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Geographic zoning of soybean maturity groups in Brazil: a spatial strategy for cultivar recommendation

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ABSTRACT: Brazil is the largest soybean producer in the world, representing about 40 % of world production. Soybean fields span all regions of the country, resulting in high environmental diversity for cultivation. The wide adoption of earlier-maturing cultivars and intensified cropping systems have thrown up challenges when selecting the best adapted cultivars for each region. In this study, we aimed to develop an updated geographic map of soybean yield adaptation, based on relative maturity (RM), in order to increase accuracy in cultivar development and recommendation. Data from yield trials of 175 locations were used, covering latitudes from 7 to 33° S. These trials were conducted over four crop seasons, from 2014/2015 to 2017/2018. Altogether, 160 cultivars with different RM were evaluated across locations. Grain yield (GY) was adjusted using the linear mixed model to identify the most adapted RM group in each location. Subsequently, the regression kriging method was adopted to spatialize this optimized RM, and consider the latitude, longitude and elevation as predictors. We concluded that under Brazilian soybean growing conditions, cultivars with RM from 5.5 to 6.4 are best adapted in the subtropical region, whereas cultivars with RM from 7.0 to 8.4 are best adapted in the tropical region. The adaptation of later-maturing cultivars with RM from 8.5 to 9.4 is restricted to the northernmost regions. There is a transitional tropical-subtropical zone where cultivars with RM from 6.0 to 6.9 are the best adapted. Latitude and elevation are key factors for soybean yield adapting, with elevation promoting slight deflections in adaptation zones, favoring earlier cultivars.

Keywords: agronomic mapping, adaptability, grain yield, cultivar recommendation, geospatial analysis

Introduction

Brazil is the world's largest soybean producer, representing approximately 40 % of global production. The area under cultivation in the country totals approximately 47 million hectares, increasing by more than 20 million hectares from 2010 to 2024, according to reports from the United States Department of Agriculture (USDA, 2024). Currently, soybean fields cover practically all Brazilian regions, which results in high environmental diversity for cultivation, reaching territorial extensions in excess of 30° of latitude across uneven edaphoclimatic conditions.

Soybean is a photothermal-sensitive species. Thus, a cultivar adaptation is restricted to specific latitude ranges and edaphoclimatic regions (Lu et al., 2017; Bu et al., 2021; Song et al., 2023; Vollmann and Škrabišová, 2023). However, the recent development and adoption of broadly adapted and earlier soybean cultivars has become increasingly common, especially in tropical regions (Li et al., 2024). The main purpose of reducing the soybean growth cycle is to enable the successful cultivation of a second crop within the same season. In this context, efforts have been made in breeding programs to select earlier, more stable and high-yielding cultivars.

In the Brazilian seed market, early indeterminate soybean cultivars with branched architecture have been increasingly favored, primarily on account of their phenotypic plasticity under diverse environmental conditions (Balbinot Junior et al., 2018; Milioli et al., 2022). These cultivars tend to exhibit greater adaptability in response to plant density and environmental variations, which contribute to stable yield performance. Concurrently, breeding programs have optimized key agronomic and adaptive traits (photoperiod response, relative maturity (RM), plant height, lodging, and yield components) to meet the demands of intensive production systems, and thereby reduce the crop cycle while maintaining or even increasing yield (Bezerra et al., 2022; Medeiros et al., 2024).

Over the last few years, these changes in the development of new cultivars have likely influenced the adaptive amplitude of RM groups, shaping yield potential and redefining key aspects for cultivar recommendation (Mendonça et al., 2022; Souza et al., 2024; Wadt et al., 2025). This has been essential to the improvement of different soybean production systems, such as soybean–maize and soybean–cotton rotations in tropical environments, in order to maximize profitability and mitigate cultivation risks (Nóia Júnior and Sentalhas, 2019; Oligini et al., 2023). In this study, we aimed to understand, from an updated geographical perspective, the yield adaptation levels of soybean cultivars according to their RM across growing regions of Brazil, with the goal of enhancing accuracy in cultivar development and recommendation, as well as supporting breeding program strategies in these regions.

Materials and Methods

Experimental data

Grain yield (GY) data from trials conducted at 175 locations, covering all Brazilian soybean-producing regions, were used. These trials were located predominantly in the most relevant regions for soybean production (Figure 1). They were conducted from the 2014/15 to 2017/18 growing seasons, covering all soybean macro-regions of Brazil, with latitudes ranging from 7 to 33° S and elevations from 9 to 1,188 m.

