Delineating Soybean Maturity Groups across the United States

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**ABSTRACT**

Photoperiod and in-season temperature are the primary factors that dictate the region where a soybean (Glycine max (L.) Merr.) variety is adapted. The first study that defined hypothetical maturity groups (MGs) zones across the US was 45 yr ago, and the most recent used data up to 2003. Although, photoperiod remains constant, climatic conditions, management practices, and soybean genetics have changed during the past decades. Therefore, the objective of this study was to re-delineate soybean MGs across the US using recent genetics. Soybean MG-specific yield data from variety trials conducted in 2005–2015 were aggregated from 312 locations across the United States. Seven MG zones were identified starting from MG = 0 in North Dakota to MG = 6 in southern Georgia and South Carolina. The width of MG = 4 and 5 zones cover the largest geographic region extending from north of latitude 28°N to 39°N. Additionally, in contrast to previous studies, the MG zones were defined by a downward deflection of the MG lines moving from East to West rather than convex parallel lines. Due to the strong effect of planting date on MG selection, a multi-location-year experiment should be conducted across the United States using multiple MGs evaluated in several planting dates. Such study could provide further insight on location-specific optimum MG. Overall results, update current knowledge by providing valuable information for decision making and regional modeling. This work highlights the need to continuously monitor and adjust the MG zones due to the constantly changing climate, management, and genetics.

Core Ideas

- Seven maturity group zones were identified across the United States.
- The width of maturity group zones 4 and 5 cover the largest geographic region.
- Maturity group zones were defined by a downward deflection of the maturity group lines.
- Maturity group adaptation zones need to be continuously monitored and adjusted.

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**Abbreviations:** MG, maturity group.
correlates with increased protein content and overall seed composition. Also, due to the increased demand of vegetable oil, soybean’s oil profile has received much attention (Clemente and Cahoon, 2009). Therefore, breeders have been using seed composition as additional selection criteria for germplasm development, and since 2002 new soybean varieties with improved seed composition have been developed. Furthermore, second generation Roundup Ready soybean along with other herbicide traits as well as new seed treatments have been released. Also, the management practices applied in variety trials (row spacing, seeding rate etc.) varied among states as well as their effect on soybean yields the past 20 yr (Mourtzinis et al., 2015).

Additionally, the climatic conditions have been variable over the past 20 to 80 yr and it has been shown that the observed elevated temperatures have had variable results on soybean yield across the United States (Mourtzinis et al., 2015).

There is information in the literature about region-specific optimum MGs in the U.S. Midsouth (Parker et al., 1981; Armstrong et al., 2009; Barreiro and Godsey, 2013; Ciampitti et al., 2015) but there is a lack of similar peer-reviewed studies covering the entire U.S. soybean growing area. The objective of this study was to delineate soybean MG adaptation zones across the United States using recent soybean genetics, management practices, and climatic conditions from 27 states (312 sites).

**MATERIALS AND METHODS**

Soybean MG-specific yield data from variety performance trials were aggregated for this study. These trials are typically performed yearly in several locations across each state and for this study, data from 27 states (312 sites) across the United States (Fig. 2) and for periods up to 14 yr, depending on data availability, were collected resulting in a database with 1551 location–years (~203,500 MG-specific yields). In every trial, a range of 2 to 4 MGs were tested by planting several varieties to the nearest 10th (e.g., 2.7, 2.8, 2.9 etc.) for MG designation. The location-specific average planting date (as days of the year) across years are shown in Fig. 3. Planting dates were not considered as a factor in the analysis due to: (i) missing information in several trials (Indiana, Michigan, New York, South Carolina, and Virginia), and (ii) severe imbalance in available planting date information (early vs. common). In most trials the planting dates were very similar from year to year (± 3–5 d from average) and only a few trials deviated by more than 2 wk from the average planting date. Therefore, these data are not suitable to test the additional effect of planting date on MG selection.

