4/21	4/6	4/10	4/9	4/19
	Guiyang	106.65	26.62	I-VIII	4/25	4/24	4/16	4/22	
	Kunming	102.76	25.13	I-VIII		6/1	6/12	5/22	
	Guangzhou	113.35	23.16	I-VIII		7/14		7/14	
	Nanning	108.24	22.57	I-VIII	4/28	3/19	4/8	3/14	

expressed as follow:RMG= $\beta_0 + \beta_1$DPM+ ε.

The β_0 and β_1 are unknown constants called intercept and slope, respectively, and ε is a random error.

The 816 sites where all the respective cultivars were collected and their coordinate information were used to make MG distribution map of China (in Fig. 1). Data were compiled and exported from Excel into a text format suitable for integration into ArcGIS (Supplementary Table 3). A shapefile was created utilizing the latitude and longitude data for each site inside ArcCatalog. The shapefile was then added to a project in ArcMap that contained the shapefile of China as a background reference. To create adaptive soybean MG zones across China based on RMG data obtained from these locations, an interpolation between the data was completed using the geostatistical analysis method of Kriging interpolation in ArcMap10.1 (Allen, 2010). Notably, due to the absence of cultivar collections in Tibet and Taiwan, as well as the limited soybean planting area in the Linzhi region of the Tibetan Autonomous Region, the results pertaining to these regions were omitted from the map. Similarly, the soybean planting area in Qinghai Province was also quite limited, with only a single sample obtained from Haidong City. Recognizing that Haidong City's location at the border of Qinghai and Gansu Provinces might not accurately represent soybean cultivars across the entire Qinghai Province, the results for Qinghai province were also excluded.

The Kriging interpolation method can be simply expressed as the formula:

$$z(x) = \sum_{i=1}^{n} w_i z_i$$

The z(x) is the unknown sample point, z_i represents the value of the ith known sample point near the unknown sample point, and w_i are the weights assigned to each z(x) value, and n is the number of the closest neighboring sampled data points used for estimation.

3. Results

3.1. Establishment of RMG and DPM linear regression models for soybean cultivars in China

To establish linear models for individual trials, we utilized DPM and MG data from reference cultivars that were planted in 126 trials (Table 2). These models comprised 28 in 2011, 31 in 2012, 34 in 2013, 23 in 2014, and 10 in 2015. We obtained data for more than two years from each site, resulting in 50 models in NE, 17 in NW, 41 in HH, and 31 in SC. Most of the fitting equations had an R square higher than 0.8; however, some models had poorer fitting but still passed the significance test. The results unveiled that fitting equations for locations with similar latitudes tended to bear resemblance to one another. For instance, in 2012, the fitting equation for Jiusan was *RMG= 0.076DPM-7.618*, while for Zhalantun it was *RMG= 0.07DPM-7.096*, and for Hailun it was *RMG= 0.088DPM-8.467*. Furthermore, we observed similarities in the fitting equations of the same location in different years. For example, the equations of Hailun in 2011 and 2012 were *RMG= 0.086DPM-8.19* and *RMG= 0.084DPM-8.112*, respectively. However, there were noticeable differences in fitting equations between different years across most locations.

3.2. Grouping the soybean cultivars into appropriate MGs

We calculated RMGs for 766 Chinese cultivars by using linear

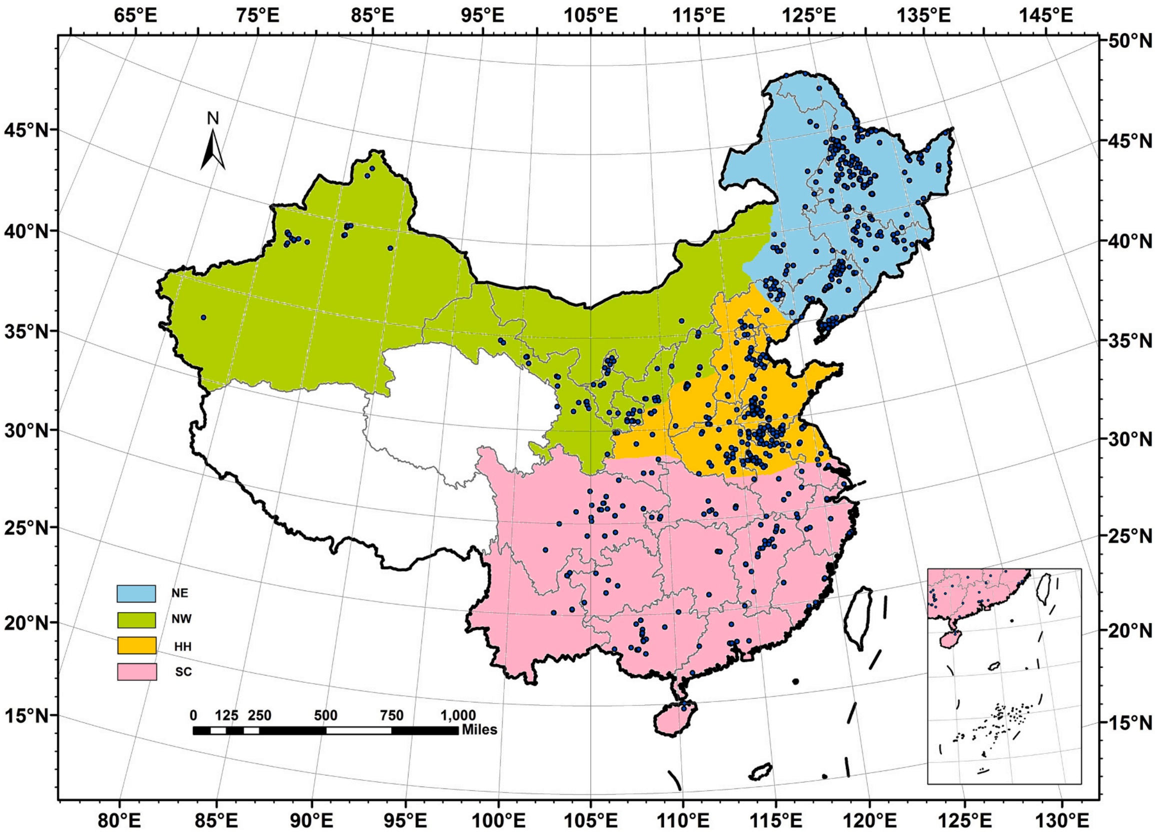

Fig. 1. The geological distribution of original sites of soybean cultivars collected for RMG evaluation. The samples were from 29 provinces in China. Four sub-regions of soybean cultivation area were marked in different colors on the map. NE, Northeast Spring Planting Sub-region; HH, Huang-Huai-Hai Summer Planting Region; NW, Northwest Spring Planting Sub-region; SC, South Multiple Cropping Region.

