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Management strategies for early- and late-planted soybean in the north-central United States

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Management strategies for early- and late-planted soybean in the north-central United States

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Abstract

It is widely recognized that planting soybean [*Glycine max* (L.) Merr.] early is critical to maximizing yield, but the influence of changing management factors when soybean planting is delayed is not well understood. The objectives of this research were to (a) identify management decisions that increase seed yield in either early- or late-planted soybean scenarios, and (b) estimate the maximum break-even price of each management factor identified to influence soybean seed yield in early- or late-planted soybean. Producer data on seed yield and management decisions were collected from 5682 fields planted with soybean during 2014–2016 and grouped into 10 technology extrapolation domains (TEDs) based

Abbreviations: AI, aridity index; AOSR, agronomic optimum seeding rate; CI, conditional inference; GDD, growing degree day; POST, post-emergence; PRE, pre-emergence; RM, relative maturity; RSS, residual sum of squares; RZWHC, rhizosphere water holding capacity; ST, seed treatment; TED, technology extrapolation domain

on growing environment. A subsample of 1512 fields was classified into early- and late-planted categories using terciles. Conditional inference trees were created for each TED to evaluate the effect of management decisions within the two planting date timeframes on seed yield. Management strategies that maximized yield and associated maximum break-even prices varied across TEDs and planting date. For early-planted fields, higher yields were associated with artificial drainage, insecticide seed treatment, and lower seeding rates. For late-planted fields, herbicide application timing and tillage intensity were related to higher yields. There was no individual management decision that consistently increased seed yield across all TEDs.

1 | INTRODUCTION

Timely planting of soybean [*Glycine max* (L.) Merr.] is extremely important to maximize seed yield in the north-central United States. Several field experiments have shown seed yield reduction when planting date is delayed beyond early- to mid-May (Hu & Wiatrak, 2012; Robinson, Conley, Volenec, & Santini, 2009). For example, in Iowa, a seed yield reduction of 0.13 Mg ha^{-1} wk^{-1} (−0.02 Mg ha^{-1} d^{-1}) was observed for soybean planted from early May to late May and −0.40 Mg ha^{-1} wk^{-1} (−0.06 Mg ha^{-1} d^{-1}) for planting dates from late May to early June (De Bruin & Pedersen, 2008). In Nebraska and Ohio, delayed planting after 1 May resulted in yield declines that ranged from −0.02 to −0.04 Mg ha^{-1} d^{-1} (Bastidas et al., 2008; Hankinson, Lindsey, & Culman, 2015). Apart from the aforementioned region-specific studies, a U.S.-wide study estimated a 10% increase in yield and approximately US$9 billion in monetary gains could be realized if soybean was planted at the optimal time across the United States (Mourtzinis, Specht, & Conley, 2019b).

Recent studies using producer data identified planting date as the most important management practice explaining field-to-field variation across regions with similar weather and soil condition in the north-central United States (Mourtzinis et al., 2018; Rattalino Edreira et al., 2017). These studies showed maximum seed yield reductions of −0.34 Mg ha^{-1} d^{-1} for each day soybean was planted after the last week of April. In regions where planting date was the most important factor influencing soybean yield, additional factors that explained a large percentage of field-to-field yield variation were topographic wetness index, subsoil pH, row width, foliar fungicide, and foliar insecticide (Mourtzinis et al., 2018).

In this study, the dataset described in Mourtzinis et al. (2018), which included data from 2014–2015, was expanded to include fields from 2014–2016 and used to identify agronomic management decisions to optimize soybean yield in early- and late-planted situations. However, unlike the previously conducted analyses, this work focused on management practices and not factors beyond producers' control such as topographic wetness index and subsoil pH. Furthermore, this research provided an estimate of the break-even price point for inputs identified as significant predictors of yield. The objectives of this research were to: (a) identify management decisions that increase seed yield in early- or late-planted soybean scenarios, and (b) estimate the maximum break-even price of each management factor identified to influence soybean seed yield in early- or late-planted soybean.

2 | METHODS

2.1 | Data collection and database description

Between 2014 and 2016, researchers, extension educators, and crop consultants from 10 north-central U.S. states (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Ohio, North Dakota, Nebraska, and Wisconsin) collected data on seed yield and management decisions from 5682 producer soybean fields. The resulting database was described in Rattalino Edreira et al. (2017) and Mourtzinis et al. (2018). Self-reported management practices included planting date, cultivar relative maturity (RM), seeding rate, row width, tillage type, artificial drainage, seed treatments, fertilizer type and amount, and lime, manure, and pesticide application. Year-specific conditions such as pest pressure, Fe deficiency chlorosis incidence, and weather adversities were reported by producers. A few fields with extremely low yield due to unmanageable production site adversities (hail, waterlogging, wind, and frost) were excluded from the analyses. The procedure to exclude these fields consisted of three steps: (a) grouping fields within regions with similar soil and climate (further described in Section 1.2 Soybean field classification), (b) selecting fields within the 25th percentile of yield data distribution within each region–year, and (c) excluding fields affected by any of the aforementioned adversities reported by producers. Fields that were both affected by reported adversities and fell within the 25th percentile of yield within their region were excluded from further analysis. Fields planted after 15 June that also had wheat (*Triticum aestivum* L.) as a previous crop were removed from further analyses to exclude double crop soybean production systems, which are rare in the majority of the study area.

2.2 | Soybean field classification

Fields were grouped into technology extrapolation domains (TEDs) according to growing conditions, as characterized by growing degree days (GDDs), aridity index (AI), and root zone water holding capacity (RZWHC). Growing degree days is a measure of heat accumulation and is used to predict crop development, and it was calculated using a base temperature of 0 °C. Aridity index is a measure of how dry an area is and is calculated as the ratio of mean annual precipitation and mean annual potential evapotranspiration. Root zone water holding capacity is a measure of how much water the soil can hold within the rootable depth. More information about TEDs and the calculation of GDDs and AI is available in Rattalino Edreira et al. (2018).

Technology extrapolation domains were selected for this study when more than 180 fields were located within a TED, as that number balanced having a diversity of environments included while still having a sufficient number of fields to detect differences in yield due to management (see more information in Section 1.3 Statistical analysis). The 10 TEDs included in this study contained 1512 of the 5682 total fields. Some soybean-producing regions were not included in this study due to an insufficient number of fields.

The geographic distribution of the 10 TEDs is available in Figure 1. The six-digit numbers following the TED numbers in the legend of Figure 1 are the reference numbers to locate these TEDs in the global database at yieldgap.org. All TEDs were rainfed except for TED 2, which was irrigated. Within each TED, fields were classified as early- or late-planted when falling within the first or the third terciles of planting date data distribution, respectively (Table 1). Some TEDs have a different number of fields in the early- and late-planted tercile due to many fields being planted on the first or last day within each timeframe.

