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Dynamics of corn dry matter content and grain quality after physiological maturity

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Abstract

Delayed corn (*Zea mays* L.) harvest after physiological maturity (PM) is a universal practice in the U.S. Corn Belt to reduce grain drying cost. However, corn yield is speculated to be lost due to kernel dry matter loss from seed respiration. We evaluated the impact of in-field dry down on corn dry matter content and grain quality after PM at two locations in Iowa during 2016 and 2017. Each site-year consisted of two planting dates and three hybrids where ears were collected six to eight times from PM to harvest. Regardless of site-year and hybrid, grain moisture decreased and test weight increased linearly with harvest dates and plateaued, on average, at 118 g kg^{-1} moisture and 752 kg m^{-3} test weight. Test weight was strongly associated with grain moisture. The standard test weight of 722 kg m^{-3} coincided with calendar dates around the first to second week of October. Kernel weight was unchanged and ear loss from lodging was minimal across harvest dates but differed among hybrids for each harvest date. These differences were not influenced by hybrid relative maturity (RM). Grain protein, oil, and starch concentrations were almost unchanged between PM and harvest though they were affected by the main and/or interaction effects between harvest dates and hybrids for most site-years. Results suggest that corn can be harvested at any time after PM without any dry matter and quality penalties and harvest should be done based on grain moisture and standard test weight to minimize in-field grain loss.

1 | INTRODUCTION

"Mystery yield loss, phantom yield loss, or invisible yield loss", are the terms used in popular press articles to describe corn yield loss due to delayed harvest after reaching PM (Finck, 1995; PFN, 1995; Vogel, 1984). These concepts of yield losses were first reported in research by Nielsen, Brown, Wuethrich, and Halter (1996) in Indiana from 1991 to 1994. They documented about 1% dry matter loss for every 1% decrease in corn grain moisture from 280 to 180 g kg^{-1} (28 to 18%) after PM. Since Nielsen et al. (1996), there have been a few attempts to verify this phenomenon resulting in inconsistent results (Elmore & Roeth, 1999; Pordesimo, Saxton, Paul, & Belm, 2006; Thomison, Mullen, Lipps, Doerge, & Geyer, 2011).

Many farmers and retail seed salespersons who experienced corn yield losses due to delayed harvest attest in popular farm press yield losses up to 1255 kg ha^{-1} due to delayed harvest from PM [~300 g kg^{-1} grain moisture] to harvest maturity [~150 g kg^{-1} grain moisture] (ISA, 2015).

Abbreviations: PM, physiological maturity; RM, relative maturity.

Some of these claims indicate that the yield loss occurs within a very short period of 1 to 2 wk (250 to 180 g kg^{-1} grain moisture). If this amount of yield loss occurs, it would be more economical to dry corn mechanically. According to ISA (2015), a 1255 kg ha^{-1} yield loss equates to US$173 ha^{-1} while it only costs $133 ha^{-1} to remove 100 g kg^{-1} (10%) grain moisture; indicating a net $40 ha^{-1} loss due to field drying and reinforcing a need to install a high-speed drying system to dry high moisture (260 to 280 g kg^{-1}) corn. However, installing a drying system requires a major capital investment and thus needs research-based justification.

Delaying corn harvest after PM is a universal management strategy in the Corn Belt to reduce grain drying cost. Several studies evaluated the effects of delayed harvest on corn yield across a wide range of geographical regions, where some results are positive and others are negative with no consistency over the years. Nolte, Byg, and Gill (1976) reported that corn yield losses increase from 10 to 40 kg ha^{-1} d^{-1} delay in harvest after 260 g kg^{-1} grain moisture. According to USDA research in the 1970s in Illinois, Indiana, Iowa, and Nebraska, corn harvest losses increased from 5% in October to 18% in December (Hoeft, Nafziger, Johnson, & Aldrich, 2000). Bruns and Abbas (2004) found no yield loss with delayed harvest in 2000, but 15% loss between the first and last harvests in 2001. Knittle and Burris (1976) found no change in kernel dry matter of four hybrids across six harvest dates at two locations when grain moisture decreased from 500 to 120 g kg^{-1}. Several other researchers found similar results of no dry matter loss as grain moisture decreased from 600 to 90 g kg^{-1} (Brooking, 1990; Elmore & Roeth, 1999; Hunter, TeKrony, Miles, & Egli, 1991; Paszkiewicz et al., 1996; Pordesimo et al., 2006). Most recently, Thomison et al. (2011) investigated corn dry matter response to harvest date, plant population, and hybrid in Ohio and concluded that delayed harvest between October and November did not cause any yield reduction, but further delay in harvest after November caused significant yield loss.