regressions of DPM on assumed RMG values (Supplementary Table 2). These cultivars span a broad range of MGs, ranging from MG 000 to MG IX. Among them, Dongnong 41 (MG m1.6) was identified as the earliest cultivar, while Huaxia 5 (MG 9.5) held the distinction of being the latest. A larger proportion of cultivars belonged to MG I-III (Fig. 2). MG III had the highest number of cultivars (170), accounting for 22.19 % of the total number of cultivars, followed by MG II (166 cultivars), accounting for 21.67 %. Only two cultivars were identified in MG IX, representing 0.26 % of all cultivars. MGs 000, 00, 0, I, IV, V, VI, VII, and VIII encompassed 7, 33, 87, 142, 100, 20, 12, 24, and 3 cultivars, respectively (Table 3).

3.3. MG distribution in different ecological regions

Among the four regions, soybean cultivars from HH exhibited the narrowest MG range, while those from SC displayed the widest range (as depicted in Fig. 3). The cultivars identified from NE were classified into MG000 to IV. MG I and MG II were the major MGs in this region, which contained 124 and 126 cultivars, accounting for 28.25 % and 28.70 % of the total cultivars in NE (Table 3). In NW, the 52 cultivars covered MG 0 through V. Notably, MG IV was the predominant MG in this region, representing 42.31 % of the total cultivars. Soybean cultivars hailing from HH were assigned to MG II through V, with 89 out of the 95 cultivars falling under MG III and MG IV. Meanwhile, the 180 cultivars from SC spanned MG I to MG IX. Notably, MG III accounted for the largest proportion, comprising 28.65 % of the cultivars. Generally, cultivars in MG 0 and earlier groups were primarily distributed in NE, while those in MG VI and later groups were mainly found in SC. Cultivars in MGs II-IV were distributed throughout all soybean-producing regions, and the proportion of MG III cultivars in the three regions (NE, HH, and SC) was relatively similar.

3.4. MG distribution in different sowing-season ecotypes of soybean cultivars in China

In the current study, a total of 620 spring-sowing soybean cultivars were identified, spanning an MG range from MG 000 to MG V (Table 3). The largest proportion of these cultivars belonged to MG II (165 cultivars), accounting for 26.61 % of the total, followed by MG I (142 cultivars), accounting for 22.90 %. These soybeans were mainly planted in NE and NW regions, with only a few cultivars grown in SC. For summer-sowing soybeans, there were 143 cultivars identified with a MG range of MG II-IX, among which MG III cultivars accounted for the largest proportion. Soybean cultivars of MG II-IV were primarily grown in HH, whereas those of MG VI-IX were predominantly cultivated in SC. Additionally, MG V soybeans were found in both HH and SC regions. As for autumn-sowing soybeans, only three cultivars were found in SC, all of which were assigned to MG VII.

3.5. Geographic distribution of the cultivars from different MGs across China

The Kriging interpolation results have revealed the distribution of adaptive soybean MG zones across China (Fig. 4). It was observed that the region suitable for growing MG 000 soybeans is extremely limited. Generally, MG 00 cultivars were mainly distributed in the northern parts of Daxinganling area, above the 50°N latitude line. Representative cultivars falling within the MG 000–00 category comprised Heihe 35 (MG m1.2), Heihe 49 (MG m1.1), Dongnong 44 (MG m0.5), Kenjiandou 25 (MG m0.1), etc. As for MG 0 cultivars, they were prevalent in the central region of Heilongjiang province, as well as the northern parts of Inner Mongolia and central and northern regions of Xinjiang, etc. Representative cultivars of MG 0 included Jiangmodu 1 (MG 0.1), Heihe 43 (MG

Table 2
The estimated regressions for RMG adjustment at different sites in 2011–2015.