There were irrigated trials in many states (North Dakota, Wisconsin, Arkansas, Georgia, Louisiana, Kansas, Michigan, Missouri, Mississippi, Nebraska, Oklahoma, Tennessee, South Carolina, and Colorado) which were included in the analysis.
There were no available data in West Virginia and Florida and there was a lack of trial data in parts of southern Missouri, northeastern Minnesota, eastern Ohio, and western Texas, Arkansas, Colorado, Nebraska, and South Dakota. For each location included in the study, yield, MG, and location coordinates were recorded.

The first step of the analysis was to identify the MG with the maximum yield in every location–year–specific trial. Considering MG as continuous variable, its linear and quadratic form were regressed against yield using the REG procedure in SAS 9.4 (SAS Institute, Cary, NC). The MG that maximized yield was identified by calculating the derivative of the location–year–specific model. In the location–years that the quadratic function was not statistically significant, and the MG with the greatest mean yield was considered as "optimum". It should be noted that the MGs with the greatest average yield in every test were very similar to those identified by the regression method with an MG = 0.02 absolute mean error difference (MG average – MG regression) and an MG = 0.4 root mean square error.

Using these results, a new database was constructed including the location–year–specific optimum MG, latitude, longitude, and elevation information. Then spatial analysis was performed to predict the optimum MG in unobserved locations. The analysis was performed using the GLM procedure to extract the residuals from the model that fitted MG as a function of latitude, longitude, their interaction, and their quadratic forms. The model captured 87% of the observed variability and thus used for spatial extrapolations. Then using the VARIOGRAM procedure, the semivariance of the residuals was fitted. The semivariance was plotted against the actual data and the spherical covariance structure was identified as the most appropriate. Then, taking into account the spherical covariance structure, regression analysis of MG as a function of latitude, longitude, elevation, their interactions, and their quadratic forms was performed using the MIXED procedure. The predicted optimum MG values, as a function of coordinates and elevation, were utilized in the KРИG2D procedure to spatially predict the optimum MG for longitudes between –106.00 to –72.00 and latitudes between 27.00 to 50.00 by 0.5 × 0.5 degrees. Finally, the data were extracted and inputted in ArcGIS 10 (ESRI, 2011) to develop a contour map of optimum soybean MG zones across the examined region of the conterminous United States.

**RESULTS AND DISCUSSION**

The map with the soybean MG adaptation zones (Fig. 4) shows that MG 0 varieties are best adapted to the region North of latitude 47°N, which covers most of North Dakota, northwestern South Dakota, and northern Minnesota. The MG 1 varieties are better adapted to central and North South Dakota, central Minnesota, northern Wisconsin and Michigan, and all of New York. The areas from southern Michigan, Wisconsin, Minnesota, and South Dakota extended across northern Iowa and Nebraska are better suited for MG 2. Although soybean is not a major crop in Colorado, MG 2 varieties are better adapted in the northern part of the state whereas MG 3 varieties are better adapted to the rest of the state. The results suggest that MG 3 varieties are adapted to the major soybean-producing states such as the southern half of Nebraska and Iowa.
central Illinois, central and northern Indiana and the entirety of Ohio and Pennsylvania. Additionally, MG 3 soybean is better suited to the northern half of Missouri and Kansas. The MG 4 varieties are adapted to a wide range of latitudes including the southern half of Kansas, Missouri, Illinois, and Indiana as well as the entirety of Oklahoma and Kentucky. The MG 5 varieties seem to be better suited to most of the southern states apart from the southern part of Georgia and South Carolina where MG 6 varieties were better suited.

