Published online August 10, 2017

Planting Date, Maturity, and Temperature Effects on Soybean Seed Yield and Composition

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] production has greatly increased in the upper U.S. Midwest over the last decade, but little information exists regarding the interactive effects of environment and spring management decisions on soybean seed yield and composition. Our objective was to assess the effect of four planting dates (PDs), four cultivar maturity groups (MGs), and ambient temperature between R5 to R8 (T5–T8) on soybean seed yield and composition. Field studies were established between 2014 and 2016 at three locations in Wisconsin and one in Minnesota. Across environmental conditions and management decisions, greater seed yield was positively correlated with protein and oil contents but negatively correlated with linoleic, linolenic, and sucrose contents. Multivariate data analysis showed positive synergies between early planting (late April–early May) and MG 2 for yield, oil, and oleic acid across the examined region. A MG 2 was the highest yielding and a ~1200 kg ha^{-1} yield difference was observed between early and late PDs. These results underline the complexity of the soybean yield-composition relationships. Additionally, the large variability in the responses of constituents to management decisions and temperature variations highlights the importance of a producer knowing the product's end use (e.g., high yield vs. high protein) and accordingly modifying the growing environment by selecting an appropriate PD and MG for the respective region. To provide more accurate recommendations to a broader range of producers, multi-environment studies are imperative to capture large environmental variability in important soybean production areas across the United States.

Core Ideas

- Planting date and maturity group decisions can greatly affect yield and composition.
- Temperature had a significant effect on seed yield and composition.
- Planting date × maturity group should be chosen based on the product's end use.

Soybean maturity selection is an important management decision. Maturity group zones represent regions where a cultivar is best adapted without implying that MG-specific cultivars cannot be grown elsewhere (Boerma and Specht, 2004). Hypothetical MG zones were first developed by Scott and Aldrich (1970), followed by the work of Zhang et al. (2007) who redefined the optimum MG zones using yield variety trial data from 1998 to 2003. Most recently, Mourtzinis and Conley (2017) re-delineated MG zones across the United States using 2005 to 2015 yield variety trial data. In their study, although the zones were generated using a vast amount of information, the results are restricted to the PD range of the variety trials.

Since the 1970s, the length of the growing season has increased, most notably in the northern Corn Belt (Kucharik et al., 2010) where producers are planting 1 to 3 wk earlier (Conley and Santini, 2007). Soybean yield increases have been documented with earlier planting, where early May PDs consistently result in the greatest yield (De Bruin and Pedersen, 2008; Gaspar and Conley, 2015; Marburger et al., 2016). In Wisconsin, Gaspar and Conley (2015) saw a 21.2 kg ha^{-1} d^{-1} yield decline when planting was delayed past the first week in May. Since MG selection does not increase input costs, with earlier PDs, many producers question the optimum MG for planting soybean in their region (Gaspar and Conley, 2015; Salmerón et al., 2015).

While early planting is a prudent management practice to increase soybean yield, logistical, equipment, environment, and labor challenges can delay planting. However, when early planting is possible, soybean is exposed to a greater risk of a spring killing frost, early season insects and seedling diseases, and damaging rainfall events that may result in suboptimal stand. In such years, replanting may be necessary. Furthermore, the climate variability that is affecting state and regional soybean yields (Mourtzinis et al., 2015) may also cause more frequent replanting situations. Proper replanting methods and optimal final plant stands (>247,000 plants ha^{-1}) have been determined by Gaspar and Conley (2015), and yet, the proper MG to use in replant or late planting scenarios are unclear. Recent research conducted in the Midsouth, where a wide range of PDs and MGs are possible, has heavily investigated the MG × PD interaction to maximize yield (Salmerón et al., 2014, 2016). However, the challenges in the northern Corn Belt include later spring PDs and killing fall

Published in Agron. J. 109:1–10 (2017)
doi:10.2134/agronj2017.05.0247
Available freely online through the author-supported open access option

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Abbreviations: MG, maturity group; PD, planting date.

frosts, which limit the growing season. Therefore, growers would benefit economically from data outlining the proper MG range to use depending on the PD, to maximize yield and avoid fall frost damage in their respective latitudinal zone.

Soybean seed contains protein and oil and depending on the end use, other important constituents such as specific amino acids (nutritionally essential and non-essential), non-protein-based amino acids, sugars, and fatty acids whose relative concentration contributes to oil stability. For example, soybean oil with higher oleic and lower linoleic and linolenic content exhibits increased oil stability (Wilson, 2004). Sugars, such as sucrose, raffinose, and stachyose, are also important since their relative concentrations contribute to flavor, taste, energy, and digestibility of feed (Liu, 1997). The value of the crop has long been based on the seeds' relatively high protein and oil content. Currently cultivated varieties planted in Wisconsin contain approximately 30 to 40% protein and 15 to 20% oil (Roth et al., 2014). The protein and oil content of soybean has largely been controlled through breeding, and by the environmental conditions and geographical location of production. Helms and Orf (1998) showed that traditional breeding efforts could increase protein by 5 to 7%, but this simultaneously decreased yield by 70 to 110 kg ha^{-1} resulting in an overall decrease in protein ha^{-1}. The effect of the production location has possibly the greatest influence on seed yield, where soybean grown in the northern Corn Belt is consistently lower in protein compared to those grown in southern states (Rotundo et al., 2016). Hurburgh et al. (1990) found that soybean from northern states contained 1.5 to 2% less protein and 0.2 to 0.5% more oil than soybean produced in the South and southeastern United States. Significant spatial and temporal variability exists for protein (Hurburgh et al., 1990) and oil (Brumm and Hurburgh, 2006). Rotundo et al. (2016) determined that the spatial variation occurs at scales lower than politically defined regional and state lines. Many underlying weather and environmental factors have been suggested to explain this variation, including differences in temperature throughout the growing season (Gibson and Mullen, 1996; Howell and Cartter, 1958; Thomas et al., 2003; Wilson, 2004; Wolf et al., 1982; Yaklich and Vinyard, 2004). The effect of temperature, specifically during seed fill, has been heavily credited with altering seed composition and was found to be consistent across six varieties in a Kentucky study (Kane et al., 1997). Wolf et al. (1982) reported increased protein and oil

Table 1. Location description of the trials throughout Wisconsin and Minnesota during 2014, 2015, and 2016.