Site	2011		2012		2013		2014		2015	
	Regression equation	R^2	Regression equation	R^2	Regression equation	R^2	Regression equation	R^2	Regression equation	R^2
Heihe	RMG= 0.047DPM-4.792	0.872	RMG= 0.037DPM-3.528	0.897	RMG= 0.052DPM-5.594	0.898	RMG= 0.055DPM-6.111	0.978	RMG= 0.069DPM-7.124	0.972
Jiusan			RMG= 0.076DPM-7.618	0.928	RMG= 0.064DPM-6.56	0.966				
Zhalantun	RMG= 0.075DPM-7.293	0.966	RMG= 0.07DPM-7.096	0.945	RMG= 0.062DPM-6.35	0.949	RMG= 0.082DPM-8.116	0.966	RMG= 0.081DPM-8.126	0.952
Hailun	RMG= 0.086DPM-8.19	0.971	RMG= 0.084DPM-8.112	0.978	RMG= 0.085DPM-8.151	0.982	RMG= 0.085DPM-8.577	0.982		
Tsitsihar	RMG= 0.168DPM-14.96	0.953	RMG= 0.085DPM-7.591	0.960	RMG= 0.151DPM-15.149	0.972	RMG= 0.08DPM-7.319	0.981		
Kiamusze			RMG= 0.074DPM-7.278	0.899			RMG= 0.083DPM-7.753	0.989		
Suihua	RMG= 0.094DPM-8.818	0.935	RMG= 0.093DPM-9.088	0.952	RMG= 0.102DPM-9.931	0.979	RMG= 0.079DPM-7.76	0.976	RMG= 0.1DPM-9.705	0.968
Daqing	RMG= 0.11DPM-10.297	0.996	RMG= 0.094DPM-8.774	0.993	RMG= 0.112DPM-10.85	0.985				
Harbin	RMG= 0.098DPM-10.505	0.968	RMG= 0.115DPM-12.04	0.970	RMG= 0.13DPM-12.626	0.790				
Changchun	RMG= 0.089DPM-7.924	0.958	RMG= 0.098DPM-9.775	0.959	RMG= 0.101DPM-9.346	0.931	RMG= 0.099DPM-9.191	0.959	RMG= 0.086DPM-7.101	0.981
Gongzhuling	RMG= 0.118DPM-10.513	0.807	RMG= 0.097DPM-9.634	0.951	RMG= 0.094DPM-8.354	0.980	RMG= 0.112DPM-10.382	0.986		
Chifeng	RMG= 0.178DPM-15.128	0.979			RMG= 0.117DPM-9.387	0.975				
Tieling			RMG= 0.07DPM-5.292	0.945	RMG= 0.091DPM-7.632	0.975				
Shenyang	RMG= 0.093DPM-7.622	0.984	RMG= 0.089DPM-7.697	0.948	RMG= 0.083DPM-6.974	0.961	RMG= 0.076DPM-5.652	0.974		
Shihezi	RMG= 0.126DPM-12.257	0.967	RMG= 0.088DPM-7.72	0.954	RMG= 0.141DPM-14.172	0.947	RMG= 0.126DPM-12.344	0.920		
Yan'an			RMG= 0.056DPM-2.093	0.986	RMG= 0.08DPM-5.552	0.975				
Zhenyuan	RMG= 0.067DPM-5.443	0.981			RMG= 0.048DPM-1.936	0.966				
Yinchuan	RMG= 0.077DPM-5.701	0.961	RMG= 0.109DPM-10.427	0.966	RMG= 0.071DPM-4.613	0.971	RMG= 0.064DPM-4.204	0.970		
Fenyang	RMG= 0.091DPM-6.742	0.995	RMG= 0.086DPM-6.465	0.986	RMG= 0.086DPM-6.309	0.986	RMG= 0.054DPM-2.205	0.991	RMG= 0.054DPM-2.173	0.982
Beijing	RMG= 0.081DPM-5.944	0.991	RMG= 0.079DPM-5.482	0.991	RMG= 0.097DPM-7.659	0.989	RMG= 0.067DPM-4.651	0.966	RMG= 0.09DPM-5.906	0.973
Cangzhou	RMG= 0.148DPM-12.717	0.994	RMG= 0.087DPM-6.311	0.990	RMG= 0.068DPM-3.868	0.982				
Jinan	RMG= 0.134DPM-9.96	0.955			RMG= 0.077DPM-4.637	0.966				
Jining	RMG= 0.079DPM-4.854	0.988			RMG= 0.053DPM-2.416	0.934	RMG= 0.068DPM-4.322	0.994		
Zhengzhou					RMG= 0.088DPM-5.538	0.976	RMG= 0.137DPM-10.371	0.969		
Shangqiu	RMG= 0.116DPM-8.592	0.982	RMG= 0.112DPM-8.778	0.967	RMG= 0.101DPM-7.609	0.989				
Xuzhou	RMG= 0.045DPM-1.073	0.890	RMG= 0.067DPM-4.358	0.959	RMG= 0.08DPM-5.55	0.950	RMG= 0.073DPM-4.395	0.957	RMG= 0.076DPM-4.338	0.972
Suzhou			RMG= 0.066DPM-3.016	0.968	RMG= 0.084DPM-4.566	0.972				
Fuyang	RMG= 0.08DPM-4.541	0.991	RMG= 0.089DPM-5.614	0.989	RMG= 0.12DPM-7.787	0.785				
Nanjing	RMG= 0.092DPM-4.94	0.979	RMG= 0.074DPM-1.524	0.990	RMG= 0.074DPM-1.376	0.990				
Nanchong	RMG= 0.049DPM-1.517	0.987	RMG= 0.059DPM-2.587	0.990	RMG= 0.048DPM-1.075	0.981	RMG= 0.044DPM-0.026	0.987	RMG= 0.049DPM-0.797	0.986
Wuhan	RMG= 0.06DPM-2.298	0.991	RMG= 0.048DPM-0.932	0.986	RMG= 0.045DPM-0.458	0.990	RMG= 0.049DPM-0.986	0.987	RMG= 0.041DPM-0.173	0.987
Nanchang	RMG= 0.78DPM-4.073	0.963	RMG= 0.123DPM-7.872	0.956	RMG= 0.156DPM-10.968	0.988	RMG= 0.126DPM-9.42	0.988	RMG= 0.109DPM-7.799	0.984
Guiyang	RMG= 0.111DPM-5.6	0.994	RMG= 0.108DPM-5.916	0.974	RMG= 0.157DPM-9.463	0.980	RMG= 0.088DPM-4.064	0.891		
Kunming			RMG= 0.142DPM-10.371	0.994	RMG= 0.128DPM-8.657	0.985	RMG= 0.13DPM-9.139	0.988		
Guangzhou			RMG= 0.306DPM-19.08	0.992			RMG= 0.288DPM-15.829	0.961		
Nanning	RMG= 0.196DPM-10.952	0.967	RMG= 0.245DPM-15.896	0.972	RMG= 0.182DPM-10.558	0.981	RMG= 0.245DPM-15.793	0.99		

RMG, relative maturity group; DPM, days to physiological maturity (R7).

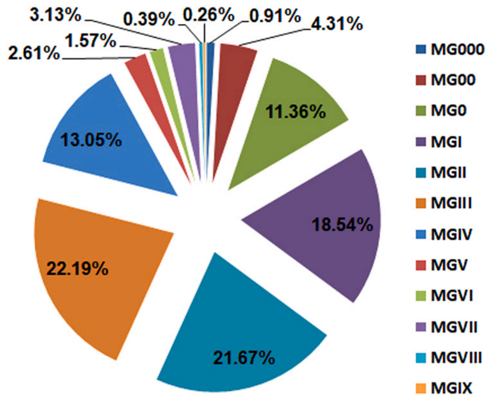

Fig. 2. The percent distribution of Chinese soybean cultivars in MGs.