Core Ideas

- Management decisions that increased soybean yield were region specific.
- No single management decision consistently increased seed yield across the entire study region.
- Integrated pest management principles should be followed when deciding the use of pesticide inputs.

2.3 | Statistical analysis

To explore the relationship between seed yield and management decisions within the two planting date timeframes, two conditional inference (CI) trees were created for each TED—one for early-planted fields and one for late-planted fields (Table 2). Conditional inference trees were used to identify and visualize interactions among independent variables with less risk of overfitting than other recursive decision tree algorithms (Hothorn, Hornick, & Zeileis, 2006). Significance testing was used to perform splits within CI trees, with the lowest p value determining each split. The null hypothesis for each split was that the dependent variable (seed yield) was independent of the management decision variable.

The above described CI tree analysis was implemented using the package *partykit* within R 3.2.4 statistical software (Hothorn & Zeileis, 2015; R Development Core Team, 2016). The independence-test criterion for splits was univariate p value ($\alpha = .05$). Interior nodes were required to maintain at least 33% of the data. At minimum, terminal nodes included 10 fields. Overfitting was prevented by constraining trees at a maximum depth of 10 nodes. To quantify the minimum detectible yield difference given the number of trees used to create each CI tree, power analysis was performed using the package *pwr* within R 3.2.4 (Champley et al., 2018). One-way ANOVA tests were performed to determine the effect size (f) when the significance (alpha) level was .05 and the power level was 0.80. The average standard deviation of yield within each TED and planting date timeframe was 0.264 Mg ha^{-1}, and was used to calculate minimum detectable difference from the effect size (f). Effect size as measured by Cohen's f is a standardized, unitless measure. Under the range of sample sizes present between planting date timeframes and TEDs (Table 1) and the possible unevenness of splits in the CI trees, the effect sizes ranged from 0.27 to 0.66. After converting f to Cohen's d, d was divided by standard deviation to estimate the minimum detectable difference in

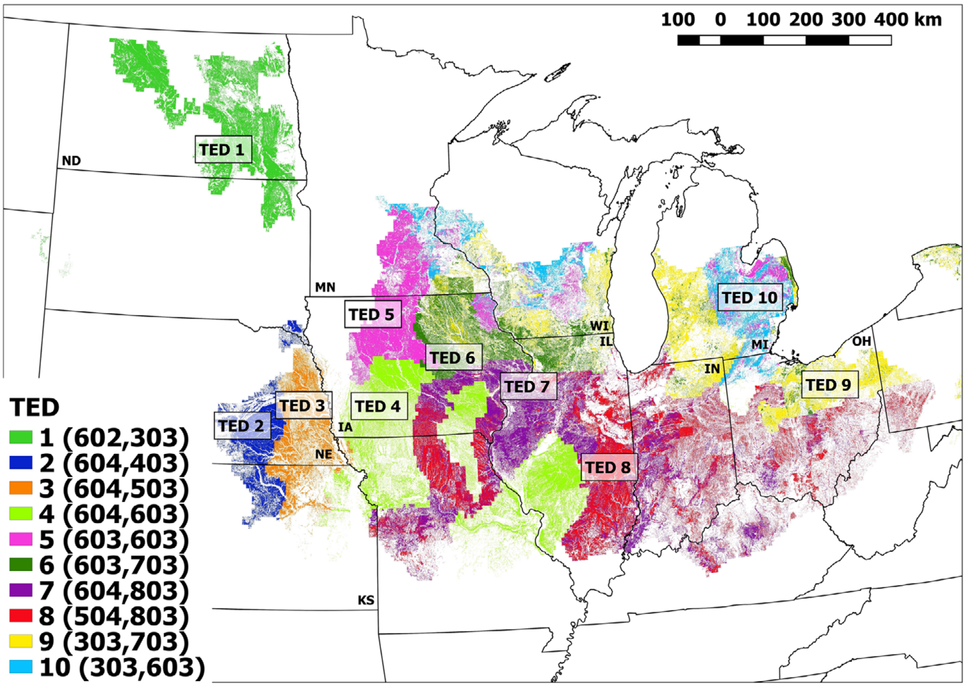

FIGURE 1 Technology extrapolation domains (TEDs) distributed across the north-central U.S. region. The six-digit numbers following the TED numbers are the reference numbers to locate these TEDs in the global database at yieldgap.org

TABLE 1 Range of planting dates, average planting date, and number of fields for early- and late-planted soybean fields within each technology extrapolation domain (TED)

	Early			Late			Minimum difference between early- and late-planted fields[a]
TED	Date range	Average date	Number of fields	Date range	Average date	Number of fields	
							days
1	24 Apr. –18 May	8 May	65	26 May–14 June	30 May	71	8
2	6 Apr. –6 May	1 May	105	17 May–6 July	21 May	111	11
3	21 Apr. –14 May	7 May	59	22 May–1 July	5 June	64	8
4	22 Apr. –7 May	3 May	79	20 May–30 June	30 May	85	13
5	18 Apr. –11 May	6 May	90	22 May–13 June	26 May	84	11
6	17 Apr. –8 May	4 May	89	21 May–10 June	25 May	99	13
7	10 Apr. –7 May	1 May	54	22 May–23 June	27 May	59	15
8	10 Apr. –8 May	2 May	89	22 May–19 June	28 May	84	14
9	29 Apr. –15 May	6 May	56	26 May–16 June	31 May	62	11
10	26 Apr. –16 May	8 May	53	25 May–15 June	31 May	54	9

[a] Minimum difference between early- and late-planted fields is the number of days between the last early-planted field and the first late-planted field.

yield. The range of effect size (f) of 0.27–0.66 corresponds to a range in minimum detectable difference in yield of 0.033–0.088 Mg ha^{-1}.

The following variables were considered binary (yes/no): artificial drainage, fungicide seed treatment, insecticide seed treatment, inoculant seed treatment, nematicide seed treatment, starter fertilizer (all possible fertilizer sources and placements), starter P, foliar fungicide, foliar insecticide, and manure application. The following variables were considered categorical: tillage (minimal or intense), herbicide (none, pre-emergence only, post-emergence only, or both), row width (narrow, medium, or wide), and previous crop (corn [*Zea mays* L.], soybean, wheat, sunflower [*Helianthus annuus* L.], sorghum [*Sorghum bicolor* L.], cereal rye [*Secale cereal* L.], sugarbeet [*Beta vulgaris* L.], popcorn, alfalfa [*Medicago sativa* L.], oat [*Avena sativa* L.], barley [*Hordeum vulgare* L.], hay, potato [*Solanum tuberosum* L.], or corn silage).