Year	Location	Latitude and longitude	Soil type†‡	Clay§	OM¶	pH¶	P¶	K¶	Precip.#	GDD††	Frost‡‡
				—— g kg^{-1} ——			—— Bray^{-1} ——		mm		
2014	Arlington, WI	43°18′8″ N, 89°20′8″ W	Plano SL	225	40	7	75	238	498 (–13)	1320	5 Oct.
	Hancock, WI	44°7′10″ N, 89°32′7″ W	Plainfield S	40	9	6.2	93	95	450 (–64)	1240	5 Oct.
	St. Paul, MN	44°59′46″ N, 93°10′25″ W	Waukegan SL	230	38	6.1	138	275	560 (75)	1341	30 Oct.
	Spooner, WI	45°49′29″ N, 91°52′9″ W	Mahtomedi LS	90	16	6.3	76	186	683 (183)	1208	4 Oct.
2015	Arlington, WI	43°18′8″ N, 89°20′8″ W	Plano SL	225	36	7	60	273	526 (18)	1396	16 Oct.
	Hancock, WI	44°7′10″ N, 89°32′7″ W	Plainfield S	40	17	6	126	51	467 (–46)	1311	14 Oct.
	St. Paul, MN	44°59′46″ N, 93°10′25″ W	Waukegan SL	230	40	6.8	113	301	582 (92)	1448	17 Oct.
	Spooner, WI	45°49′29″ N, 91°52′9″ W	Mahtomedi LS	90	14	7	68	144	551 (53)	1289	16 Oct.
2016	Arlington, WI	43°18′8″ N, 89°20′8″ W	Plano SL	225	34	7	53	191	543 (23)	1509	24 Oct.
	Hancock, WI	44°7′10′″ N, 89°32′7′″ W	Plainfield S	40	7	5.9	54	40	700 (200)	1389	13 Oct.
	St. Paul, MN	44°59′46″ N, 93°10′25″ W	Waukegan SL	230	38	6.1	110	259	642 (144)	1655	21 Oct.
	Spooner, WI	45°49′29″ N, 91°52′9″ W	Mahtomedi LS	90	12	6	68	84	465 (–62)	1346	12 Oct.

† Soil type from web soil survey (https://www.nrcs.usda.gov). Plano: fine-silty, mixed, superactive, mesic Typic Argiudolls; Plainfield: mixed, mesic Typic Udipsamments; Waukegan: mixed, superactive, mesic Typic Hapludolls; Mahtomedi: mixed, frigid, Typic Udipsamments.

‡ LS, loamy sand; S, sand; SL, silt loam.

§Average clay basis for this soil type.

¶ OM, organic matter. pH, P, and K values are a composite of individual sites each year.

Precip., Cumulative precipitation across the growing season from May through September. Deviation from the 30-yr average is reported in parentheses. The Hancock and Spooner locations received supplemental irrigation as needed. Data collected from the Wisconsin State Climatology office (Madison, WI) and Minnesota State Climatology Office (St. Paul, MN).

†† Total accumulated growing degree days (GDD) base 10°C from 1 May through 1 October at each location each year.

‡‡ The date of the first fall frost at each location each year. Four-hour period under 0°C.

content, increased oleic acid, and decreased linolenic and linoleic acids as the temperature during seed fill was increased. More recently, Naeve and Huerd (2008) collected field grain samples from different growing regions within Minnesota and found that oil concentrations increased by 6.6 g kg^{-1} $^{o}C^{-1}$ during seed fill, but protein was not affected. The temperature during seed fill explained more variation in oil content than a specific year did.

In the northern United States, selection of both MG and PD affect the environment in which soybean progresses from R5 through R7 (seed fill). For producers in the northern Corn Belt to better compete in the world soybean market and qualify for quality premiums from soybean purchasers, a better understanding of how temperature during seed fill affects soybean seed yield and composition components, specifically the amino acids profile, has become more important over the past decade. Therefore, the objectives of this study were to (i) determine the MG × PD range that maximizes seed yield, and (ii) quantify the effects of temperature during R5 to R8 (T5–T8) on soybean seed composition characteristics in the northern Corn Belt.

MATERIALS AND METHODS

Field Experiment

Field trials were conducted at four agricultural research stations located at different latitudes from southern Wisconsin, central Wisconsin, and Minnesota through northern Wisconsin during 2014, 2015, and 2016 (Table 1) resulting in 12 environments (year × location). The trials were a randomized complete block design in a split-plot arrangement with four replications. The whole plot factor was five PDs targeted at 1 and 20 May, and 1, 10, and 20 June. Actual PDs in each location and year are listed in Table 2. The subplot was comprised of two varieties (within MG) within each PD. The two varieties were targeted at MGs 2.0, 1.5, 1.0, and 0.5, and were all Pioneer brand (DuPont Pioneer, Wilmington, DE) glyphosate [*N*-(phosphomethyl) glycine]-resistant soybean cultivars seeded at 345,800 seeds ha^{-1} (Table 3). Plots at Arlington and Hancock were seeded in four 76-cm rows at a length of 6.4 m, while St. Paul plots were 7.6 m long. Spooner plots were seeded in six 38-cm rows at a length of 7 m. The middle two or four (Spooner) rows of each plot were harvested at maturity with an Almaco (SPC-40, ALMACO, Nevada, IA) plot combine to determine yield. Yield was computed by adjusting moisture to 130 g kg^{-1}.