0.0), Huajiang 4 (MG 0.2), Kenjiandou 27 (MG 0.4), Keshan 1 (MG 0.5), Heihe 36 (MG 0.6), etc. MG I cultivars were primarily distributed in the southern region of Heilongjiang province, the central parts of Inner Mongolia, and the northern region of Jilin province. Representative cultivars of MG I included Hefeng 50 (MG 1.0), Suinong 28 (MG 1.3), Suinong 26 (MG 1.4), Kangxianchong 8 (MG 1.5), Kenfeng 16 (MG 1.6), etc. MG II cultivars were mainly distributed in the area between latitude 40–44°N, which included central and southern Jilin province, northern Hebei province, northern Shanxi province, western Gansu province, and central and southern parts of Xinjiang. Among the representative cultivars falling within MG II were Changnong 16 (MG 2.2), Jiyu 72 (MG 2.5), Chidou 1 (MG 2.6), Jiyu 86 (MG 2.5), Jindou 20 (MG 2.6), Xiangchundou 23 (MG 2.7), etc. Soybeans in MG 000- II zones were mainly planted in spring. The primary distribution of MG III cultivars encompassed the latitude range of 34–40°N, encompassing regions such as central and southern Liaoning Province, central and eastern Gansu province, the Ningxia Hui Autonomous Region, northern and central Shaanxi province, central and southern Shanxi province, Beijing, Tianjin, Shandong province, central and northern Henan province, northern Anhui province, central Hubei province, and northern Hunan province. Representative cultivars of MG III included Kaiyu 12 (MG 3.1), Zhonghuang 30 (MG 3.2), Jindou 19 (MG 3.5), Qihuang 34 (MG 3.6), Zhonghuang 13 (MG 3.7), etc. Soybeans in the MG III zone were primarily planted during spring or summer. The key distribution area for MG IV cultivars extended across the latitude range of 28–34°N, encompassing regions such as southern Gansu province, southern Shaanxi province, northern Jiangsu province, central and southern Anhui province, southern Henan province, eastern Chongqing, eastern Hubei province, northern Jiangxi province, western Zhejiang province, northeast Fujian province, central Hunan province, northern Guizhou province, and eastern Yunnan province. Representative cultivars of MG IV included Zhonghuang 42 (MG 4.3), Yudou 22 (MG 4.4), Fudou 9 (MG 4.2), Xudou 16 (MG 4.5), Chengdou 6 (MG 4.5), Fendou 56 (MG 4.5), Qiandou 8 (MG4.6), etc. Soybeans within the MG IV zone were predominantly cultivated during the summer. The primary distribution area for MG V and higher group cultivars lay to the south of the 28°N latitude in China. Representative cultivars from the MG V and higher groups included Diandou 7 (MG 5.3), Nannong 88–31 (MG 6.2), Guixia 1 (MG 7.3), Zheqiudou 2 (MG 7.7), Nandou 12 (MG 7.9), and Huaxia 3 (MG 8.3). These soybeans in the MG V and higher zones were primarily planted during the summer or autumn.

4. Discussion

The data in this study includes 126 environments (location × year), and the RMGs of major Chinese cultivars grown in the last decade were evaluated. To our knowledge, this study represents the first comprehensive assessment of the RMGs of Chinese soybean cultivars. The significance of this research lies in its potential to enhance the breeding efficiency of soybean cultivars and foster international communication regarding Chinese soybean cultivars. Previous studies focused on assessing MG assignments of certain accessions from germplasm banks; however, these accessions were not actively utilized in current soybean production (Li et al., 2017; Liu et al., 2017; Wang et al., 2006).

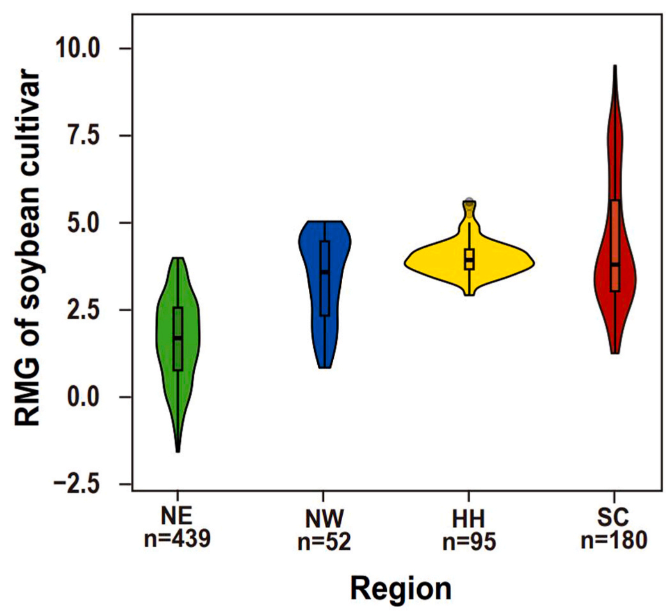

Fig. 3. RMG distribution of soybean cultivars in different regions.

Table 3
MG distribution in various soybean ecotypes.

MG	Total	Spring-sowing				Summer-sowing			Autumn-sowing
		NE	NW	SC	Total	HH	SC	Total	SC
MG 000	7	7			7				
MG 00	33	33			33				
MG 0	87	86	1		87				
MG I	142	124	7	11	142				
MG II	166	126	8	31	165	1		1	
MG III	170	58	12	53	123	47		47	
MG IV	100	5	22	31	58	42		42	
MG V	20		2	3	5	5	10	15	
MG VI	12						12	12	
MG VII	24						21	21	3
MG VIII	3						3	3	
MG IX	2						2	2	
Total	766	439	52	129	620	95	48	143	3