The experimental design adopted was randomized complete block, with three replications, and each plot was composed of four rows of 5.0 m each, spaced 0.5 m apart. On average, 60 soybean cultivars (commercial and pre-commercial inbred lines), with different RM were evaluated in each trial. In all, 160 cultivars were evaluated, which were distributed in the entry-lists of each location. GY data were the measurement of grain weight (kg ha^{-1}), corrected to 13 % (wet basis) moisture, from two central rows of each plot. The maturity date was considered at the R8 stage of plants, with 95 % of the pods mature (Fehr et al., 1971). Crop management was conducted according to technical recommendations for soybean crop (Seixas et al., 2020). As for fertilizer use, all trials received at least 300 kg ha^{-1} of NPK formulation (00-20-20) or an equivalent. Pesticides were sprayed as needed, based on the crop sanitary condition. In general, the sowing was carried out under no-till conditions during the season appropriate to each region, as recommended in the agricultural zoning guide to climate risk for Brazil (MAPA, 2025).

Yield data analysis: relative maturity × location (RM × L)

Initially, the cultivars were grouped into RM ranges, then the groups were named from G1 to G10 (Table 1). Cultivars maturing earlier than 4.5 and later than 9.4 were not evaluated in the trials, due to adaptation restrictions in the main soybean-producing regions of Brazil. The GY data taking into account each RM group and location were adjusted using the following linear mixed model:

$$y = X\beta + Z_1u_1 + Z_2u_2 + Z_3u_3 + Z_4u_4 + Z_5u_5 + Z_6u_6 + Z_7u_7 + e \quad (1)$$

Table 1 – Relative maturity (RM) groups of soybean cultivars assessed in Brazilian growing conditions from 2014 to 2018, and respective class midpoints and number of entries for each group (from G1 to G10).

Group	RM	Midpoint	Entries
G1	4.5-4.9	4.7	04
G2	5.0-5.4	5.2	08
G3	5.5-5.9	5.7	25
G4	6.0-6.4	6.2	21
G5	6.5-6.9	6.7	17
G6	7.0-7.4	7.2	20
G7	7.5-7.9	7.7	20
G8	8.0-8.4	8.2	24
G9	8.5-8.9	8.7	19
G10	9.0-9.4	9.2	02

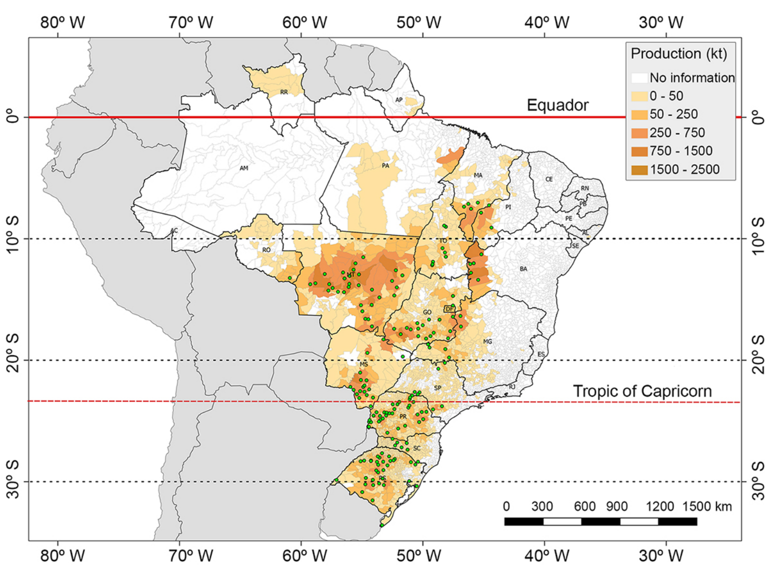

Figure 1 – Yield trials locations (green dots) from 2014/2015 to 2017/2018 seasons. The background color (orange) indicates the total production of soybean throughout the Brazilian territory, based on Brazilian Institute of Geography and Statistic survey (IBGE, 2023).

where: y is the vector of experimental observations, X and Z_i (i = 1 to 7), the incidence matrices, β the vector of fixed effects ($\beta' = [\beta_0 \vdots \beta_1]$, in which β_0 is the intercept, and β_1 the vector of RM group effects), u_i (i = 1 to 7) the vectors of random effects, with $u_i \sim N\left(0,\sigma^2_{ui}\right)$ associated to the effects of year, location, block within location, cultivar within RM group, interaction between RM group and year, interaction between RM group and location, and interaction between RM group, location, and year, respectively, and e is the vector of experimental errors, with $e \sim N\left(0,\sigma^2_e\right)$.