Seed Composition Analysis

A grain subsample was collected for each plot during harvest and analyzed for constituent determination using near-infrared (NIR) spectroscopy. Specifically, samples were analyzed for protein, oil, 18 amino acids (cysteine, lysine, methionine, threonine, tryptophan, alanine, arginine, aspartic acid, glutamic acid, glycine, histidine, proline, serine, isoleucine, leucine, phenylalanine, valine, and tyrosine), oleic, linoleic, linolenic, palmitic and stearic fatty acids, raffinose, stachyose, and sucrose contents. A Perten DA7200 Feed Analyzer was used for the NIR analysis and was fitted with equations developed by the University of Minnesota using ISIscan software (Infrasoft Intl. LLC., State College, PA) and validated by Caltest, LLC (Clifton Park, NY). Soil samples were taken at each location and analyzed for percent clay, organic matter, pH, and macronutrients at the University of Wisconsin Soil and Plant Analysis Laboratory (Marshfield, WI) (Table 1). Fertility and in-season pest control followed University

Table 2. Actual date of planting for each environment (year × location) in 2014, 2015, and 2016.

	Arlington, WI			Hancock, WI			St. Paul, MN			Spooner, WI		
Planting date	2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
1	6 May	30 Apr.	3 May	5 May	1 May	2 May	7 May	30 Apr.	4 May	10 May	6 May	6 May
2	21 May	18 May	20 May	27 May	20 May	20 May	23 May	20 May	19 May	21 May	20 May	20 May
3	30 May	1 June	31 May	5 June	1 June	2 June	4 June	12 June	1 June	30 May	1 June	31 May
4	11 June	10 June	9 June	18 June	10 June	10 June	25 June	29 June	20 June	10 June	10 June	10 June

Table 3. Varieties planted on each planting date at the study locations.

		Location							
		ARL, HAN, STP†				SPO‡			
		Planting date							
Variety	Maturity group	1	2	3	4	1	2	3	4
P22T69R	2.2	+	+	+	+				
P19T01R	1.9	+	+	+	+				
P16T04R	1.6	+	+	+	+	+	+		
P15T83R	1.5	+	+	+	+	+	+		
P10T91R	1			+	+	+	+	+	+
P10T02R	1			+	+	+	+	+	+
P06T28R	0.6			+	+	+	+	+	+
P05T24R	0.5			+	+	+	+	+	+

† ARL, Arlington, WI; HAN, Hancock, WI; STP, St. Paul, MN.
‡ SPO, Spooner, WI.

of Wisconsin-Madison recommendations for best management practices (Davis et al., 2015). The average environment-specific air temperatures between R5 to R8 were also recorded from weather stations near each experimental site.

Statistical Analysis

Yield and compositional data were analyzed separately using PROC MIXED in SAS Version 9.4 (SAS Institute Inc., Cary, NC). Response surface methodology was used to examine the effect of PD as a day of the year, MG, and their interaction on seed yield. Both variables were treated as continuous, and their linear and quadratic forms were included in the model as fixed effects. Random effects included replication, replication × environment, replication × environment × PD, and the overall error term. The same approach was followed to examine the effect of T5 to T8 (average ambient temperatures between developmental stages R5 and R8), MG, and their interaction on yield. Planting date and air temperature variables were not used in the same model to avoid multicollinearity issues due to their correlation ($r = -0.39$, $P < 0.0001$).

Analysis of constituent variables was challenging due to their correlation with each other (Table 4). The appropriate analysis should account for their covariances, and therefore a multivariate approach, where the response variables are contained in a single variable as described by Bowley (2008), was followed. Initially, to avoid algorithm convergence issues due to the large concentration differences among variables (e.g., protein vs. single amino acid), all variables were standardized by subtracting the overall mean and dividing by the standard deviation. Then, to overcome computational issues due to the high dimensionality of the data, different models (a model for a set of response variables) were fitted. The first set of dependent variables accounted for protein and oil content. The second set accounted for the sum of protein and oil, and the sum of non-protein amino acids (taurine, hydroxyproline, lanthionine, hydroxylysine, and ornithine). The third set accounted for the sum of five essential amino acids (cysteine, lysine, methionine, threonine, and tryptophan), the sum of non-essential amino acids (alanine, arginine, aspartic, glutamic, glycine, tyrosine, proline, and serine), raffinose, and sucrose contents. The fourth set accounted for the sum of the five essential amino acids as a percentage of the 18 total, the sum of non-essential amino acids as a percentage of the 18 total, and sucrose content. Finally, the fifth set accounted for the fatty acids contents (palmitic, stearic, oleic, linoleic, and linolenic).

To examine the effect of PD, MG, and their interactions, and the effect of T5 to T8 and interactions with MG on all compositional variables described above, the same response surface methodology as yield was followed in PROC MIXED with the addition of a repeated statement. The subject in repeated statement was an identification variable that was created to give each experimental unit a unique number in order measures from the same experimental unit to be identified. The unstructured covariance structure (UN) was used due to its superiority (lower Akaike information criterion [AIC]) compared to other structures (e.g., compound symmetry, first-order autoregressive). For all analysis, degrees of freedom were calculated using the Kenward Rodger's approximation (Littell et al., 2006) and the level of significance was set to 5% ($\alpha = 0.05$). To test the sensitivity of the results to the set of modeled variables, different combinations of variables were used and fitted using the same models. In all cases, there were no differences in the results.