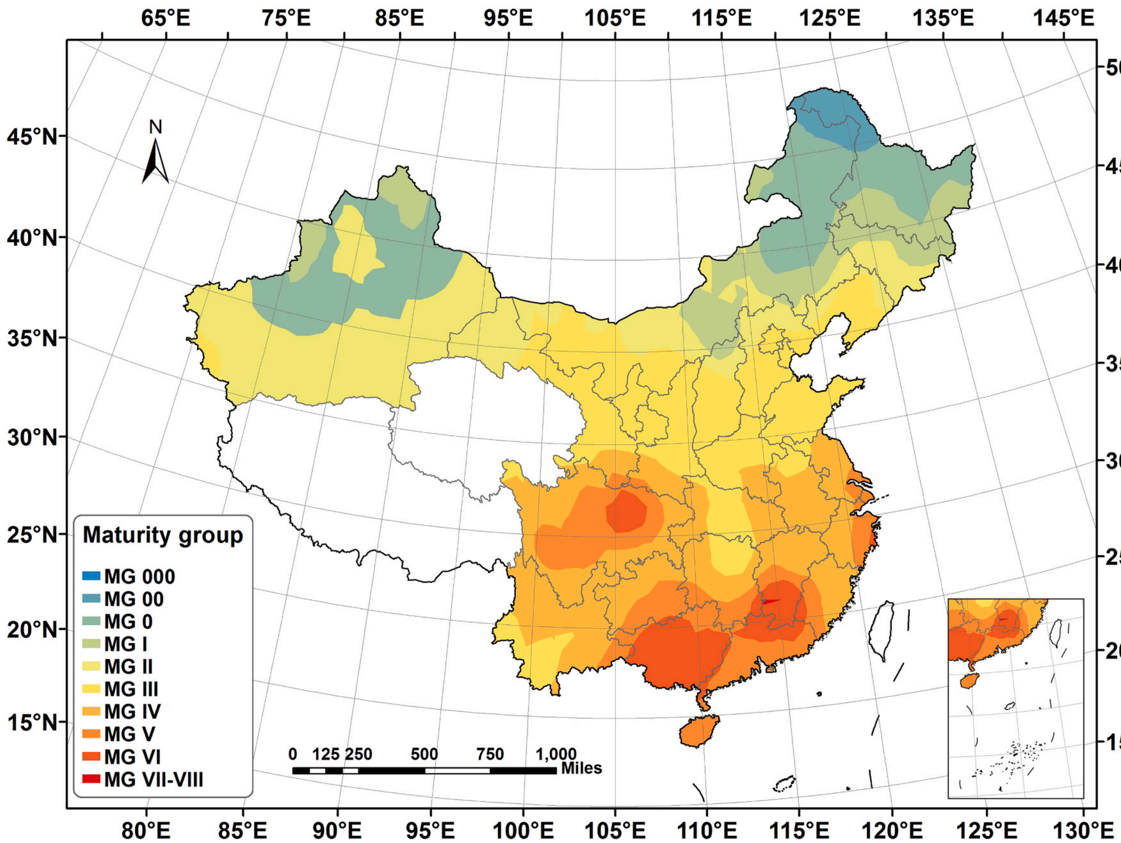

Fig. 4. The geological distribution of Soybean maturity group zones across China.

Moreover, their comparison of photothermal response characteristics posed challenges due to their classification solely into MGs, lacking the rank-based RMG system (with a decimal value from 0 to 9 appended to the group). To overcome this issue, Song et al. (2019) defined MGs 00, 000, and 0000 as negative (minus) values and used a linear regression model to establish the RMG identifying system. This approach facilitated precise MG classification for soybean cultivars and accurate comparison of photothermal response characteristics among accessions within the same MG.

The results of this study showed that the MGs of Chinese soybean cultivars ranged from MG000 to IX, which was consistent with the findings of Wang et al. (2006). However, no MG0000 cultivars were found among the 766 cultivars involved in this study. Notably, the cultivars Dongnong 41 and Dongnong 41-c, which were identified as MG0000 in the study of Jia et al. (2014), were categorized as MG000 in this study. Despite this difference, the majority of cultivars evaluated in this study had consistent RMGs with previous studies by Jia et al. (2014) and Wu et al. (2012). One significant advantage of this study was that the RMG results were determined under multi-environmental conditions, making the results more reliable than previous studies. It was also noteworthy that Heihe 43, currently the most widely-planted soybean cultivar in China, had an RMG of 0.0, providing a valuable reference for MG classification not only in China but also worldwide (Jia et al., 2023).

The results indicate that MG III and MG IV soybean cultivars exhibit adaptability across a broad spectrum of latitudes in China. This versatility stems from their suitability for cultivation as both spring-sowing soybeans in NE, NW, and SC, as well as summer-sowing soybeans in HH, as corroborated by earlier investigations by Li et al. (2017) and Liu et al. (2017). This flexibility in planting time allows these cultivars to be adapted to different climatic conditions and agricultural practices, which contributes to their widespread use and importance in soybean production systems in China. Moreover, the MG III and MG IV cultivars are also adapted to major soybean-producing states in the US, including the southern half of Nebraska and Iowa, central and southern Illinois, as well as the entirety of Kansas, Missouri, Indiana, Ohio, and Pennsylvania, Oklahoma, and Kentucky, according to Mourtzinis and Conley (2017). This means we can make attempts to introduce soybean cultivars from these regions in the future. Furthermore, the study identified a significant number of MG III cultivars in SC; however, this didn't necessarily imply the dominance of MG III cultivars in the region. In the trials conducted to assess the RMG of soybeans, the early spring planting dates led to extended growth periods for summer- and autumn-sowing soybean cultivars in SC. Consequently, these cultivars became more susceptible to both biotic and abiotic factors. Consequently, numerous late-maturing soybean cultivars exhibited a "stay-green" syndrome induced by infection of diseases or insect pests at the time of harvesting, complicating a precise assessment of their maturity (Li et al., 2019; Cheng et al., 2022; Wei et al., 2022). While soybeans of MG V or higher, typically cultivated in summer or autumn, comprised a substantial portion of soybean production in SC (Li et al., 2017; Liu et al., 2017; Wang et al., 2006), their accurate MG classification necessitates further investigation.

The study also highlighted that soybeans from HH exhibited the narrowest MG range among the primary soybean-producing areas. This was due to soybeans in this region being primarily rotated with wheat and planted after its harvest (Qin et al., 2015; Zhang et al., 2021). This double-cropping system imposed stringent demands on the sowing timing and growth duration of soybeans, resulting in a relatively limited MG range for soybeans in this region. Consequently, the number of cultivars utilized in this area was notably smaller compared to other regions, contributing to the presence of widespread cultivars like Yuejin 5 and Zhonghuang 13 in this locality.

The initial step in this study involved conducting geographic visualization analysis of soybean MG zones across China using GIS. The mapping locations selected for this research encompassed the key soybean-producing provinces in China, with a specific emphasis on areas characterized by substantial soybean acreage. This comprehensive coverage contributed to the reliability of the obtained results. In contrast, the determination of adaptive soybean MG zones in the US relied on production surveys (Mourtzinis and Conley, 2017; Zhang et al., 2007). However, the complexity of soybean ecotypes in China, stemming from their extensive distribution and diverse cropping systems, renders the precise demarcation of MG zones considerably more intricate and challenging. The distribution of MG zones in China and the United States was compared in this study. In the region north of latitude 42°N, the distributions of MG were similar in China and US, and the cultivars in this region mainly belonged to MG II or MGs earlier than MG II (Mourtzinis and Conley, 2017; Zhang et al., 2007). Compared to China, the distribution of MG zones in US is more closely associated with latitude. In the region south of latitude 42°N, there were differences in the distribution of MGs in the two countries. In the latitude range of 38–42°N, US cultivars were predominantly classified as MG III, with some belonging to MG II and MG IV. In contrast, Chinese cultivars were primarily assigned to MG II and MG III. Within the latitude range of 34–38°N, US cultivars were largely categorized as MG IV and MGV, whereas Chinese cultivars leaned towards MG III and MG IV. Further, in the 30–34°N latitude range, US cultivars spanned MG V and MG VI, while Chinese cultivars spanned MG III-IX, with some also belonging to MG I and MG II in practical production (Mourtzinis and Conley, 2017; Zhang et al., 2007). The regular association of MG distribution with latitude observed in the US may be due to the dominant single cropping system and relatively stable ecological conditions in soybean planting areas. In the US, soybeans are typically sown in spring and harvested in autumn, and this pattern is relatively stable. In contrast, China's farming system and soybean ecotypes are more intricate (Zhang et al., 2010). In NE, soybean is planted in spring and harvested in autumn like the US, thus, the distribution of MG in this region is similar to the US. However, in HH, where soybean planting occurs in summer, approximately one and half months later than in US regions with equivalent latitudes, the cultivars exhibit an MG that is 1–2 units earlier than their spring-planted counterparts in the US.