The yield loss from delayed harvest was reported to be attributed to seed physiological processes, agronomic management, environmental conditions, disease pressures, and corn genetics. Seed respiration was thought to be the possible cause of corn yield loss across harvest dates (Finck, 1995; PFN, 1995). However, their cause of yield loss failed to support the findings of many studies (Knittle & Burris, 1976; Saul & Steele, 1966; Seitz, Sauer, Mohr, & Aldis, 1982). Seed respiration is a metabolic process of retrieving stored energy and C by using oxygen and releasing CO_2. Knittle and Burris (1976) found that seed respiration rate reduced dramatically from 35 d after silking (490 g kg^{-1} grain moisture) to 80 d after silking (250 g kg^{-1} grain moisture) from 3.05 to 1.08 μL O_2 min^{-1} g^{-1} and was not significant from 80 to 95 d after silking (167 g kg^{-1} grain moisture; 0.85 μL O_2 min^{-1} g^{-1}). Additional research on kernel dry matter loss in storage environment documented only 1% dry matter loss in 10 to 50 d for 230 to 280 g kg^{-1} moisture corn (Saul & Steele, 1966; Seitz et al., 1982); this dry matter loss was mainly due to storage fungi, not seed respiration. These results suggest that dry matter loss would be minimal during the field drying period in the Corn Belt with a typical average air temperature of 13 to 18°C in late September and 10 to 15°C in early October.

Core Ideas

- In-field dry down does not affect corn dry matter after physiological maturity.
- Corn yield can be lost due to lodging and ear drop after physiological maturity.
- Harvest corn above 200 g kg^{-1} grain moisture before in-field losses increase.

Stalk lodging, disease development, insect feeding, or harvest loss were also reported as possible causes of corn yield loss due to delayed harvest. Heavy rainfall with high wind frequently causes stalk lodging. Fungal stalk rots in the Corn Belt during harvest can also cause extensive stalk lodging (Lipps, Dorrance, & Mills, 2004; White, 1999). Delayed harvest further magnifies corn stalk rot, resulting in severe yield loss and slows down harvest operations. Thomison et al. (2011) reported corn yield loss from December harvest was due to lower stalk strength and greater stalk lodging. Several other researchers documented stalk lodging due to delayed harvest as a major factor contributing to corn yield losses (Allen, Musick, & Hollingsworth, 1982; Bruns & Abbas, 2004; Hoeft et al., 2000; Johnson, B.J., Henry, & Hall, 1963; Lauer, 2004; Nolte et al., 1976; Thomison et al., 2011). Allen et al. (1982) found 42% greater stalk lodging resulted in 30% yield loss when harvested at 150 g kg^{-1} grain moisture compared to 250 g kg^{-1} moisture. Nolte et al. (1976) suggested to harvest corn at 220 to 260 g kg^{-1} grain moisture to reduce harvest losses. They also found that stalk lodging increased around 5% wk^{-1} after mid-October in Ohio and one-third of lodged ears were missed by the combine head. In addition to stalk lodging, delayed harvest increases corn ear rot development and insect damage that can cause significant yield losses. ASABE (2014) estimated yield loss due to corn borer damage at about 0.33% d^{-1} delayed harvest after mid-October. However, the widespread use of bacillus thuringiensis corn has greatly reduced this problem.

Hybrid selection, one of the important farm management decisions farmers make each year, influences date of corn maturity and stalk lodging when harvested late (Minyo, Geyer, Thomison, Bishop, & Lohnes, 2008). The variation of corn yield response to delayed harvest in the literature was partly due to hybrid genetics and environmental conditions.