RESULTS AND DISCUSSION

The 12 environments included in this study provided a wide range of climate variation (Table 1). At the three sites in Wisconsin, cumulative precipitation varied compared to the 30-yr average in all the 3 yr, whereas in Minnesota, cumulative precipitation was 13 to 23% above the 30-yr average. Similar variation in temperatures was observed among sites and years. Temperatures in 2014 and 2015 were similar resulting in small differences in May to September growing degree days (GDDs) (Table 1). However, the 2016 growing season was warmer resulting in 11 to 23% greater GDD accumulation. This weather variability among the 12 growing seasons allowed us to examine the region-wide effects of management practices (PD and MG), temperature, and their interactions on soybean seed yield and composition.

Across the 12 environments in the study, soybean seed yield was positively correlated with both protein and oil contents (Table 4). The stronger correlation with oil ($r = 0.40$) compared to protein ($r = 0.20$) suggest that oil content may be a more important factor affecting seed yield. Yield was positively correlated with all examined constituents apart from linoleic and linolenic fatty acids and sucrose. Protein and oil exhibited a negative correlation ($r = -0.25$) as has been reported by Carrera et al. (2011). The sum of essential and non-essential amino acids was each positively correlated with protein content, $r = 0.77$ and $r = 0.93$, respectively. The sum of essential amino acids as a percentage of the 18 amino

Table 4. Pearson correlations of all response variables across years and locations.

Variables	Yield	Protein	Oil	P+O†	Es. AAs‡	Non-es. AAs§	Non-P AAs¶	Es. AAs (% of 18)#	Non-es. AAs (% of 18)††	Palmitic	Stearic	Oleic	Linoleic	Linolenic	Raffinose	Stachyose	Sucrose
Yield	1	0.20***	0.40***	0.49***	0.11***	0.08*	0.26***	–0.01	–0.02	0.33***	0.21***	0.56***	–0.48***	–0.50***	0.18***	0.19***	–0.20***
Protein	0.20***	1	–0.25***	0.64***	0.77***	0.93***	0.07*	–0.70***	0.83***	0.16***	0.04	0.16***	–0.22***	–0.16***	–0.22***	–0.20***	–0.28***
Oil	0.40***	–0.25***	1	0.58***	–0.47***	–0.46***	0.49***	0.17***	–0.43***	0.51***	0.28***	0.65***	–0.49***	–0.65***	0.51***	0.43***	–0.14***
P+O	0.49***	0.64***	0.58***	1	0.27***	0.41***	0.45***	–0.45***	0.35***	0.54***	0.26***	0.64***	–0.57***	–0.65***	0.22***	0.18***	–0.34***
Es. AAs	0.11***	0.77***	–0.47***	0.27***	1	0.89***	–0.10**	–0.23***	0.64***	–0.17***	–0.24***	–0.17***	0.06*	0.15***	–0.44***	–0.33***	–0.28***
Non-es. AAs	0.08*	0.93***	–0.46***	0.41***	0.89***	1	–0.02	–0.64***	0.88***	–0.02	–0.18***	–0.05	–0.08*	0.08*	–0.37***	–0.32***	–0.22***
Non-P AAs	0.26***	0.07*	0.49***	0.45***	–0.10**	–0.02	1	–0.15***	–0.03	0.53***	–0.38***	0.64***	–0.68***	–0.26***	0.29***	0.19***	–0.26***
Es. AAs (% of 18)	–0.01	–0.70***	0.17***	–0.45***	–0.23***	–0.64***	–0.15***	1	–0.75***	–0.24***	–0.02	–0.20***	0.28***	0.10**	–0.01	0.06	0.04
Non-es. AAs (% of 18)	–0.02	0.83***	–0.43***	0.35***	0.64***	0.88***	–0.03	–0.75***	1	0.08*	–0.13***	–0.05	–0.11**	0.06	–0.40***	–0.43***	-0.08*
Palmitic	0.33***	0.16***	0.51***	0.54***	–0.17***	–0.02	0.53***	–0.24***	0.08*	1	0.28***	0.60***	–0.64***	–0.25***	0.35***	0.28***	0.20***
Stearic	0.21***	0.04	0.28***	0.26***	–0.24***	–0.18***	–0.38***	–0.02	–0.13***	0.28***	1	0.26***	–0.09**	–0.42***	0.37***	0.39***	0.34***
Oleic	0.56***	0.16***	0.65***	0.64***	–0.17***	–0.05	0.64***	–0.20***	–0.05	0.60***	0.26***	1	–0.94***	–0.70***	0.56***	0.41***	–0.11***
Linoleic	–0.48***	–0.22***	–0.49***	–0.57***	0.06	–0.08*	–0.68***	0.28***	–0.11**	–0.64***	–0.09**	–0.94***	1	0.51***	–0.44***	–0.27***	0.04
Linolenic	–0.50***	–0.16***	–0.65***	–0.65***	0.15***	0.08**	–0.26***	0.10**	0.06	–0.25***	–0.42***	–0.70***	0.51***	1	–0.29***	–0.21***	0.38***
Raffinose	0.18***	–0.22***	0.51***	0.22***	–0.44***	–0.37***	0.29***	–0.01	–0.40***	0.35***	0.37***	0.56***	–0.44***	–0.29***	1	0.86***	0.18***
Stachyose	0.19***	–0.20***	0.43***	0.18***	–0.33***	–0.32***	0.19***	0.06	–0.43***	0.28***	0.39***	0.41***	–0.27***	–0.21***	0.86***	1	0.10**
Sucrose	–0.20***	–0.28***	–0.14***	–0.34***	–0.28***	–0.22***	–0.26***	0.04	–0.08*	0.20***	0.34***	–0.11***	0.04	0.38***	0.18***	0.10**	1

* Significant correlations at $\alpha = 0.05$.

** Significant correlations at $\alpha = 0.01$.

*** Significant correlations at $\alpha = 0.001$.

† P+O, sum of protein and oil.