In SC, the soybean ecotypes are exceptionally diverse, and the cropping systems exhibit considerable variability. Consequently, the MGs of soybean cultivars need to accommodate a wide array of environmental factors, including climate, landforms, and various cropping practices. This intricate interplay results in a significant span within the MG range of cultivars in this region. For instance, in Jiangxi province, spring-sowing cultivars rotated with sesame and peanut range from MG I to III, summer-sowing cultivars planted on rice field ridges span MG IV to VI, and autumn-sowing cultivars rotated with rice encompass MG VII to VIII. Comparatively, a distinctive feature of soybean MG distribution in China is the occurrence of the same MG crossing different regions. This phenomenon sets Chinese soybean MG distribution apart from that of the US and highlights the complexity of soybean cultivation practices and ecotypes within China.

This study is of great significance for soybean introduction between different regions in China. The preliminary results of the study indicated that MG III cultivars could be planted in all four regions. For example, a summer soybean cultivar, Zhonghuang 39 (MG III), was introduced from HH to the SC as a spring soybean and achieved great yield performance. In addition, this study also provides a reference for the international exchange of soybean germplasm resources. For example, the MG 000 and MG 00 soybeans from China can be exchanged with those from Canada (Field Crops Team, 2011), northern Europe (Kurasch et al., 2017), as well as Russian Far East (Jia et al., 2014). Soybeans of MG 0 to II can be exchanged with those from the northern United States (Mourtzinis and Conley, 2017), parts of southern and central Europe (Kurasch et al., 2017,), and northern Japan (Liu et al., 2017). MG III and IV soybeans can be exchanged with those from the central regions of the United States (Mourtzinis and Conley, 2017), while soybeans later than MG IV can be exchanged with those from southern region of the United States (Mourtzinis and Conley, 2017), South America (Alliprandini et al., 2009) and other tropical and subtropical regions of the world.

5. Conclusions

Soybean RMG identification of Chinese cultivars was carried out at 36 sites in China using the international soybean MG digitized classification system. Adaptable MG zones for soybeans across China were analyzed accordingly. The results showed that soybean cultivars of MG III and MG IV were distributed most widely in China. The distribution of soybean MGs in China is in accordance with that in the US in the region northern than 42°N but differs in the region southern than 42°N due to the different cropping systems. These results hold the potential to enhance predictions regarding the optimal areas for new soybean cultivars and furnish soybean growers with recommendations for introducing soybeans from other regions.

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CRediT authorship contribution statement

Wenwen Song: Conceptualization, Software , Data curation, Writing – original draft. **Luping Liu:** Methodology, Formal analysis, Writing – review & editing. **Shi Sun:** Methodology, Formal analysis, Investigation. **Tingting Wu:** Data curation, Visualization, Writing – review & editing. **Haiyan Zeng:** Formal analysis, Investigation. **Shiyan Tian:** Formal analysis, Investigation. **Bincheng Sun:** Data curation, Investigation. **Wenbin Li:** Data curation, Investigation. **Lijun Liu:** Data curation, Investigation. **Shuming:** Data curation, Investigation. **Han Xing:** Data curation, Investigation. **Xin'an Zhou:** Data curation, Investigation. **Hai Nian:** Data curation, Investigation. **Wencheng Lu:** Data curation, Investigation. **Xiaozeng Han:** Data curation, Investigation. **Shouyi Wang:** Data curation, Investigation. **Weiyuan Chen:** Data curation, Investigation. **Tai Guo:** Data curation, Investigation. **Xiqing Song:** Data curation, Investigation. **Zhongyan Tian:** Data curation, Investigation. **Yanxi Cheng:** Data curation, Investigation. **Shuhong Song:** Data curation, Investigation. **Lianshun Fu:** Data curation, Investigation. **Huicai Wang:** Data curation, Investigation. **Ruiping Luo:** Data curation, Investigation. **Xueyi Liu:** Data curation, Investigation. **Qi Liu:** Data curation, Investigation. **Guohong Zhang:** Data curation, Investigation. **Sihui Lu:** Data curation, Investigation. **Ran Xu:** Data curation, Investigation. **Suzhen Li:** Data curation, Investigation. **Weiguo Lu:** Data curation, Investigation. **Qi Zhang:** Data curation, Investigation. **Zongbiao Wang:** Data curation, Investigation. **Chengong Jiang:** Data curation, Investigation. **Weiliang Shen:** Data curation, Investigation. Mingrong Zhang: Data curation, Investigation. **Danhua Zhu:** Data curation, Investigation. **Ruizhen Wang:** Data curation, Investigation. **Yuan Chen:** Data curation, Investigation. **Tiejun Wang:** Data curation, Investigation. **Xingtao Zhu:** Data curation, Investigation. **Yong Zhan:** Data curation, Investigation. **Bingjun Jiang:** Writing – review & editing. **Cailong Xu:** Formal analysis. Shan Yuan: Formal analysis. **Wensheng Hou:** Writing – review & editing. **Junyi Gai:** Conceptualization. **Cunxiang Wu:** Conceptualization, Supervision. **Tianfu Han:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the link to our data as the Attach file step.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126982.

References

Allen, D.W., 2010. GIS Tutorial 2: Spatial Analysis for ArcGIS 10. ESRI, Redlands. CA.

Alliprandini, L.F., Abatti, C., Bertagnolli, P.F., Cavassim, J.E., Gabe, H.L., Kurek, A., Matsumoto, M.N., de Oliveira, M.A.R., Pitol, C., Prado, L.C., Steckling, C., 2009. Understanding soybean maturity groups in Brazil: environment, cultivar classification, and stability. Crop Sci. 49 (3), 801–808. https://doi.org/10.2135/cropsci2008.07.0390.

Boerma, H.R., Specht, J.E., 2004. Soybeans: Improvement, Production and Uses, third ed. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA, pp. 621–677.