TABLE 2 Summary of management decisions within each technology extrapolation domain (TED) for early (E) and late (L) planting timeframes displayed as percent of fields with that treatment, except for average seeding rate (1000 seeds ha^{-1}) and average yield (Mg ha^{-1})

Management decision		TED 1		TED 2		TED 3		TED 4		TED 5		TED 6		TED 7		TED 8		TED 9		TED 10	
		E[a]	L[b]	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Artificial drainage		43	23	–[c]	–	20	20	–	75	89	77	80	84	83	71	78	46	66	73	66	80
Seed treatment	Fungicide	55	68	46	–	59	50	71	69	61	64	71	63	–	59	–	61	–	73	53	56
	Insecticide	42	46	44	–	–	48	63	69	54	61	54	55	–	54	58	49	–	69	49	52
	Inoculant	65	79	–	–	–	–	–	–	10	–	–	–	19	–	–	–	20	–	–	–
	Nematicide	–	–	–	–	–	–	30	26	14	–	24	–	20	–	–	–	–	–	–	–
Starter fertilizer	Starter fertilizer	28	44	16	–	15	14	–	–	–	–	–	10	–	15	–	10	–	–	23	22
	P fertilizer	37	39	–	–	14	11	–	–	–	–	–	–	–	–	–	–	–	–	21	19
Manure	Manure	–	–	–	–	–	–	–	14	–	17	–	–	–	–	11	1	14	8	15	2
Foliar application	Fungicide	12	–	23	–	25	13	20	31	61	19	45	48	65	19	34	–	29	–	26	–
	Insecticide	40	31	19	–	20	11	19	29	39	29	43	35	61	24	33	21	23	19	19	17
Average seeding rate (1000 ha^{-1})[d]		420	417	415	408	375	367	366	378	368	378	380	373	385	410	395	395	378	408	395	398
Row width	Narrow	5	13	4	5	0	0	15	5	9	19	3	6	9	8	18	17	11	23	25	31
	Medium	78	66	28	7	53	45	38	56	47	39	74	55	57	86	66	77	57	58	58	30
	Wide	17	20	67	86	46	53	47	39	44	42	22	39	33	5	11	5	32	19	15	39
Tillage	Intense	22	17	16	39	–	–	47	–	13	17	20	15	17	25	13	15	20	15	21	20
	Minimal	35	27	82	57	–	–	28	–	64	70	69	80	56	66	56	74	64	65	58	41
Herbicide application timing	Both PRE + POST	58	37	87	76	–	89	–	–	80	74	78	79	83	83	82	89	80	65	57	67
	POST only	22	28	9	14	–	3	–	–	20	20	12	13	7	8	15	5	18	29	43	30
	PRE only	9	1	0	0	–	5	–	–	0	6	6	3	0	2	1	6	2	6	0	4
	None	11	5	5	10	–	3	–	–	0	0	4	5	9	7	2	0	0	0	0	0
Previous crop	Corn	43	33	93	92	–	80	100	95	91	86	99	93	96	92	92	87	84	85	83	74
	Soybean	22	13	–	–	–	2	–	–	–	4	–	–	–	–	–	5	4	13	6	9
Average yield, Mg ha^{-1}		2.8	2.4	5	4.7	3.9	3.6	4.5	4	4.3	3.7	4.3	3.7	4.5	4.1	4.3	4	3.8	3.5	3.9	3.6

[a] E is for early planted soybean, as determined using the first third of planted soybeans within each TED.

[b] L is for late planted soybean, as determined using the last third of planted soybeans within each TED.

[c] Variable excluded from analysis for that TED and planting date timeframe due to 90% or more of fields being treated identically or greater than 50% of fields not having adequate data for that particular variable.

[d] Average seeding rate for each TED and planting date timeframe is presented in 1000 seeds ha^{-1}, differing from other treatments that are displayed as percentages.

Minimal tillage included no-tillage, strip-tillage, ridge-tillage, or harrow while intense tillage included chisel plow, moldboard plow, disk, field cultivator, and/or soil finisher implements. For row width, <25 cm, 25–56 cm, and >56 cm were considered, narrow, medium, and wide, respectively. Seeding rate and RM were considered continuous variables. For each TED and planting date combination, independent variables where 90% of fields had the same treatment were excluded from the analysis, such as artificial drainage in early-planted fields in TED 2. If the management decision for more than half of the fields in a TED was not available from our survey form for a particular management decision, the management decision was also excluded from analysis, such as inoculant seed treatment in late-planted fields in TED 8. A summary of management decisions within each TED and planting date timeframe is shown in Table 2.

For in-season management decisions that increased yield, the maximum break-even price was calculated. The maximum break-even price is the highest price a producer can pay for a treatment and still expect a profit, or in other words, have a positive return on investment. Grain yield benefit was calculated using the CI trees by subtracting the average yield from the node without the yield-improving treatment from the average yield from the node with the yield-improving treatment. Grain yield was multiplied by grain price to calculate the maximum break-even price under three different grain price scenarios: \$297, \$333, and \$368 Mg^{-1}. These three values represent conservative, but realistic, price scenarios, given that between January 2015 and June 2019, the lowest observed grain price was \$297 Mg^{-1}, and the median observed price was \$368 Mg^{-1} (USDA NASS, 2019). Costs for implementing each decision includes both products and their application. Product costs were estimated in 2017 using a phone survey of retailers in the 10 participating states (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Ohio, North Dakota, Nebraska, and Wisconsin), and application costs were averaged from state custom application budgets.

3 | RESULTS

3.1 | Early-planted fields

Among early-planted fields, management factors that were associated most consistently with changes in soybean seed yield within several TEDs included artificial drainage (TEDs 1, 6, and 10), insecticide seed treatment (TEDs 1, 6, and 10), and seeding rate (TEDs 7, 8, and 10) (Figure 2; Table 3). In TED 6, maximum average seed yield for early-planted soybean was 4.8 Mg ha^{-1} and was associated with fields without artificial drainage (Figure 2). In TED 1, soybean not treated with insecticide seed treatment yielded 0.39 Mg ha^{-1} more when artificial drainage was present, compared to yields in fields without artificial drainage (Table 3). There was also an increase in soybean seed yield in TED 10 when artificial drainage was present (Table 3).

In TED 1, the highest seed yield (3.06 Mg ha^{-1}) was achieved when insecticide seed treatment was applied to soybean cultivars with a MG > 0.9. On average, TED 1 fields with insecticide seed treatment yielded 0.5 Mg ha^{-1} greater than fields without insecticide seed treatment (Table 3). In TED 6, fields with artificial drainage and both herbicide timings, but lacking nematicide seed treatment, had 0.09 Mg ha^{-1} greater yield with insecticide seed treatments compared to fields without insecticide seed treatments (Figure 2). Technology extrapolation domain 10 also had higher yield in fields that had artificial drainage. Seed yield was further associated with insecticide seed treatment, resulting in lower seed yield when seed was not treated with an insecticide compared to seed treated with an insecticide (Table 3).