Nielsen et al. (1996) found all three hybrids showed significant dry matter loss due to delayed harvest in 3 of 4 yr. Paszkiewicz et al. (1996) found no change in kernel dry matter after PM for 14 of 18 hybrids in one study and 37 of 42 hybrids in another study. Hunter et al. (1991) found similar results of no kernel dry matter loss after PM for one hybrid in the first year and for three hybrids in second year.

Although several studies evaluated corn yield response to harvest dates, little is known regarding the impact of delayed harvest on corn grain quality. Cloninger, Horrocks, and Zuber (1975) investigated corn grain quality as affected by harvest dates in Missouri and reported that delayed harvest did not affect grain protein concentration but decreased oil concentration. Further evaluation of the dynamics of corn dry matter content and grain quality across harvest dates after PM for newer hybrids would help farmers select better hybrids for their environments in the Corn Belt. The objective of our research was to evaluate the impact of dry down period on corn dry matter content and grain quality after reaching PM. We hypothesized that dry matter content and grain quality would not be affected by delayed harvest regardless of hybrid and environment.

2 | MATERIALS AND METHODS

2.1 | Experimental site

A total of 4 site-years of research trials were conducted in Iowa during 2016 and 2017 at two research farms [Southeast Research Farm (41.20° N, 91.49° W), Crawfordsville and Northern Research Farm (42.93° N, 93.79° W), Kanawha] to evaluate the response of corn dry matter content and grain quality to harvest dates after reaching PM. The soil texture at Southeast Research Farm was Mahaska silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) in 2016 and Taintor silty clay loam (fine, smectitic, mesic Vertic Argiaquolls) in 2017 and at Northern Research Farm was Canisteo clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) in both 2016 and 2017. Soil