Boyer, C.N., Stefanini, M., Larson, J.A., Smith, S.A., Mengistu, A., Bellaloui, N., 2015. Profitability and risk analysis of soybean planting date by maturity group. Agron. J. 107 (6), 2253–2262. https://doi.org/10.2134/agronj15.0148.

Cavassim, J.E., Alliprandini, L.F., de Oliveira, R.A., Daros, E., Guerra, E.P., 2013. Stability of soybean genotypes and their classification into relative maturity groups in Brazil. Am. J. Plant Sci. 4 (11), 2060–2069. https://doi.org/10.4236/ajps.2013.411258.

Cheng, R., Mei, R., Yan, R., Chen, H., Miao, D., Cai, L., Fan, J., Li, G., Xu, R., Ye, W., Su, S., Han, T., Gai, J., Wang, Y., Tao, X., Xu, Y., 2022. A new distinct geminivirus causes soybean stay-green disease. Mol. Plant 15 (6), 927–930. https://doi.org/10.1016/j.molp.2022. . 03.011.

Dardanelli, J.L., Balzarini, M., Martínez, M.J., Cuniberti, M., Resnik, S., Ramunda, S.F., Herrero, R., Baigorri, H., 2006. Soybean maturity groups, environments, and their interaction define mega-environments for seed composition in Argentina. Crop Sci. 46 (5), 1939–1947. https://doi.org/10.1007/s00122-022-04134-8.

Dong, Y., Zhao, L., Liu, B., Wang, Z., Jin, Z., Sun, H., 2004. The genetic diversity of cultivated soybean grown in China. Theor. Appl. Genet. 108 (5), 931–936. https://doi.org/10.1007/s00122-003-1503-x.

Edwards, J.T., Purcell, L.C., Karcher, D.E., 2005. Soybean yield and biomass responses to increasing plant population among diverse maturity groups: II. Light interception and utilization. Crop Sci. 45 (5), 1778–1785. https://doi.org/10.2135/cropsci2004.0570.

Fehr, W.R., Caviness, C.E., 1977. Stages of soybean development. Spec. Rep. 80 (Iowa Agric. Home Econ. Exp. Stn., Ames).

Field Crops Team, 2011. New Ontario soybean maturity map. Field Crop Rep. 8. ⟨http://www.ontariosoilcrop.org/wp-content/uploads/2015/07/v8crpadv_soy4-2011_new_ontario_soybean_maturity_map.pdf⟩ (accessed 3 Mar. 2014).

Gai, J., Wang, Y., Zhang, M., Wang, J., Chang, R., 2001. Studies on the classification of maturity groups of soybeans in China. Acta Agron. Sin. 27 (3), 286–292. ⟨https://zwxb.chinacrops.org/CN/Y2001/V27/I03/286⟩.

Garner, W., Allard, H.A., 1920. Effect of the relative length of day and night and other factors of the environment on growth and reproduction in plants. J. Agric. Res. 18 (11), 553–606.

Gupta, S., Agrawal, N., Tripathi, R., Kumawat, G., Nataraj, V., Maranna, S., Satpute, G.K., Ratnaparkhe, M.B., Rajesh, V., Chandra, S., 2021. Long juvenility trait: a vehicle for commercial utilization of soybean (*Glycine max*) in lower latitudes. Plant Breed. 140 (4), 543–560. https://doi.org/10.1111/pbr.12926.

Gupta, S., Kumawat, G., Agrawal, N., Tripathi, R., Rajesh, V., Nataraj, V., Maranna, S., Satpute, G.K., Kandel, H.J., Samarappuli, D.P., Johnson, K.L., Berti, M.T., 2021. Soybean relative maturity, not row spacing, affected interseeded cover crops biomass. Agriculture 11 (5), 441. https://doi.org/10.3390/agriculture11050441.

Hartwig, E., 1970. Growth and reproductive characteristics of soybeans [*Glycine max* (L.) Merr.] grown under short-day conditions. Trop. Sci. 12 (1), 47–53.

Hymowitz, T., Newell, C.A., 1981. Taxonomy of the genus Glycine, domestication and uses of soybeans. Econ. Bot. 35, 272–288. https://doi.org/10.1007/BF02859119.

Jia, H., Jiang, B., Wu, C., Lu, W., Hou, W., Sun, S., Yan, H., Han, T., 2014. Maturity group classification and maturity locus genotyping of early-maturing soybean varieties from high-latitude cold regions. PLoS One 9 (4), e94139. https://doi.org/10.1371/journal.pone.0094139.

Jia, H., Liang, X., Lu, W., Zhang, L., Wu, T., Song, W., Sun, S., Zhang, L., Yan, H., Guo, R., Chen, Y., Li, B., Wu, C., Han, T., 2023. Fine identification of maturity groups of regional trial check varieties in Northern Heilongjiang Province. Soybean Technol. 1, 1–11. ⟨https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C44YLTlOAiTRKibYlV5Vjs7ioT0BO4yQ4m_mOgeS2ml3UMT8PkLFqA7BdbBNCC4zQnDOQBOqVSk9a_JWRbqp3S9O&uniplatform=NZKPT⟩.

Kurasch, A.K., Hahn, V., Leiser, W.L., Vollmann, J., Schori, A., Bétrix, C.A., Mayr, B., Winkler, J., Mechtler, K., Aper, J., Sudaric, A., Pejic, I., Sarcevic, H., Jeanson, P., Balko, C., Signor, M., Miceli, F., Strijk, P., Rietman, H., Muresanu, E., Djordjevic, V., Pospišil, A., Barion, G., Weigold, P., Streng, S., Krön, M., Würschum, T., 2017. Identification of mega-environments in Europe and effect of allelic variations at maturity *E* loci on adaptation of European soybean. Plant Cell Environ. 40 (5), 765–778. https://doi.org/10.1111/pce.12896.

Langewisch, T., Lenis, J., Jiang, G.L., Wang, D., Pantalone, V., Bilyeu, K., 2017. The development and use of a molecular model for soybean maturity groups. BMC Plant Biol. 17 (1), 1–13. https://doi.org/10.1186/s12870-017-1040-4.

Li, J., Wang, X., Song, W., Huang, X., Zhou, J., Zeng, H., Sun, S., Jia, H., Li, W., Zhou, X., Li, S., Chen, P., Wu, C., Guo, Y., Han, T., Qiu, L., 2017. Genetic variation of maturity groups and four E genes in the Chinese soybean mini core collection. PLoS One 12 (2), e0172106. https://doi.org/10.1371/journal.pone.0172106.