Of the TEDs with a significant difference in yield corresponding to seeding rate, higher yields were consistently observed where seeding rate was lower. Among TED 10 fields with artificial drainage and where insecticide seed treatment was applied, soybean yield was greater when seeding rate was ≤383,000 seeds ha^{-1} (Table 3). Other TEDs with higher yield at lower seeding rates were TEDs 7 and 8. In TED 7, fields planted early at ≤403,000 seeds ha^{-1} resulted in a soybean seed yield 0.90 Mg ha^{-1} greater than fields planted at >403,000 seeds ha^{-1} (Table 3). In TED 8, fields with seeding rates ≤383,000 seeds ha^{-1} showed greater seed yield than fields with higher seeding rates (Figure 3).

3.2 | Late-planted fields

Among late-planted fields, management factors that were correlated with changes in soybean seed yield within several TEDs included herbicide application timing (TEDs 2, 5, and 10) (Table 3) and tillage intensity (TEDs 6 and 8) (Figures 4 and 5, respectively). In TED 2, fields that received no herbicide application or only a POST-herbicide application were associated with the lowest soybean seed yield (4.33 Mg ha^{-1}). In TED 5 fields where soybean was planted in narrow or medium row widths, seed yield was correlated with herbicide application. Greater soybean seed yield (0.72 Mg ha^{-1}) was associated with fields that received a PRE- and POST-herbicide application compared to fields that only received a PRE or POST herbicide application (Table 3). Across late-planted fields in TED 10, when a PRE and POST or only a PRE herbicide was applied,

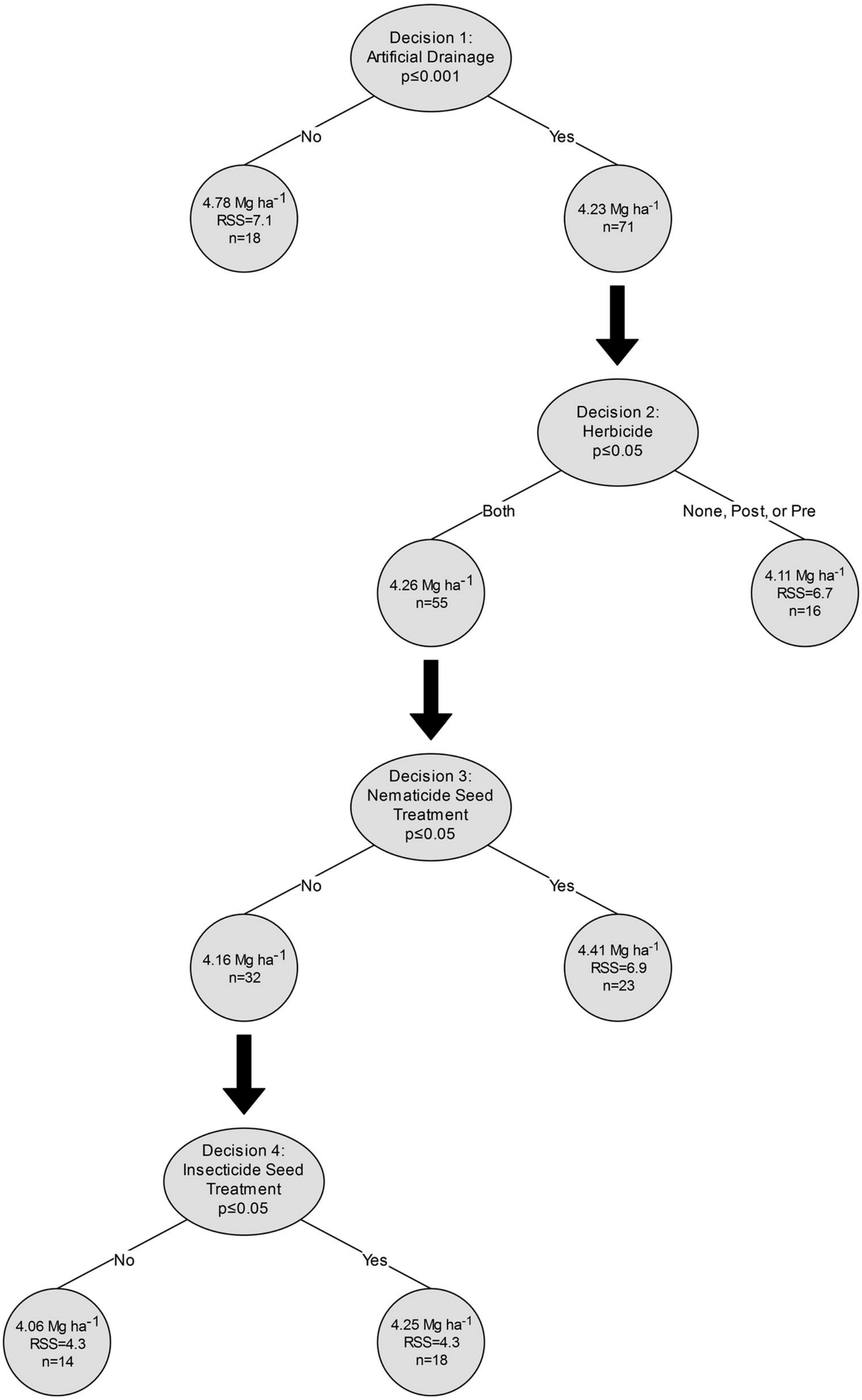

FIGURE 2 Conditional inference tree for technology extrapolation domain (TED) 6 showing significant management decisions for predicting yield in early-planted soybean fields where RSS is the residual sum of squares for each terminal node, and *n* is the number of fields present in each node

TABLE 3 Summary of conditional inference trees for early and late-planted fields in technology extrapolation domains (TEDs) 1, 2, 3, 4, 5, 7, 9, and 10. Bracketed values are the number of fields (n) and average yield (Y, Mg ha^{-1}), and RSS is the residual sum of squares. Conditional inference trees did not identify any significant decisions for late-planted fields in TED 3