This model was fitted using the *lme4* package in R software (version 4.4.1). Subsequently, the corresponding deviance was analysed to verify the significance of model effects (α = 0.05). The predictor of $X\beta + u_6$ (adjusted means for each combination of RM group and location), denoted as $\hat{y}_{RM \times L}$, was then adopted to define the best RM group adapted to each location (RM_B). This final result was defined as in Eq. (2):

$$RM_B = \arg\max_{RM}(\hat{y}_{RM \times L})RM \quad (2)$$

The results for RMB represent the RM group for each location with maximized grain yield. The midpoints of these groups were then considered the optimal RM values (RMop) of the different locations, and were subsequently used for spatialization by regression-kriging.

Geographic zoning of yield adaptation

The regression-kriging method (Hengl et al., 2004) was used to delineate the geographic yield adaptation zones of the soybean cultivars, based on their RM. In this method, initially, multiple linear regression (MLR) is plotted between the regionalized variable and predictors, using data from sampled locations, in order to extrapolate the RM predictions to unsampled locations. Additionally, the variation not explained by predictors through regression is interpolated using ordinary kriging, according to the following model:

$$\hat{z}(s_0) = \sum_{k=0}^{p} \hat{\beta}_k \cdot \hat{q}_k(s_0) + \sum_{i=1}^{n} \widehat{\lambda_i} \cdot e(s_i) \quad (3)$$

where: $\hat{z}(s_0)$ is the best RM in an unsampled location, $\hat{\beta}_k$, the estimated regression coefficients associated to the predictors (k = 0, 1, 2, ... p), $\hat{q}_k(s_0)$ the k^{th} predictor value at an unsampled location, where $\hat{q}_0(s_0) = 1$, $\widehat{\lambda_i}$, weights determined by covariance function, and $e(s_i)$ corresponds to regression residuals.

For MLR fitting the predictors' latitude, longitude and elevation were considered, with elevation obtained from "Digital Elevation Model"-SRTM (Farr et al., 2007). Next, a "backward" procedure was applied to select the most appropriate model, based on the values of adjusted coefficients of determination (R^2_{adj}). An isotropic distribution of effects along the map was predefined. Following this, the exponential variogram model was considered as the best adjusted to the RM_{op} spatial distribution. The minimum residual sum of squares was adopted as the model selection criterion. The regression-kriging procedure was carried out using the *rsaga* and *gstat* packages in R software version 4.4.1. Map creation was implemented using the Quantum GIS version 3.4.4. A flowchart summarizing all the methodological steps for this study is shown in Figure 2.

Results

Deviance analysis for grain yield

The differences observed ($p < 0.05$) between RM levels are due to the differential response of the cultivars, with different RM, across all the environments sampled (Table 2). This component explains 31.72 % of the total variation. The interaction between the RM groups and assessed locations (RM × L) was significant ($p < 0.05$), explaining 25.91 % of the total variation. This interaction corresponds directly to the specific adaptation of the cultivars, grouped by RM_r, across sampled locations.

The interaction between RM groups and growing seasons (RM × Year), which was also significant ($p < 0.05$), is attributed to environmental variations such as crop management, sowing time, and non-permanent soil and weather conditions. This component can be used as an indicator of stability once it measures the repeatability of results over seasons. Similarly, the "RM × L × Year" interaction ($p < 0.05$) suggests that the levels of specific adaptation of each RM group in each location varied slightly over time (only 2.40 % of total variation). Therefore, it is necessary to further investigate this temporal variation to understand and identify adaptive trends in soybean germplasm across the regions.

Table 2 – Analysis of deviance results, variance components and coefficients of determination (R^2) of the multi-location trials for grain yield, considering 159 cultivars and 175 Brazilian locations, over four subsequent growing seasons (from 2014/2015 to 2017/2018).

Source of variation	Deviance	LRT (χ^2)	AIC	Variance	Standard deviation	R^2
						%
RM	618355	1334.49*	618383	634244	796.39	31.73
RM/Cultivar	615142	953.36*	615776	100309	316.72	12.62
RM × L	616695	1660.14*	616727	422829	650.25	25.91
RM × Year	614839	693.55*	614685	47943	218.96	2.94
RM × L × Year	614645	102.90*	614663	39125	197.80	2.40
Residual		-	-	388079	622.96	24.42
Model	619690	-	-	-	-	100

*Significant values by the χ^2 test at 5 % of significance. RM = relative maturity; L = location; LRT = likelihood ratio test; AIC = Akaike information criterion.