These results are somewhat similar to Zhang et al. (2007) who reported that MG 0 or earlier are better suited North of latitude 46°N including northern Wisconsin and Michigan using a different dataset (139 sites). Results from our study suggest that MG 0 should be restricted to North Dakota and northern Minnesota. Also, Zhang et al. (2007) used convex parallel lines to delineate optimum MG regions and they continued the lines to the western regions of the High Plains states (North and South Dakota) where there was a lack of trial data. Our updated map uses vastly more data, different methodology in data analysis, and extends the trial locations beyond those Zhang et al. (2007) used. Additionally, these data do not agree with Scott and Aldrich (1970) who suggested that MG 00 is better adapted to all of North Dakota. Nevertheless, this is an older study in which the hypothetical zones were based on photoperiod. Although photoperiod did not change, it has been shown that in-season temperatures increased in North Dakota since 1994 (Mourtzinis et al., 2015) which could have allowed for earlier planting of MG 0 varieties. Since photoperiod of a given location during specific months is constant through time, the difference among the zones reported in 1970 (Scott and Aldrich, 1970), 2003 (Zhang et al., 2007), and our study suggest that the effect of temperature, driven by climate change, is also an important factor that affects the adaptation potential of different soybean MGs.

The later MGs adaptation zones are also different from what was reported from Scott and Aldrich, (1970) who suggested that MG 7 to 8 are better adapted in southern states. During the past 30 yr, farmers in the South have started to plant earlier in the season, mainly to avoid extreme summer heat and drought stress during reproductive stages (Edwards et al., 2003; Heatherly and Elmore, 2004; Heitholt et al., 2005). Therefore, MG = 5 to 6 were identified as the most adapted across the southern states, and these results are in further agreement with Zhang et al. (2007).

The MG optimum zones, defined by the downward deflection of the MG lines moving from East to West, are consistent with several state-specific MG optimum zones. Our results are in agreement with the MGs that exhibited the greatest

Fig. 3. Location-specific average planting dates across the examined region of the continental United States. Note: DOY denotes day of the year.
simulated relative yield potential in Iowa and Missouri (Archontoulis et al., 2014). In the southern United States, our results agree with the recommended MGs in Kansas (3.8–4.8) for similar planting dates (mid-May to mid-June) (Ciampitti et al., 2015). However, our results do not agree with what is recommended in Oklahoma (Armstrong et al., 2009), where the reported optimum MGs are those reported in the map developed by Scott and Aldrich (1970). Nevertheless, another study in Oklahoma suggested that MG = 4 and 5 planted before 29 May provide the greatest probability to achieve maximum soybean yield (Barreiro and Godsey, 2013). These recommendations are consistent with our results that MG = 4.5 to 5.5 have been identified as the most suitable for that state. Furthermore, our results are in partial agreement with a study in Georgia that found optimum MG = 5 to 8 for planting dates from May to early June (Parker et al., 1981). For similar planting dates, our data suggest that suitable MGs are 5.5 to 6.5. Nevertheless, the Georgia study was conducted more than 35 yr ago, and since then, management, genetics, and climate has been changed. This is an additional indication that location–specific optimum MGs should be continuously monitored and adjusted. For irrigated soybean planted in April in Mississippi, an MG = 4 has been recommended whereas, in non-irrigated sites planted in early May, MGs 4 to 7 resulted in similar yields (Heatherly, 2005). Our data suggest that MG = 5.2 to 5.7 are most suitable for planting dates between late April to mid-May. It should be noted that for Mississippi, we used irrigated and non-irrigated data but the majority were from non-irrigated trials.

For several northern states, there is a lack of peer-reviewed recommendations about region-specific optimum MGs. However, examining the available information, our results are similar to the optimum MGs recommended in North Dakota, where MG = 00 and MG = 1 are suitable in the northern and southeastern part of the state, respectively (Kandel, 2010). The same level of agreement between our study and what is currently recommended was also observed in Minnesota (Kandel, 2010). A simulation study found that MG = 0 had the greatest relative yield potential in Minnesota at 46° latitude (Archontoulis et al., 2014). This result is slightly different from our results that MG = 1 was found to be the most suitable. Nevertheless, in that study the simulated relative yield differences among MG = 00, 0, and 1 were minimal. A fairly wide range of optimum MGs (MG = 0–3) is recommended in South Dakota (Hall et al., 2012) which is similar to the optimum MGs in our study for the same state. According to Michigan State University Extension, the range of suitable MGs in the central part of the state is 1.8 to 2.6 and between 2.4 to 3.2 for the southern region (Stanton, 2014). These recommended MGs

Fig. 4. Soybean maturity group zones across the examined region of the continental United States.
are in close agreement with our results. Similar results to ours have also been reported in Illinois, where MG = 3.7 exhibited the highest 15-yr average yield in the central part of the state, although no specific MG recommendation was implicitly stated (Nafziger, 2015).