‡ Essential amino acids.

§ Non-essential amino acids.

¶ Non-protein amino acids.

Essential amino acids as percentage of the sum of the 18 amino acids (essential + non-essential).

†† Non-essential amino acids as percentage of the sum of the 18 amino acids (essential + non-essential).

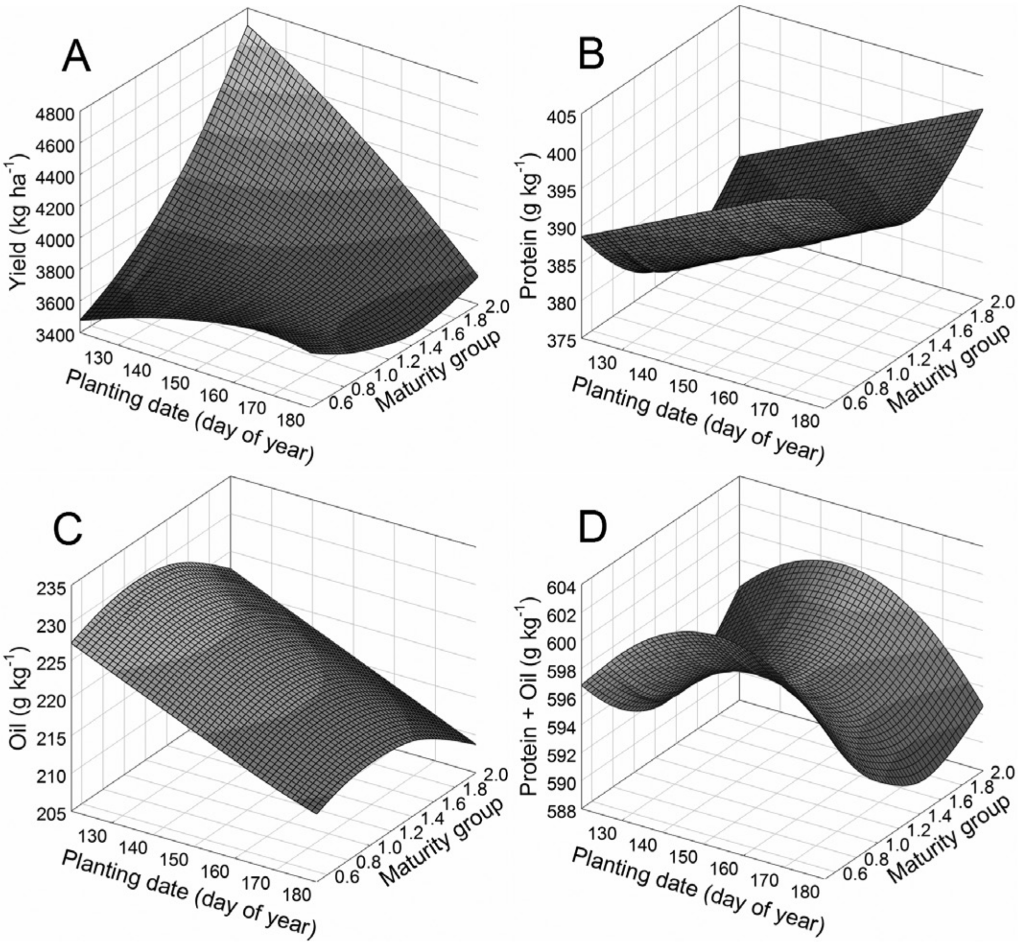

Fig. 1. Maturity group × planting date (as day of year) response surface of (A) yield (kg ha^{-1}), (B) protein (g kg^{-1}), (C) oil (g kg^{-1}), and (D) protein+oil (g kg^{-1}).

acids was negatively correlated ($r = -0.70$) with protein, whereas for non-essentials, the correlation was positive ($r = 0.83$). Given the importance of the relative concentrations of amino acids on soybean quality, these results imply that protein content alone may not be the most appropriate quality indicator. Other interesting responses involve the correlations among fatty acids. Positive correlations were detected among palmitic, stearic, and oleic contents and also between linoleic and linolenic contents. However, palmitic, stearic, and oleic contents were negatively correlated with linoleic and linolenic. Additionally, positive correlations among raffinose, stachyose, and sucrose were observed. Overall, across environmental conditions and management decisions, higher seed yield was correlated with high protein and oil contents but with lower linoleic, linolenic, and sucrose contents. These results underline the complexity of the soybean yield-composition relationships and further justify an in-depth examination of environmental and management factors that can affect them.

Planting Date × Maturity Group Effects

Across the examined region, large yield variability was observed due to PD and MG combinations (Fig. 1A). The figure shows the yield response for several PD × MG combinations and shows that the greatest seed yield resulted from early planting (late April–early May) and MG 2. This result agrees with the highest-yielding MG identified by Mourtzinis and Conley (2017) for the same region. In that study, MG 1.4 to 2.2 resulted in the highest yields in Spooner and Arlington, WI, the northernmost and southernmost sites of the study, respectively. For MG 2, a large yield difference (~1200 kg ha^{-1}) was observed between early and late PDs. Similar yield losses due to delayed planting have been reported by other studies in the region (Conley et al., 2012; Gaspar and Conley, 2015). For shorter season MGs, such as a 0.5, PD had little effect on yield, but the maximum was only 75% of the late MG's planted early. There are situations in which early planting is not possible due to weather constraints, but there must be large economic benefits associated with agronomic practices that may delay soybean planting, such as fall planted cover crops, since early planting with a longer MG has no additional inputs costs associated with the increased yield potential. Maturity group selection and PD are simple and yet important management decisions that should not be separate across the examined region.