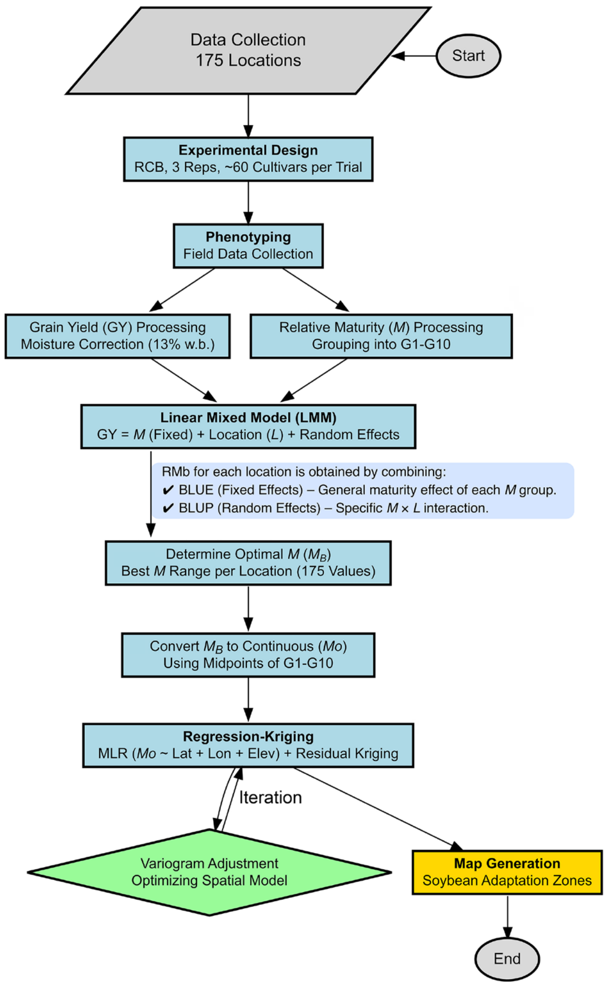

Figure 2 – Flowchart summarizing the methodological steps to determine the yield adaptation zones for soybean cultivars in Brazil, according their relative maturity (RM). Trial data from 175 locations, designed in randomized complete block (RCB), with three replicates (Reps) and ~60 cultivars per trial. The trials were evaluated for grain yield (GY) and RM were used for zoning, based on latitude, longitude and elevation (Lat, Lon and Elev). A linear mixed model (LMM) was used to estimate the best RM group for each location (RM_B), incorporating both fixed (BLUE) and random (BLUP) effects. The RM_B ranges were then converted into so-called optimum values (RM_{op}) per location taking the ranges midpoints of each group (from G1 to G10), which were modeled using multiple linear regression (MLR) combined with kriging. Spatial interpolation was refined through variogram adjustment, generating the soybean adaptation zones based on the RM groups. w.b. = wet basis

Zoning the soybean adaptation according to RM

The highest optimal RM values (RM_{op}) were estimated for lower latitude regions, with a maximum value of 9.3 in northernmost locations, such as in the Brazilian states of Roraima and Amapá. Conversely, the lowest RM_{op} values were estimated for higher latitude regions, presenting a minimum value of 5.3 in the states of Rio Grande do Sul and Santa Catarina. This indicates that in the different regions and cropping systems in Brazil, there is a current demand for cultivars with different RM levels, with an amplitude reaching 4.0 points on the soybean RM scale.

The results confirmed that the soybean yield adaptation according to the RM groups was significantly ($p < 0.05$) influenced by latitude and elevation (Table 3). However, the longitude did not influence ($p > 0.05$) the adaptation levels. There was strong negative correlation between the optimal RM values and latitude ($r = -0.82$; $p < 0.05$), indicating that for each degree reduction in latitude, there is an average increase of approximately 0.14 points in the RM_{op} at a given position. There is also negative correlation ($r = -0.16$; $p < 0.05$) between elevation and RM_{op} values. Next, an increase in elevation of 500 m, corresponds to an approximate reduction of 0.2 points (-0.0004×500) in RM_{op} (Table 3).

The adaptation zones indicate that G3 (RM from 5.5 to 5.9) are the best adapted to the southernmost locations, specifically covering the Brazilian states of Rio Grande do Sul, Santa Catarina and the southwest, southeast, and south of Paraná regions (Figure 3). Whereas G4 (with RM from 6.0 to 6.4) was the best adapted to Paraná state, covering its center, north, northwest and west, as well as southwest of Mato Grosso do Sul and São Paulo states. This group was also shown to be the best adapted to the north of Santa Catarina and central east of Rio Grande do Sul, mainly in the low-elevation locations of these states, close to the Atlantic Ocean coast.

In the transitional zone between the Brazilian subtropical and tropical regions (23°27′ S), G4 (RM from 6.0 to 6.4) and G5 (RM from 6.5 to 6.9) groups were the best adapted. This zone includes the north and northwest of Paraná, central south and east of Mato Grosso do Sul, north and northwest of São Paulo, south and southwest of Minas Gerais, including its Triângulo Mineiro and Alto Paranaíba regions (Figure 3).