Li, K., Zhang, X., Guo, J., Penn, H., Wu, T., Li, L., Jiang, H., Chang, L., Wu, C., Han, T., 2019. Feeding of *Riptortus pedestris* on soybean plants, the primary cause of soybean staygreen syndrome in the Huang-Huai-Hai river basin. Crop J. 7 (3), 360–367. https://doi.org/10.1016/j.cj.2018.07.008.

Liu, X., Li, C., Cao, J., Zhang, X., Wang, C., He, J., Xing, G., Wang, W., Zhao, J., Gai, J., 2021. Growth period QTL-allele constitution of global soybeans and its differential evolution changes in geographic adaptation versus maturity group extension. Plant J. 108 (6), 1624–1643. https://doi.org/10.1111/tpj.15531.

Liu, X., Wu, J., Ren, H., Qi, Y., Li, C., Cao, J., Zhang, X., Zhang, Z., Cai, Z., Gai, J., 2017. Genetic variation of world soybean maturity date and geographic distribution of maturity groups. Breed. Sci. 67 (3), 221–232. https://doi.org/10.1270/jsbbs.16167.

Mohammed, Y.A., Gesch, R.W., Matthees, H.L., Wells, S.S., 2022. Maturity selection but not sowing date enhances soybean productivity and land use in a winter camelina–soybean relay system. Food Energy Secur. 11 (1), e346 https://doi.org/10.1002/fes3.346.

Morris, T.C., Vann, R.A., Heitman, J., Collins, G.D., Heiniger, R.W., 2021. Maximizing soybean yield by understanding planting date, maturity group, and seeding rate interactions in North Carolina. Crop Sci. 61 (6), 4365–4382. https://doi.org/10.1002/csc2.20603.

Mourtzinis, S., Conley, S.P., 2017. Delineating soybean maturity groups across the United States. Agron. J. 109 (4), 1397–1403. https://doi.org/10.2134/agronj2016.10.0581.

Pu, M., Pan, T., 1982. A study on the regionalization of soybean production area in China. Soybean Sci. 1, 105–121.

Qin, W., Wang, D., Guo, X., Yang, T., Oenema, O., 2015. Productivity and sustainability of rainfed wheat-soybean system in the North China Plain: results from a long-term experiment and crop modelling. Sci. Rep. 5 (1), 1–16. https://doi.org/10.1038/srep17514.

Rod, K.S., Shockley, J., Knott, C.A., 2021. Seed yield, seed quality, profitability, and risk analysis among double crop soybean maturity groups and seeding rates. Agron. J. 113 (2), 1792–1802. https://doi.org/10.1002/agj2.20626.

Sampaio, L., Battisti, R., Lana, M., Boote, K.J., 2020. Assessment of sowing dates and plant densities using CSM-CROPGRO-Soybean for soybean maturity groups in low latitude. J. Agric. Sci. 158 (10), 819–832. https://doi.org/10.1017/S0021859621000204.

Scott, W.O., Aldrich, S.R., 1970. Modern Soybean Production, first ed. S & A Publ. Inc, Champaign, IL.

Shanmugasundaram, S., 1981. Varietal differences and genetic behavior for the photoperiodic responses in soybeans. Kyushu Univ. Ins. Trop. Agric. Bull. 4, 1–61.

Song, W., Sun, S., Ibrahim, S.E., Xu, Z., Wu, H., Hu, X., Jia, H., Cheng, Y., Yang, Z., Jiang, S., Wu, T., Sinegovskii, M., Sapey, E., Nepomuceno, A., Jiang, B., Hou, W., Sinegovskaya, V., Wu, C., Gai, J., Han, T., 2019. Standard cultivar selection and digital quantification for precise classification of maturity groups in soybean. Crop Sci. 59 (5), 1997–2006. https://doi.org/10.2135/cropsci2019.02.0095.

Song, W., Sun, S., Wu, T., Yang, R., Tian, S., Xu, C., Jiang, B., Yuan, S., Hou, W., Wu, C., Han, T., 2023. Geographic distributions and the regionalization of soybean compositions across China. Food Res. Int. 164, 112364 https://doi.org/10.1016/j.foodres.2022.112364.

Wang, Y., Qin, J., Gai, J., He, G., 2006. Classification and characteristic of maturity groups of Chinese landraces of soybean [*Glycine max* (L.) Merr.]. Genet. Resour. Crop Evol. 53 (4), 803–809. https://doi.org/10.1007/s10722-004-5731-y.

Wang, Y.S., Gai, J.Y., 2000. Study on cultivating regions of soybeans in China. Soybean Sci. 19 (3), 203–209 http://en.cnki.com.cn/Article_en/CJFDTOTAL-DDKX200003001. htm.

Wei, Z., Guo, W., Jiang, S., Yan, D., Shi, Y., Wu, B., Xin, X., Chen, L., Cai, Y., Zhang, H., Zhang, H., Li, Y., Huang, H., Li, J., Yan, F., Zhang, C., Hou, W., Chen, J., Sun, Z., 2022. Transcriptional profiling reveals a critical role for *GmFT2a* in soybean staygreen syndrome caused by the pest *Riptortus pedestris*. New Phytol. 2022 https://doi.org/10.1111/nph.18628.

Wu, C., Li, J., Sha, A., Zeng, H., Sun, S., Yang, G., Zhou, X., Chang, R., Nian, H., Han, T., 2012. Maturity group classification of check varieties in national soybean uniform trials of China. Acta Agron. Sin. 38 (11), 1977–1987. https://doi.org/10.3724/SP.J.1006.2012.01977.

Zhang, L., Chen, Y., Wu, C., Han, T., 2010. Comparison of soybean variety trial systems and procedures in the USA and China. Crop Manag. 9, 1–13. https://doi.org/10.1094/CM-2010-040501-RV.
Zhang, L.X., Kyei-Boahen, S., Zhang, J., Zhang, M.H., Freeland, T.B., Watson, C.E., Liu, X., 2007. Modifications of optimum adaptation zones for soybean maturity groups in the USA. Crop Manag. 6 (1), 1–11. https://doi.org/10.1094/cm-2007-0927-01-rs.
Zhang, X., Wu, T., Wen, H., Song, W., Xu, C., Han, T., Sun, S., Wu, C., 2021. Allelic variation of soybean maturity genes *E1-E4* in the Huang-Huai-Hai river valley and the Northwest China. Agriculture 11 (6), 478. https://doi.org/10.3390/agriculture11060478.