Planting date and MG selection were important factors for soybean seed protein and oil content and their sum (Fig. 1B–1D). Late planting of all MGs resulted in the greatest protein concentrations. The opposite response was observed for oil content in that early planting resulted in the greatest oil amount. Both protein and oil were affected mainly by PD and, to a lesser degree, by MG. The observed trend of higher protein and lower oil due to late planting is consistent with a previous study (Helms et al., 1990). Because of the inverse relationship of protein and oil, the response curve for the sum was curvilinear across PD and showed a maximum at mid-May PD's. These results suggest that a single combination of

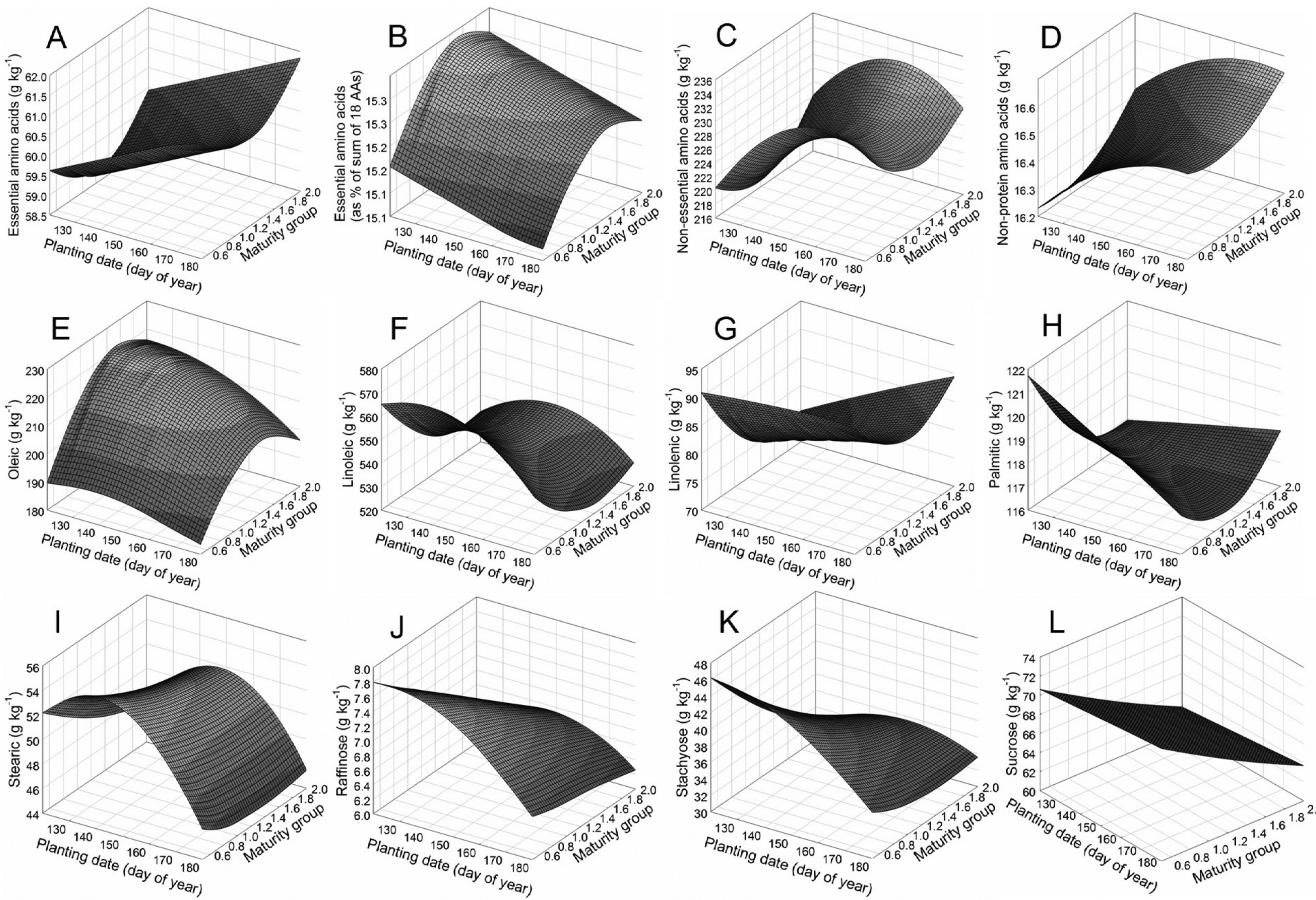

Fig. 2. Maturity group × planting date (as day of year) response surface of (A) sum of essential amino acids (g kg^{-1}), (B) sum of essential amino acids (as % of the sum of 18 amino acids), (C) sum of non-essential amino acids (g kg^{-1}), (D) sum of non-protein amino acids (g kg^{-1}), (E) oleic acid (g kg^{-1}), (F) linoleic acid (g kg^{-1}), (G) linolenic acid (g kg^{-1}), (H) palmitic acid (g kg^{-1}), (I) stearic acid (g kg^{-1}), (J) raffinose (g kg^{-1}), (K) stachyose (g kg^{-1}), and (L) sucrose (g kg^{-1}).

management practices with the goal of maximizing soybean yield, protein, and oil content may be difficult to attain. Planting a MG 2 in early May was found to maximize seed yield and oil content, but it resulted in the lowest observed protein content.