In the central north of Mato Grosso do Sul, south and southwest of Goiás, in the Federal District, and in the central and northwest of Minas Gerais, as well as in areas around latitude 18°, G6 (RM from 7.0 to 7.4) was the best adapted. This group also showed optimal adaptation in the border areas between the states of Goiás, Mato Grosso do Sul, and the southeast of Mato Grosso. G7 (RM from 7.5 to 7.9) showed the best adaptation to the north, northwest and east of Goiás, including the transition between Goiás and Mato Grosso, as well as to the southeast and northeast of Mato Grosso. This RM group also was the best adapted to the central south and southwest of Mato Grosso and in sub-regions around latitude 14°S to the north of this state. Additionally, cultivars in this group were also most adapted to the eastern region of

Table 3 – Predictors and coefficients from linear multiple regression analysis for relative maturity optimized.

Predictors	Coefficients	R	R^2	R^2_{adj}	Standard-error	t-test	p-value
Latitude[1]	0.1407*	–0.8203	0.6729	0.6691	0.0075	18.8612	< 0.0001
Elevation[2]	–0.0004*	–0.1608	0.0258	0.0145	0.0002	–2.1466	0.0408
Longitude	0.0298	–0.0356	0.0013	0.0000	0.0232	–1.2927	0.1739
Intercept	9.9569	-	-	-	1.9321	51.8432	< 0.0001

[1]The latitude values must be considered negatives for the correct use of the model. [2]Digital Elevation Model-SRTM. *Significant values at 5 % of significance.

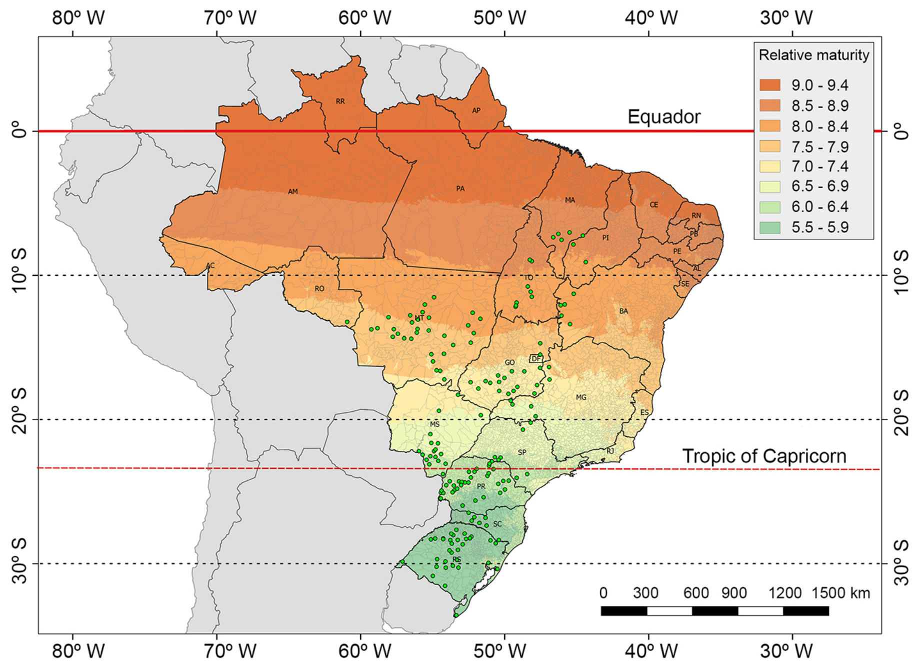

Figure 3 – Soybean geographic adaptation according to relative maturity in Brazil, considering as predictors the latitude and elevation.

Rondônia, and to the central south of Bahia, as well as to other northern and northwestern Brazilian areas.

In the mid-north and northwest of Mato Grosso — regions with the highest concentration of soybean cultivation in Brazil — as well as in other less prominent areas such as the south and central-south of Tocantins, the west and central-north of Bahia (including the Vale do São Francisco region), and the southeast of Piauí, G8 (RM from 8.0 to 8.4) was the best adapted. This group was also the best adapted to agricultural frontier regions, covering the largest areas of the Madeira-Guaporé sub-region and parts of eastern Rondônia, as well as the transitional region between the states of Mato Grosso and Pará (Figure 3).

G9 (RM from 8.5 to 8.9) was shown to be the best adapted to regions positioned around latitude 6° S, including mainly the southeast and southwest of Pará, as well as to the west of Tocantins, east and south of Maranhão, central north and part of southwest of Piauí state, known as the "MAPITO" region (referring to the acronyms of Maranhão, Piauí and Tocantins states). At latitudes around 5° S, extending northward to the northernmost Brazilian regions, including the sub-regions of Marajó Island and northeast of Pará, east, west and areas of center and north of Maranhão, in addition to the whole states of Amapá and Roraima, G10 (RM from 9.0 to 9.4) was the best adapted (Figure 3). Cultivars with RM from 9.5 to 10 were not considered because they do not compose the database used in this research.