	Early					Late			
TED	**Decision 1**	**Decision 2**	**Decision 3**	**[n,Y]**	**RSS**	**Decision 1**	**Decision 2**	**[n,Y]**	**RSS**
1	Insecticide ST[a] (No)	–	–	[33, 2.56]	–	Starter P (No)	–	[43, 2.56]	–
	–	Artificial drainage (No)	–	[26, 2.51]	3.6	–	Fungicide ST (No)	[11, 2.16]	3.4
	–	Artificial drainage (Yes)	–	[10, 2.90]	2.9	–	Fungicide ST (Yes)	[32, 2.62]	6.8
	Insecticide ST (Yes)	–	–	[27, 2.96]	–	Starter P (Yes)	–	[28, 2.18]	11.4
	–	Relative maturity ≤0.9	–	[17, 2.98]	5.4	–	–	–	–
	–	Relative maturity > 0.9	–	[12, 3.06]	2.5	–	–	–	–
2	Starter fertilizer (No)	–	–	[88, 4.91]	18.6	Herbicide (both)	–	[84, 4.84]	–
	Starter fertilizer (Yes)	–	–	[17, 5.41]	5.2	–	Relative maturity ≤ 2.7	[31, 5.02]	3.5
	–	–	–	–	–	–	Relative maturity > 2.7	[53, 4.74]	7.1
	–	–	–	–	–	Herbicide (none or POST)	–	[27, 4.33]	12.2
3	Foliar fungicide (No)	–	–	[44, 3.65]	22.3	–	–	–	–
	Foliar fungicide (Yes)	–	–	[15, 4.63]	6.3	–	–	–	–
4	Relative maturity ≤ 3	–	–	[45, 4.33]	7.3	Relative maturity ≤ 3.4	–	[57, 4.10]	11.8
	Relative maturity > 3	–	–	[34, 4.70]	8.2	Relative maturity > 3.4	–	[28, 3.79]	15.5
5	Foliar insecticide (No)	–	–	[55, 4.16]	21.5	Row width (medium or narrow)[b]	–	[49, 3.53]	–
	Foliar insecticide (Yes)	–	–	[35, 4.52]	12.0	–	Herbicide (both)	[37, 3.70]	18.0
	–	–	–	–	–	–	Herbicide (post or pre)	[12, 2.98]	5.6

(Continues)

TABLE 3 (Continued)

	Early					Late			
TED	**Decision 1**	**Decision 2**	**Decision 3**	**[*n*,Y]**	**RSS**	**Decision 1**	**Decision 2**	**[n,Y]**	**RSS**
	–	–	–	–	–	Row width (wide)	–	[35, 4.00]	10.9
7	Seeding rate ≤ 403,000 seeds ha^{-1}	–	–	[36, 4.81]	19.7	Seeding rate ≤ 358,000 seeds ha^{-1}	–	[10, 4.94]	4.3
	Seeding rate > 403,000 seeds ha^{-1}	–	–	[18, 3.91]	8.5	Seeding rate > 358,000 seeds ha^{-1}	–	[49, 3.97]	–
	–	–	–	–	–	–	Seeding rate ≤ 432,000 seeds ha^{-1}	[33, 4.17]	9.7
	–	–	–	–	–	–	Seeding rate > 432,000 seeds ha^{-1}	[16, 3.57]	3.2
9	Inoculant ST (No)	–	–	[38, 4.00]	–	Foliar Insecticide (No)	–	[50, 3.42]	22.9
	–	Foliar fungicide (N)	–	[26, 3.71]	16.8	Foliar insecticide (Yes)	–	[12, 3.98]	2.7
	–	Foliar fungicide (Y)	–	[12, 4.62]	2.0	–	–	–	–
	Inoculant ST (Yes)	–	–	[18, 3.47]	8.5	–	–	–	–
10	Artificial drainage (No)	–	–	[18, 3.42]	6.1	Herbicide (both, PRE)	–	[38, 3.83]	20.6
	Artificial drainage (Yes)	–	–	[35, 4.09]	–	Herbicide (POST)	–	[16, 3.08]	3.2
	–	Insecticide ST (No)	–	[13, 3.72]	3.8				
	–	Insecticide ST (Yes)	–	[22, 4.31]		–	–	–	–
	–	–	Seeding rate ≤ 383,000 seeds ha^{-1}	[12, 4.57]	4.2	–	–	–	–
	–	–	Seeding rate > 383,000 seeds ha^{-1}	[10, 4.00]	1.6	–	–	–	–

[a] ST:Seed treatment.

[b] Narrow rows were <25 cm, medium rows were 25-56 cm, and wide rows were >56 cm in width.

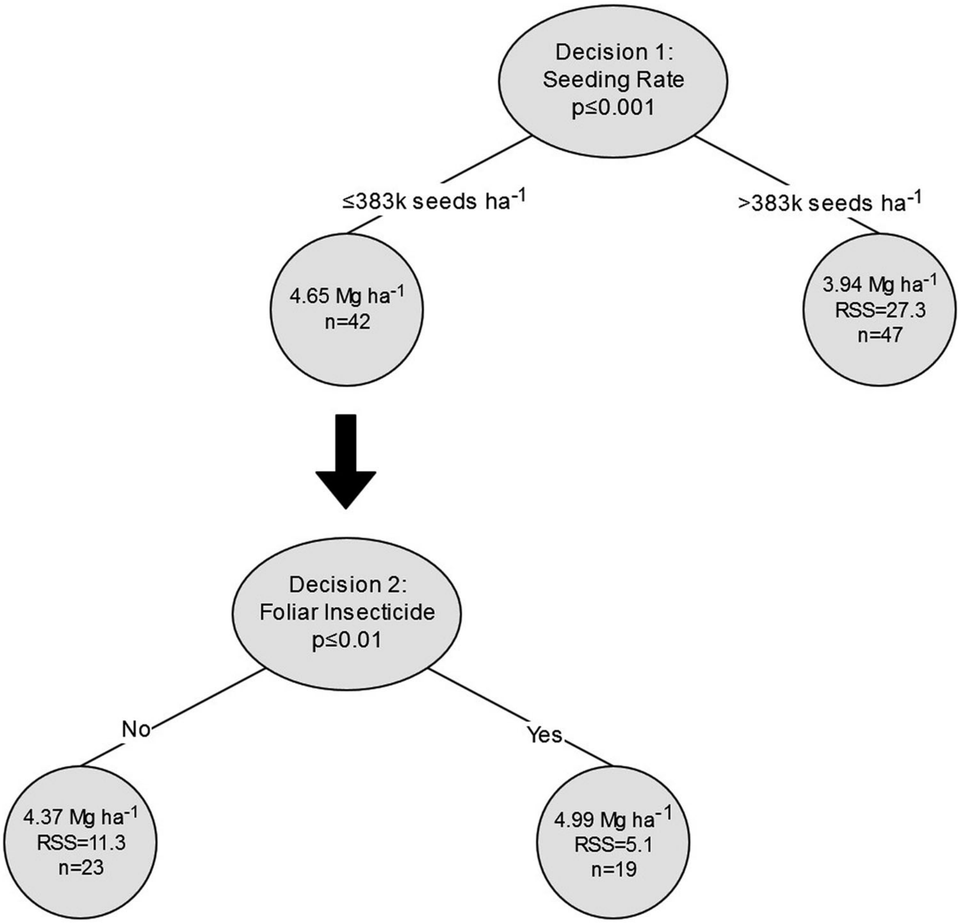

FIGURE 3 Conditional inference tree for technology extrapolation domain (TED) 8 showing significant management decisions for predicting yield in early-planted soybean fields where RSS is the residual sum of squares for each terminal node, and *n* is the number of fields present in each node

soybean seed yield was greater compared to fields that only received a POST-herbicide application (Table 3).