Soybean seed constituents respond to PDs and MGs in complex ways (Fig. 2). For example, essential amino acids follow the same response as protein to the PD × MG combinations we tested (Fig. 2A). However, their sum, as a percentage of total 18 amino acids, follows the opposite trend (Fig. 2B). Additionally, the concentrations of the five fatty acids exhibited different responses to variable PD × MG combinations (Fig. 2E–2I), whereas sugar content responses were similar (Fig. 2J–2L). Early planting was associated with lower protein and linolenic acid, and higher oil, oleic acid, and sugar contents. Our results contradict those from Jaureguy et al. (2013) in Arkansas who associated early plantings with high protein seed content. Nevertheless, in that study, researchers used breeding lines with modified seed composition (high protein, oil, oleic acid and inorganic P, and low linolenic acid, saturated fatty acids, and stachyose). These findings further highlight the complexity of the impact of soybean management on seed composition; PDs and MGs should be chosen based on the product's end use (yield vs. seed composition).

Temperature × Maturity Group Effects

Across all environments included in the study, and depending on the PD, T5 to T8 ranged between 14 and 22°C. The negative correlation between T5 to T8 and PD ($r = -0.39$, $P < 0.0001$) indicates that earlier planting resulted in warmer average air temperatures between R5 and R8. It appears that these warmer temperatures favored yields of later-maturing soybean (Fig. 3A) whereas, it slightly suppressed yields of MG 0.5 to 1.

Temperature variability, which was introduced to this study through PDs, also affected soybean composition. Increased T5 to T8 reduced protein (Fig. 3B) and favored oil (Fig. 3C) and P+O (Fig. 3D) contents. Additionally, increased T5 to T8 reduced essential (Fig. 4A), non-essential (Fig. 4C), and non-protein (Fig. 4D) amino acids, as well as linoleic (Fig. 4F) and linolenic (Fig. 4G) fatty acids. However, the relative concentration of essential amino acids as a percentage of the sum of 18 amino acids (Fig. 4B), oleic (Fig. 4E), and stearic (Fig. 4I) fatty acids, and sugars contents (Fig. 4J–4L) were increased due to the elevated T5 to T8. Overall results partially agree with Wolf et al. (1982) who reported increased protein, oil, and oleic acid, and decreased sucrose, and linolenic and linoleic acids as the temperature after the beginning of seed development increased. It should be noted that genetic improvement during the last 35 yr may be the reason for the discrepancy regarding the protein response to temperature. Similar results were observed by Naeve and Huerd (2008), who found that oil concentrations increased due to increasing temperature during seed fill in Minnesota. No effect on protein was observed in their study.

Overall, data suggest that T5 to T8 had a significant effect on the resulting soybean seed yield and composition. We found multiple constituents which showed a large variability in their responses to management decisions and temperature variations. Our findings

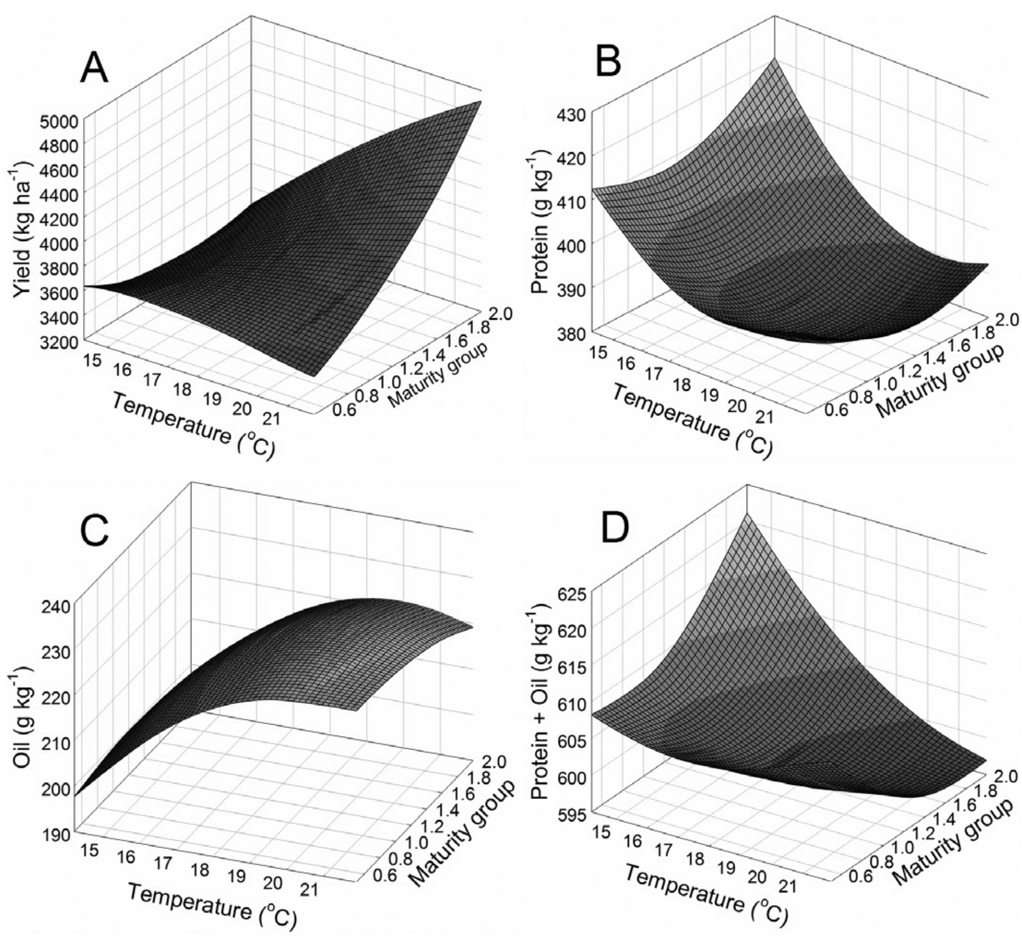

Fig. 3. Maturity group × air temperature between R5 and R8 growth stages response surface of (A) yield (kg ha^{-1}), (B) protein (g kg^{-1}), (C) oil (g kg^{-1}), and (D) protein+oil (g kg^{-1}).