The regression-kriging procedure provided predictions with good quality, resulting in a maximum standard error of 0.5 points on the soybean RM scale. However, standard errors were noticeably higher in regions with a lower density of sampled locations, suggesting the need to geographically expand test locations to provide more accurate estimates, especially in Brazilian agricultural frontiers, such as in the states of Pará, Amapá, and Roraima.

Discussion

As is well known, soybean cultivars with higher RM values are more adapted to lower latitudes, across tropical regions, but with different adaptation over latitude ranges, considering RM ≥ 7.0 cultivars.

In general, these cultivars have a longer juvenile period and higher thermal demand; therefore, even under critical photoperiod and higher temperature conditions, their cycle tends to be longer due to delay in flowering and, consequently, a longer reproductive stage (Harada et al., 2015; Wu et al., 2023; Mathur et al., 2024). Whereas cultivars with lower RM are adapted mainly to subtropical regions, generally have shorter juvenile periods and, consequently, flower earlier under short-day conditions. When submitted to low latitudes, cultivars, especially those with RM < 6.0, present reduced height, a low number of productive nodes, and, consequently, low adaptation (Lin et al., 2020; Dong et al., 2021; Staniak et al., 2023). Cultivars with RM from 6.0 to 6.9 are most adapted to the transitional zone between tropical and subtropical regions.These cultivars, primarily those developed when targeting northern environments of subtropical region, are often introduced into tropical environments, mainly through adjustments in plant density and sowing seasons. As a result, according to the RM groups, the soybean cultivars tend to exhibit different levels of adaptation according to RM values, with adaptation restricted to specific latitude ranges and influenced by elevation (Figure 3).

Latitude is crucial to defining the soybean yield adaptation and, consequently, to supporting the recommendation and use of cultivars in Brazilian growing conditions, once it can intensely affect the growth dynamics, especially through correlated variations in photoperiod and temperature (Corbellini et al., 2024). Thus, as the growing location approaches latitude 0° (Equator), cultivars with higher RM and late flowering tend to show better adaptation (Gupta et al., 2021; Tang et al., 2023). Other studies have also observed similar behavior when investigating the adaptation of cultivars with different RM across regions at varying latitudes (Alliprandini et al., 2009; Zdziarski et al., 2018; Zhang et al., 2007; Mourtzinis and Conley, 2017). However, cultivars with different RM do not present regular adaptation within the latitude ranges, as has been suggested in some of these studies, and are mainly the result of interacting effects of elevation and edaphoclimatic variations (Figure 3).

In general, lower elevations present higher temperatures, which favor higher RM cultivars due to their higher thermal demand, whereas lower RM cultivars are favored by higher elevations. Cultivars of the different RM groups present a shorter growth cycle as the temperature rises in the growing environment (Battisti et al., 2018). This condition indirectly favors higher RM cultivars due to their longer reproductive stages, especially in the grain-filling period, and generally results in a higher number of pods, grain weight and yield in comparison to those with lower RM (Kumagai and Sameshima, 2014; Kumagai et al., 2020; Wen et al., 2022). This effect can be easily observed in Brazilian coastal regions (e.g., in the state of Rio Grande do Sul), where the elevation tends to be lower and the most adapted cultivars have higher RM values than those in adjacent higher-elevation areas, even at higher latitudes (Figure 3).

Overall, the results of this study are partially convergent with the recommendations of other authors (Alliprandini et al., 2009; Zdziarski et al., 2018), although with relevant differences in certain regions. Where the latitude is higher than 30° S, Zdziarski et al. (2018) noted that cultivars with RM 5.3 and 5.4 were the best adapted. Although these cultivars were evaluated in this study and performed best in specific locations across this region, they were not the best adapted. In contrast, Bubans et al. (2021) evaluating cultivars with RM from 4.8 to 7.8, in varying plant dates, indicated later cultivars, particularly those with RM 6.3, as being the most productive. In this case, the later sowing dates likely favored later-maturing cultivars.

In the main soybean-producing regions of southern Paraná, northern Rio Grande do Sul and Santa Catarina, within the latitude range of 30 to 25° S, the results differ considerably from the recommendations of Alliprandini et al. (2009), but are partially similar to those reported by Zdziarski et al. (2018), which included RM cultivars below 6.0 for the northern Rio Grande do Sul and Santa Catarina. Likewise, Vilas-Boas et al. (2024) suggested, for this range of latitude, cultivars whose RM are under 6.0, but specifically for western Paraná.