In TED 6, late-planted fields receiving intense tillage were associated with the greatest seed yield at 4.1 Mg ha^{-1} (Figure 4). In fields with minimal tillage, foliar fungicide increased yield by 0.29 Mg ha^{-1} compared with fields without a foliar fungicide application. In TED 8, the highest yields were observed in fields with intensive tillage when corn or sorghum was the previous crop and there was no artificial drainage. Minimally tilled fields had 0.21 Mg ha^{-1} higher yield for cultivars of ≤3.8 RM compared to cultivars of >3.8 RM (Figure 5).

Foliar fungicides and insecticides improved yield for late-planted fields in three TEDs. In minimally tilled TED 6 fields, seed yield was 0.29 Mg ha^{-1} greater with an application of foliar fungicide compared to yields in fields without foliar fungicide (Figure 4). In TED 9 fields where foliar insecticide was applied, there was an increase in yield of 0.56 Mg ha^{-1} (Table 3).

3.3 | Economics

Maximum break-even price for insecticide seed treatment ranged from \$63 to \$196 ha^{-1} at a grain price of \$333 Mg^{-1} (Table 4). More frequent herbicide applications improved yield for late-planted soybean in TEDs 2, 5, and 10, and for early planted soybean in TED 6 (Table 3), with the maximum break-even price for herbicide ranging from \$50 to \$250 ha^{-1} at a grain price of \$333 Mg^{-1} (Table 4). For late-planted soybean in TEDs 2, 5, and 10, this maximum break-even price at a grain price of \$333 Mg^{-1} covers the cost of moving from an herbicide program with only a POST application to a program with both a PRE and a POST. The maximum break-even price was not high enough to cover the cost of implementing a PRE and POST program for early-planted soybean in TED 6 (Table 4).

Foliar insecticide improved yields in TEDs 5 and 8 for early-planted soybean, and in TED 9 for late-planted soybean. The maximum break-even price for foliar

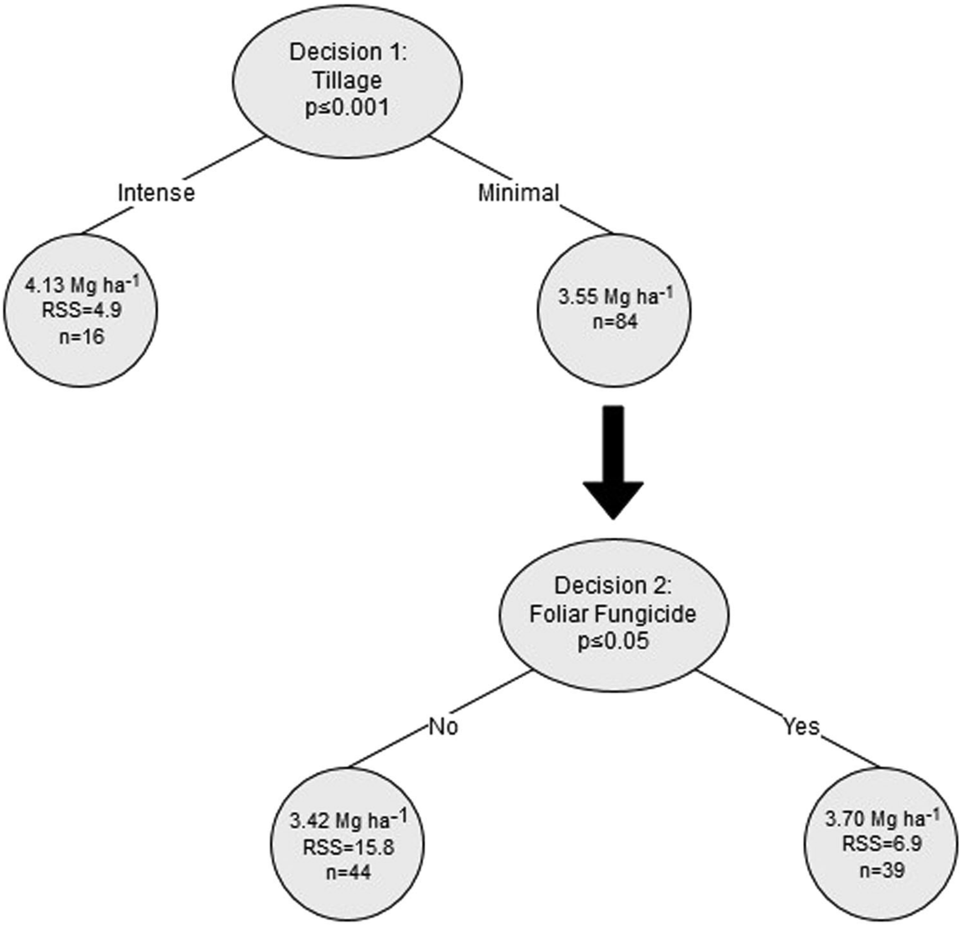

FIGURE 4 Conditional inference tree for technology extrapolation domain (TED) 6 showing significant management decisions for predicting yield in late-planted soybean fields where RSS is the residual sum of squares for each terminal node, and n is the number of fields present in each node

insecticide ranged from \$120 to \$206 ha^{-1} at a grain price of \$333 Mg^{-1}. For early-planted soybean in TEDs 5 and 8, and late-planted soybean in TED 9, the estimated cost of applying foliar insecticide is lower than the maximum break-even price (Table 4). Foliar fungicide improved yield for early planted soybean in TEDs 3 and 9, and for late-planted soybean in TED 6, with a maximum break-even price of \$326 ha^{-1}. The cost of applying foliar fungicide was lower than the maximum break-even price at a grain price of \$333 Mg^{-1} for early-planted soybean in TEDs 3 and 9. The cost of applying foliar fungicide was higher than the maximum break-even price for late-planted fields in TED 6.