It is obvious that in regions where there was a lack of available data, the standard errors were large (e.g., West Virginia, Florida, western Texas) and around clusters of proximate locations were small. However, areas where multiple soybean variety trials data were available, and the standard errors were small (Fig. 4), lie within the regions with the largest soybean cultivated area across the United States (Fig. 1). This implies that the data presented can be considered a realistic representation of the optimum MG distribution across the largest and most important soybean agricultural U.S. regions. It should be noted that the contour lines extended to western Texas and northeastern United States should be interpreted with caution since they were extrapolated from the examined region. Additionally, it is highlighted that these results are bound to the management practices (e.g., planting dates, etc.) that were applied in the variety trials, as well as to the location-specific weather conditions during the examined period. Therefore, it is critical to emphasize that the defined optimum MG zones should not be considered as the only regions that a specific MG can be grown. In favorable weather conditions and in regions where planting dates can be flexible, such as in the southern states, earlier or later maturing varieties than the optimum can also be successfully grown. This has been observed in a study conducted at several locations in the southern United States where early and late planting dates for the specific locations were tested (Salmeron et al., 2014). In that study, planting occurred earlier in spring and later in the summer by up to 40 d compared to the variety trial data we used. However, our results are within the optimum MG ranges (MGs that exhibited the highest yields) that were identified across Missouri, Arkansas, Tennessee, Mississippi, Louisiana, and Texas (Salmeron et al., 2014). It should be noted that across these states, our data included more than 450 environments (location × year) with multiple MGs, and many varieties tested within each environment. To our knowledge, this is the most comprehensive dataset ever analyzed for soybean. Our methodology provides a new approach to synthesize diverse and (largely) disconnect data from different states. This analysis and framework can be updated every year, as new data come in, to provide summary analyses for decision making and inputs for crop modelers. Nevertheless, it should be noted that early planting dates are not always possible due to weather conditions. For example, excessive rainfall can delay field preparation and planting. Therefore, even in locations where weather conditions can permit earlier planting, the optimum MG information for variable planting window can be of great importance for farmers and agronomists.

CONCLUSIONS

The constantly changing weather patterns have led scientists and farmers to change management practices and adapt to the new conditions. Therefore, the adaptivity of new soybean varieties, as a result of genetic improvement and the interactive effects with photoperiod and temperature, needs to be routinely evaluated. The soybean MG adaptation zones in this study, when compared to previous works 12 and 45 yr ago, further highlight the need to be continuously monitored and adjusted as a result of the constantly changing climate, management, and genetics.

A limitation of this study is that it does not allow to test planting date effects on the location-specific MG selection. Due to the strong effect of planting date on MG selection, a multi-location experiment should be conducted across the United States using multiple MGs grown in several planting dates. Currently, such data set is nonexistent and could provide further insight on location-specific optimum MGs across all locations of interest in the United States. Additionally, such data can be useful for crop simulation models that can dynamically simulate region-specific optimum MGs based on current and future weather projections, and under various management practices. Vast amounts of information, analyzed by multiple methods (statistical and processed based modeling), can provide further insight in region-specific MG selection.

Additionally, growers in many states follow a variety of recommendations derived from variety trials results, which are bound to the management practices used (e.g., planting date) in those trials. However, there is a recent trend of earlier recommended planting dates than the dates used in the variety trials in many regions. Therefore, we suggest that variety trials should include more planting dates (e.g., early, normal and late) or at least should be initiated earlier in the spring, to follow current planting date recommendations in every region and reflect grower management practices. Such practice would provide more insight to agronomists which in turn would provide growers with more accurate information on region-specific MG selection.

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REFERENCES