Between latitudes 25 and 20° S, which include part of the tropical-subtropical transitional zone, the recommendations of Zdziarski et al. (2018) are similar to the results of the present study. However, Alliprandini et al. (2009) also recommended RM 7.0 cultivars for the tropical-subtropical transitional zone, in northern Paraná and even RM 8.0 in the states of Mato Grosso do Sul, São Paulo, and Minas Gerais. Matsuo et al. (2022), evaluating cultivars with different RM in the Alto Paranaíba — a subregion of Minas Gerais — identified cultivars with RM ranging from 5.9 to 7.3 as the best adapted. Probably, this wider RM range is due to the restricted number of environments evaluated.

In the 20 to 10° S band, the differences between studies are more significant. Zdziarski et al. (2018) pointed out that cultivars with RM from 7.7 to 7.9 are the most adapted for southwestern Goiás and northern and northeastern Mato Grosso, but cultivars with RM from 8.0 to 8.4 were not evaluated, in this study. Alliprandini et al. (2009) also included RM 8.0 cultivars for the southwestern Goiás and RM 9.0 for northern Mato Grosso. In the 0 to 10°S band, the same authors recommended cultivars with RM of 9.0 and 10 for southern Pará and "MAPITO". Zdziarski et al. (2018) did not make recommendations for these regions.

Considering that cultivars in the studies of Alliprandini et al. (2009) were released approximately 20 years ago, the differences between the results in relation to the current study may be due to the adaptive potential of commercial cultivars and changes that soybean production systems have undergone in the last two decades in Brazil. Changes in the agronomic profile of soybean cultivars, which may explain these differences, have been reported in several studies, mainly associated with yield potential, grain composition, growth type, plant height and lodging level (Specht et al., 2014; Umburanas et al., 2022).

In general, especially in tropical regions, still considering the results of Alliprandini et al. (2009) in comparison to the current study, a trend towards a reduction in optimal RM values for each region has been observed over the years, especially in tropical areas. This trend may have resulted from scaled genetic breeding efforts, aimed at obtaining earlier cultivars adapted to lower latitudes, as well as from environmental improvements such as soil correction in agricultural frontiers, enhanced crop management, optimized sowing time, and adjusted plant density. Differently, the cultivars evaluated by Zdziarski et al. (2018) are contemporary, so the discrepancies between the results may be due to the germplasm evaluated, representativeness of the dataset, or even the analytical approach used.

The widespread adoption of the second cropping ("safrinha" in Portuguese), in large areas of the Cerrado region (Brazilian savannah), over the last few years, has required the use of earlier cultivars in order to better exploit the rainy season (Cattelan and Dall'Agnol, 2018; Parvej and Holshouser, 2025). Additionally, this may reduce the crop exposure to weather deteriorating factors and mitigate risks to the subsequent crop by sowing at a proper time, which also reduces the demand for fungicide and insecticide spraying. The adoption of no-tillage system and high-input management, with a consequent increase in soil fertility level, adjustment in plant density, and planting season also favored the northward adaptation of earlier cultivars, mainly those with indeterminate growth.

All these improvements in the soybean production system, especially in relation to reduction in RM, earlier sowing seasons, and plant density adjustments, have made the soybean production more intensive. This has driven significant changes in the soybean cultivar traits necessary to meet demands of the seed market in recent years. Therefore, new high-yield cultivars with broader geographic adaptation and flexibility to different sowing seasons, which suggests a lower environmental interaction, have become the preference. In this context, especially in earlier-maturing cultivars, high branched, with indeterminate growth type, low-lodging, short internodes, erect growth habit and leaf insertion are currently predominant in the seed market. Cultivars with these traits are part of a genetic base that has recently been exploited in Brazil, whose adoption has led to high yield levels in the Cerrado region (Silva et al., 2025).

Considering the historical timeline of soybean breeding historical in Brazil, the genetic progress in soybean tends to be different among maturity groups, taking into account the priority given to this new cultivar profile over the last few years. In addition, the dynamics of cropping systems has favored cultivars of specific RM, which indirectly promotes differential genetic gains across maturity groups. Differences in genetic gain rates have been reported between maturity groups, involving not only yield, but also adaptive, physiological, and other agronomic traits in Brazil (Todeschini et al., 2019; Umburanas et al., 2022; Campos et al., 2023). All these authors identified considerable genetic progress characterized by a reduction in RM or cycle length over the years, combined with an increase in yield. Similar trends have been observed in the USA (Rincker et al., 2014; Boehm Jr et al., 2019) and Argentina (De Felipe et al., 2016), where contemporary cultivars generally have higher yield potential, shorter plant height, lower lodging level, and, in the main, lower RM. However, unlike in the USA and Argentina, in Brazil there is low genetic divergence between cultivars from maturity groups (Santos et al., 2022), which indicates a more intensive exploiting of germplasm, principally based on wide crossing between parents from distinct maturity groups. Most likely, this approach has been the main strategy adopted in Brazil for soybean tropicalization, in order to adapt subtropical germplasm towards low latitudes.