4 | DISCUSSION

While each TED had a different combination of treatments that maximized yield under different planting date timeframes, there were some commonalities among TEDs. Among early-planted fields, management factors that influenced soybean seed yield within a few TEDs included artificial drainage (TEDs 1, 6, and 10), insecticide seed treatment (TEDs 1, 6, and 10), and seeding rate (TEDs 7, 8, and 10). Improved yield in fields with artificial drainage as compared to fields without artificial drainage is likely due to a combination of reduced plant damage from flooding and improved timeliness of farm operations such as tillage, planting, and spraying (Aldabagh & Beer, 1975; Kanwar, Johnson, Schult, Fenton, & Hickman, 1983). Improved planting conditions, particularly in wet springs, could be part of the reason there was an association between artificial drainage and higher yields for early-planted fields in three TEDs (1, 6, and 10), but the same association was only seen in one TED 8 for late-planted fields.

While insecticide seed treatments were associated with higher yields in three TEDs (1, 6, and 10) for early-planted soybean, they were not associated with a change in yield for any late-planted soybean. In Wisconsin, combined insecticide–fungicide seed treatments improved yield by 4–12% (Gaspar, Mitchell, & Conley, 2015).

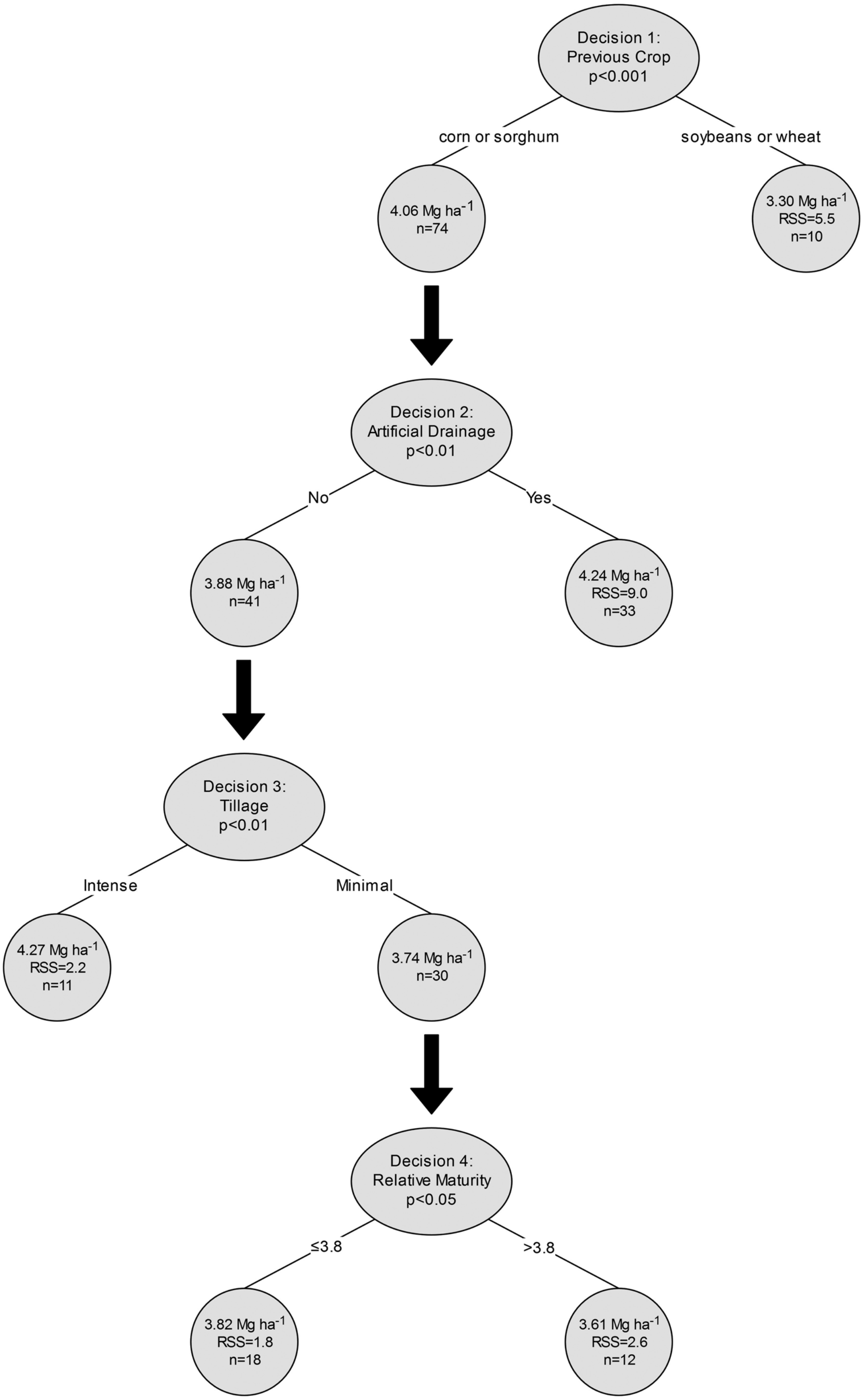

FIGURE 5 Conditional inference tree for technology extrapolation domain (TED) 8 showing significant management decisions for predicting yield in late-planted soybean fields where RSS is the residual sum of squares for each terminal node, and *n* is the number of fields present in each node

TABLE 4 Maximum break-even price a producer should pay for specific management decisions or inputs that improved yield at three grain prices ($\$297$, $\$333$, and $\$368$ Mg^{-1}), where TED is the technology extrapolation domain and PD is the planting date timeframe (E = early, L = late). Yield benefit was taken by subtracting the average yield in fields without that treatment from fields with that treatment in the conditional inference trees from Table 3. Technology extrapolation domains 4 and 7 (both planting windows) and 3 for late planting did not have in-season decisions that would have an associated break-even price. Costs for implementing each decision includes both products and their application. Product costs were estimated using a phone survey of retailers in the 10 participating states (IL, IN, IA, KS, MI, MN, OH, ND, NE, and WI), and application costs were averaged from state custom application budgets

TED	PD	Decision	Yield benefit	Maximum break-even price at the given grain price			Estimated cost of implementation
				$\$297$ Mg^{-1}	$\$333$ Mg^{-1}	$\$368$ Mg^{-1}	
			—Mg ha^{-1}—	US$ ha^{-1}			
1	E	Insecticide ST[a]	0.40	119	133	147	37
1	L	Fungicide ST	0.46	137	153	169	37
2	E	Starter fertilizer	0.50	149	167	184	81
2	L	Herbicide	0.51	151	170	188	123[b]
3	E	Foliar fungicide	0.98	291	326	361	117
5	E	Foliar insecticide	0.36	107	120	132	65
5	L	Herbicide	0.72	214	240	265	123[b]
6	E	Herbicide	0.15	45	50	55	123[b]
6	E	Nematicide ST	0.25	74	83	92	46
6	E	Insecticide ST	0.19	56	63	70	37
6	L	Foliar fungicide	0.28	83	93	103	117
8	E	Foliar Insecticide	0.62	184	206	228	65
9	E	Foliar fungicide	0.91	270	303	335	117
9	L	Foliar insecticide	0.56	166	186	206	65
10	E	Insecticide ST	0.59	175	196	217	37
10	L	Herbicide	0.75	223	250	276	123‡

[a] ST: Seed treatment.