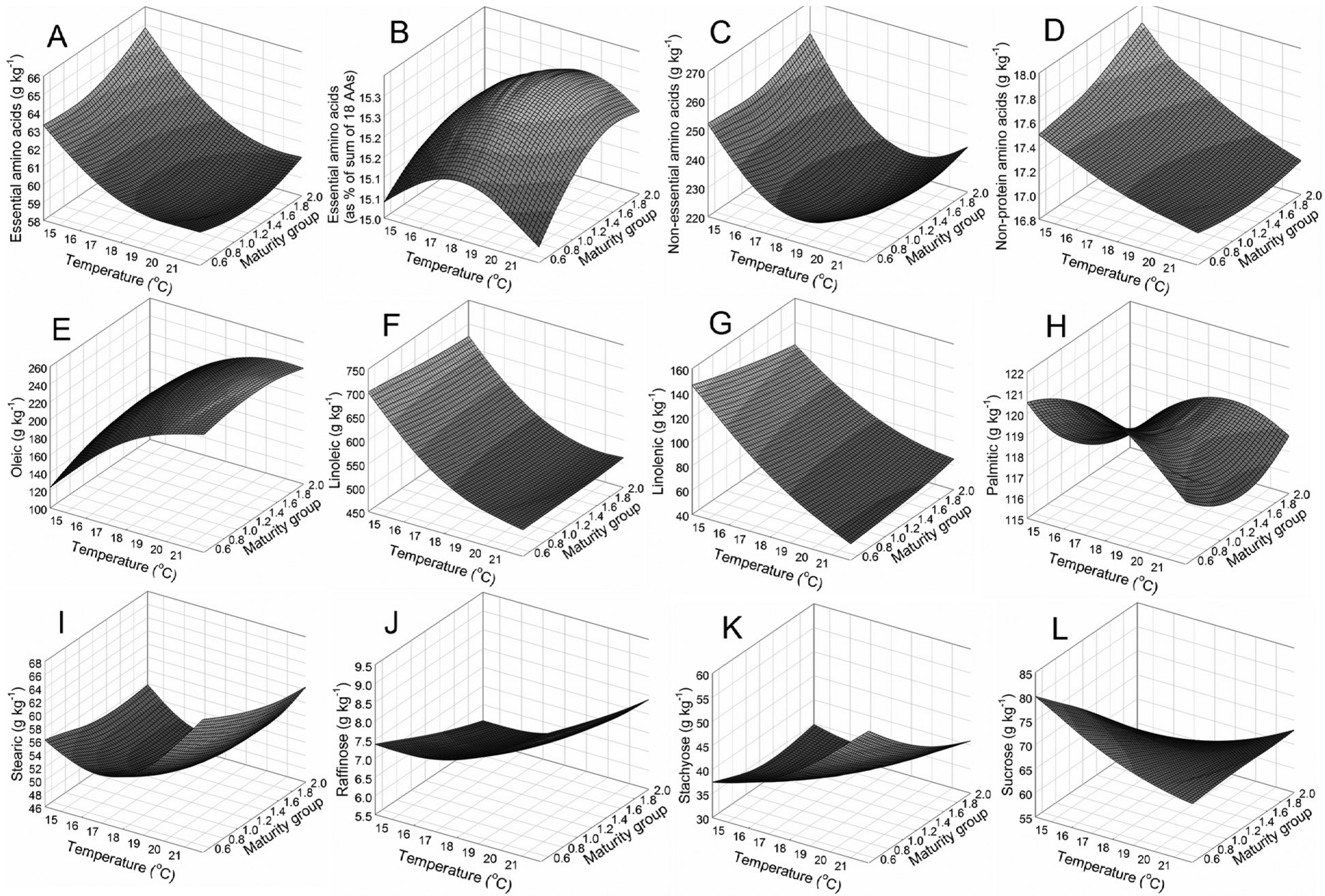

Fig. 4. Maturity group × air temperature between R5 and R8 growth stages response surface of (A) sum of essential amino acids (g kg^{-1}), (B) sum of essential amino acids (as % of the sum of 18 amino acids), (C) sum of non-essential amino acids (g kg^{-1}), (D) sum of non-protein amino acids (g kg^{-1}), (E) oleic acid (g kg^{-1}), (F) linoleic acid (g kg^{-1}), (G) linolenic acid (g kg^{-1}), (H) palmitic acid (g kg^{-1}), (I) stearic acid (g kg^{-1}), (J) raffinose (g kg^{-1}), (K) stachyose (g kg^{-1}), and (L) sucrose (g kg^{-1}).

highlight the importance of soybean producers understanding their product's end use (e.g., high yield vs. high protein and combinations), and modifying the growing environment accordingly by selecting appropriate PDs and MGs for their respective regions. Similar region-specific studies using multiple years of data can detect large environmental variability in important soybean production areas across the United States. Analysis of such data sets will ultimately provide more accurate recommendations to local producers on how to maximize their economic returns.

CONCLUSIONS

The work presented here has important implications for simple and cost-neutral, yet important, soybean management recommendations to farmers in the northern Corn Belt. Planting date and MG decisions can greatly affect yield and composition, and therefore, significantly increase or suppress overall farm profitability. The results show that the combination of early planting (late April–early May) and using the longest maturity group (MG 2) had the highest yield, oil, and oleic acid potential across the examined region. However, if a seed with high protein content is the overarching goal, a compromise in lower seed yield may be necessary.

ACKNOWLEDGMENTS

The authors wish to thank John Gaska, Adam Roth, and Dimitri von Ruckert for their technical support and Dr. Jill Miller-Garvin for her critical review. We would also like to thank the Wisconsin Soybean Marketing Board, DuPont Pioneer, and the University of Wisconsin-Madison, College of Agricultural and Life Sciences for funding this research.

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