The introduction and development of indeterminate growth cultivars began in the Brazilian South region, with cultivars from Argentina and North America, in the early 2000s (Umburanas et al., 2022). Since then, indeterminate growth cultivars have adapted to the Brazilian Center West, North and Northeast regions — initially developed mainly by Nidera (currently Syngenta) and later by GDM Seeds (Don Mario Group) — and have been quickly replaced by later determinate cultivars (Abdala et al., 2024). These cultivars have shown a higher amplitude of adaptation and adherence to diverse cropping systems and, currently, correspond to more than 70 % of the cultivars released in the last ten years (MAPA, 2024).

The analytical approach used in this study provided valuable information for supporting professionals involved in seed market and agronomic consulting, especially in the technical development and recommendation of new cultivars. It also supports farmers about choosing the most suitable cultivar for each location, considering that cultivar selection is one of the main factors contributing to yield losses

(Winck et al., 2023). Additionally, the results of this study can help to guide soybean breeding programs, not only in terms of selection strategy aimed at obtaining commercial cultivars adapted to each zone, but also in the positioning of multi-environment trials in order to optimize experimentation. Furthermore, since latitude and elevation are the main geographic variables that predefine the adaptation of soybean, once they are strictly correlated to other relevant environmental variables (i.e., growing degree days, temperature regime and precipitation patterns), these results can support and guide the germplasm exchange and cultivar introduction processes based mainly on RM, especially across countries in South America or Africa (Araújo et al., 2025).

Soybean production in low-latitude regions accounts for approximately half of the total production worldwide (Dong et al., 2021). Therefore, understanding the genetic and genomic basis, as well as the complexity behind environmental factors, which primarily influence soybean adaptation, is essential to continuing to develop new adapted cultivars and improving yield levels, especially in the face of uncertainties about climatic changes. In this study, despite the large dataset used, only phenotypic and geographic data were explored. As an opportunity of improvement and future research, edaphoclimatic variables and genome data could be incorporated into new geoestatistical and genomic prediction models, in order to increase the accuracy of genotype selection and cultivar recommendation for target regions.

In conclusion, we found evidence that although latitude is the main variable affecting soybean adaptation, elevation also makes an important contribution causing slight deflections in adaptation zones. In contrast, longitude does not show any significant effect on soybean adaptation. Therefore, soybean cultivars, classified according to RM, exhibit different levels of geographic adaptation across cropping regions in Brazil, over varying and irregular latitude ranges. In recent years, earlier-maturing cultivars have been developed for lower-latitude regions, which has promoted a general reduction in RM in tropical areas. In subtropical regions, there has been a slight trend towards RM reduction compared to findings from previous studies. Cultivars with RM from 5.5 to 5.9 are best adapted particularly to subtropical regions. In tropical regions, cultivars with RM from 7.0 to 8.4 are predominantly the best adapted. There is a transitional tropical-subtropical zone, which exhibits environmental similarities to both regions, where cultivars with RM from 6.0 to 6.9 are the best adapted. The adaptation of later-maturing cultivars with RM from 8.5 to 9.4 has been retracted to the northernmost regions, where soybean production is still limited representing the next agricultural frontier in the coming years.

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Authors’ Contributions

Conceptualization: Ferreira LU, Duarte JB. **Data curation:** Ferreira LU. **Formal analysis:** Ferreira LU. **Funding acquisition:** Ferreira LU, Muniz FRS, Steckling C. **Investigation:** Ferreira LU, Muniz FRS, Steckling C. **Methodology:** Ferreira LU, Resende RT, Trevisan BA, Duarte JB. **Project administration:** Ferreira LU, Muniz FRS, Steckling C. **Resources:** Ferreira LU, Muniz FRS. **Supervision:** Ferreira LU, Muniz FRS, Steckling C, Duarte JB. **Writing-original draft:** Ferreira LU, Muniz FRS, Steckling C, Resende RT, Trevisan BA, Duarte JB. **Writing-review & editing:** Ferreira LU, Duarte JB.

Conflict of interest

The authors have no conflicts of interest to declare.

Data availability statement

Data will be made available upon reasonable request, excluding any business-sensitive information.

Declaration of use of AI technologies

AI technologies were not used in the present study.

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