[b] Cost of adding a PRE-emergence herbicide.

However, Mourtzinis et al. (2019a) recently reported a minimal yield increase (0.13 Mg ha^{-1}) across 14 states due to combined insecticide–fungicide seed treatments. While insecticide seed treatments were not associated with a change in yield for late-planted soybean, higher yields for late-planted fields treated with foliar insecticides were observed in TED 9. Insect pest pressure can vary by soybean-planting date (Hammond, Higgins, Mack, Pedigo, & Bachinski, 1991; Zeiss & Klubertanz, 1994). Technology extrapolation domains with an association between insecticides and soybean yield had maximum break-even prices that were higher than the estimated cost of implementing the insecticide seed treatments or foliar sprays, which indicates that insecticides may be an economically feasible treatment for producers (Table 4).

Among early-planted fields in TEDs 8 and 10, fields with seeding rates greater than 383,000 seeds ha^{-1} yielded significantly less than fields with lower seeding rates. Early-planted fields in TED 7 yielded less when their seeding rate was in excess of 403,000 seeds ha^{-1}. Past studies indicate that the agronomic optimum seeding rate (AOSR) for soybean in the north-central United States is variable. For May-planted soybean in Iowa and Ohio, AOSR has been observed to vary between 157,000 and 211,800 seeds ha^{-1} and 345,800 and 481,650 seeds ha^{-1}, respectively (Barker et al., 2017; De Bruin & Pedersen, 2008). In Wisconsin, seeding rates between 296,400 and 345,800 seeds ha^{-1} yielded similarly (Gaspar et al., 2015). In a regional study, the AOSR for the Midwest was 365,000 seeds ha^{-1} (Gaspar et al., 2020). The seeding rate value selected in the CI tree analysis is likely near or in excess of the AOSR for each TED given past seeding rate studies, so the lower yield in fields with higher seeding rates in TEDs 7, 8, and 10 was likely due at least in part to high seeding rate and not just an artifact of farmers selecting higher seeding rates for fields with lower yield potential. Fields in these TEDs had similar use of tillage, foliar fungicide, foliar insecticide, and seed treatment regardless of seeding rate.

Foliar fungicides were associated with increased yield in early-planted fields in two TEDs (3 and 9) and late-planted fields in one TED 6. In TED 6 where foliar fungicide was associated with higher yields in late-planted fields, it was only in minimally tilled fields. Minimally tilled fields yielded less than intensively tilled fields, but foliar fungicide helped recover part of the difference in yield between tillage regimes in late-planted fields.

This dataset did not include information on scouting practices or insect and disease pressure. Since insect and pathogen pressure vary annually, the association between greater yields and pesticide application could change among growing seasons. It is recommended to follow state guidelines for insect and disease management based on an integrated pest management (IPM) approach. Prophylactic applications of foliar insecticide and fungicide are not recommended as they are generally not associated with an economic benefit (Bluck, Lindsey, Dorrance, & Metzger, 2015; Mourtzinis, Marburger, Gaska, & Conley, 2016; Ng, Lindsey, Michel, & Dorrance, 2018). Similarly, prophylactic use of fungicide- and/or insecticide-treated seed does not provide a consistent economic benefit for different combinations of consequential management practices, such as seeding rate (Mourtzinis et al., 2019a). Market prices and pest pressure both play an important role in determining where insecticide and fungicide applications are likely to be profitable (Gaspar et al., 2015).

Among late-planted fields, management factors that were associated with soybean seed yield within several TEDs included herbicide application timing (TEDs 2, 5, and 10) and tillage intensity (TEDs 6 and 8). Response to herbicide could be related to delayed planting resulting in the soybean canopy fully closing later in the growing season, and in some cases, never completely closing (Steele & Grabau, 1997). Full canopy closure is necessary to minimize weed pressure, especially from weeds with an extended emergence period, such as Palmer amaranth (*Amaranthus palmeri* S. Wat.) (Hock, Knezevic, Martin, & Lindquist, 2005; Jha & Norwsorthy, 2009). Of total Palmer amaranth germination throughout the growing season, more than 90% occurred prior to soybean canopy closure (Jha & Norsworthy, 2009). In TED 5, herbicide timing was associated with increase yield only when medium or narrow rows were used.

Management decisions that best correlated with soybean yield differed between early- and late-planted fields in every TED. In TED 4, RM was the decision most strongly associated with yield for both early- and late-planted fields; however, in early-planted fields longer RMs yielded better, whereas in late-planted fields the opposite was true. The management decision best correlated with yield was seeding rate for both early- and late-planted fields in TED 7, but the binary split occurred at different seeding rates.

In TED 2, starter P was associated with lower yield and in TED 6, artificial drainage was associated with lower yield. This could be due to treatments being selected by producers for specific fields, not randomly applied. Producers likely applied starter P or installed artificial drainage on fields with lower yield potential due to known fertility or drainage issues, respectively. The decrease in yield at higher seeding rates observed in early-planted soybean in TEDs 7, 8, and 10 and late-planted soybean in TED 7 could be due to producers selecting higher rates for fields with lower yield potential, since lower yield potential areas have higher agronomic optimum plant densities (Carciochi et al., 2019).

5 | CONCLUSIONS

The challenges associated with treatments being nonrandomly assigned to fields and applied in combination were outweighed by the effectiveness of survey data collection. Surveys allowed for data to be collected on 16 different management factors applied in varying combinations across 10 different states over three growing seasons. Small plot research studying a similar number of treatments and combinations in multiple environments would be cost prohibitive. Conditional inference trees did not identify all potentially significant decisions, but were useful for identifying interactions among management decisions, such as herbicide and row width in late-planted fields in TED 5 or tillage and foliar fungicide in late-planted fields in TED 6. Since producers used a combination of management decisions on each field, identifying interactions was important for this work.

Across all TEDs, early-planted soybean fields yielded higher than late-planted soybean fields. Our results showed no single management factor was responsible for higher yields across TEDs and planting windows, thus decisions need to be both region and planting date specific. These results confirm the importance of and continued need for locally driven data and IPM practices from which research-based best management practices can be developed. Our results also suggest the use of producer survey data can complement and expand the interpretative reach of in-field replicated research.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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