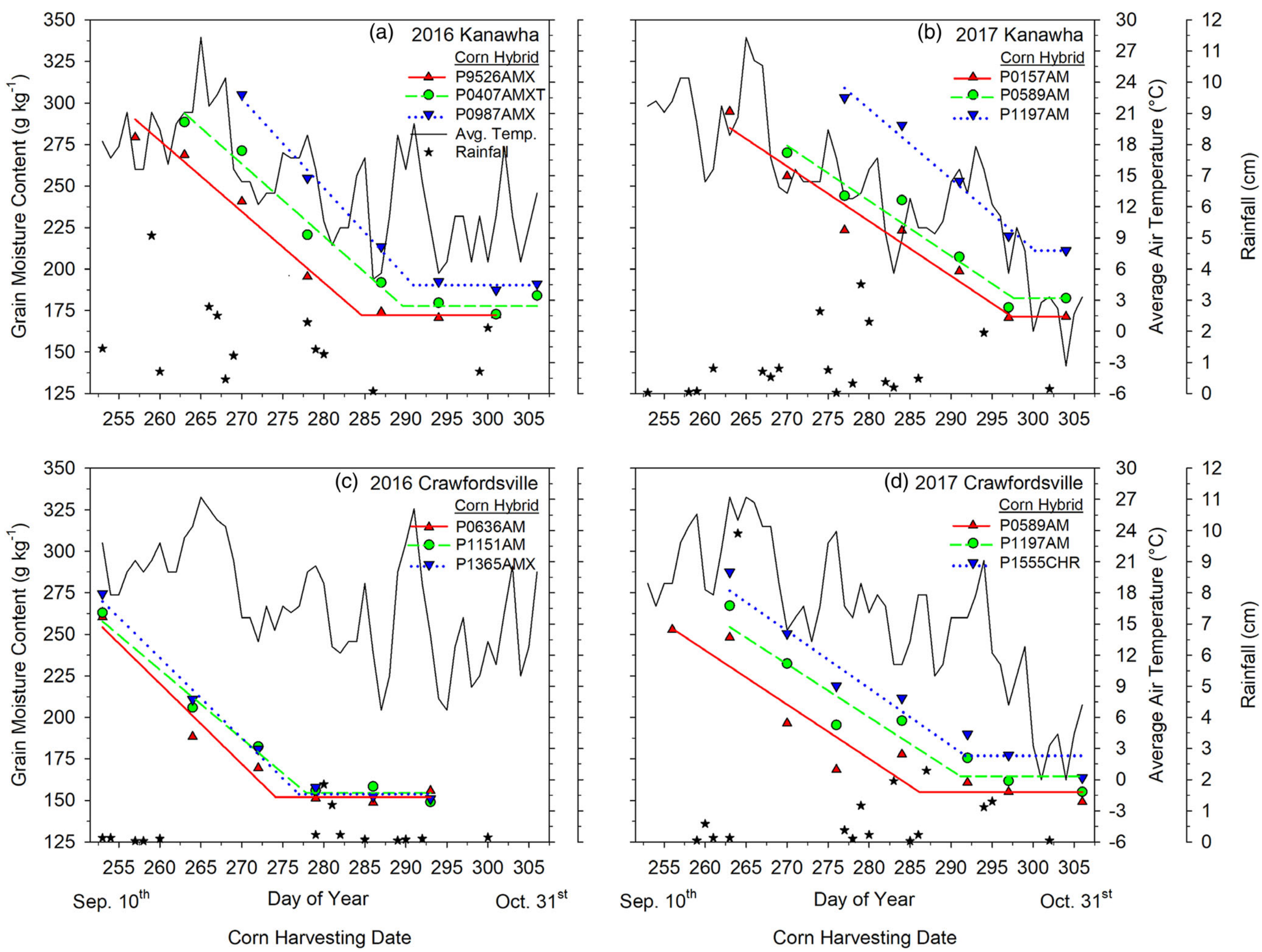

FIGURE 1 Corn grain moisture content across harvest date as predicted with linear-plateau models for research trials conducted at (a–b) Kanawha and (c–d) Crawfordsville, IA, in 2016 and 2017. Coefficients of linear-plateau models are listed in Table 2

TABLE 1 Planting date, corn hybrid with relative maturity (RM), and grain moisture content of the first harvest date for Kanawha and Crawfordsville, Iowa in 2016 and 2017

		Corn hybrid		First harvest	
			RM		Moisture
Site-year	Planting date	Name	d	Date	g kg^{-1}
Kanawha-2016	17 Apr.	P9526AMX	95	13 Sept.	279
		P0407AMXT	104	19 Sept.	289
		P0987AMX	109	26 Sept.	293
	18 May	P9526AMX	95	19 Sept.	276
		P0407AMXT	104	26 Sept.	286
		P0987AMX	109	26 Sept.	317
Kanawha-2017	17 Apr.	P0157AM	101	20 Sept.	277
		P0589AM	105	27 Sept.	270
		P1197AM	111	4 Oct.	289
	9 May	P0157AM	101	20 Sept.	313
		P0589AM	105	4 Oct.	261
		P1197AM	111	4 Oct.	317
Crawfordsville-2016	14 Apr.	P0636AM	106	9 Sept.	243
		P1151AM	111	9 Sept.	263
		P1365AMX	113	9 Sept.	275
	9 May	P0636AM	106	9 Sept.	283
		P1151AM	111	20 Sept.	229
		P1365AMX	113	20 Sept.	227
Crawfordsville-2017	13 Apr.	P0589AM	105	13 Sept.	253
		P1197AM	111	20 Sept.	267
		P1555CHR	115	20 Sept.	288
	16 May	P0589AM	105	20 Sept.	296
		P1197AM	111	27 Sept.	270
		P1555CHR	115	27 Sept.	278

drainage ranged from somewhat poorly drained to poorly drained (USDA-NRCS, 2019). The weather at both locations were characterized as a humid continental climate (i.e., large fluctuations of seasonal temperature with warm to hot summers and cold winters) with yearly average air temperature of 9°C, during crop harvesting period (9 September–2 November; Figure 1).

2.2 | Experimental design and crop management

Each experiment was designed as a split-plot with four replications where the main plot was planting date and the subplot was hybrid. There were two planting dates and three hybrids from different RM at each site (Table 1). We included two planting dates to achieve two different in-field dry down environments for each hybrid. Corn was planted after soybean [*Glycine max* (L.) Merr.] in 76-cm row spacing with 86,450 seeds ha^{-1}. Each experimental plot was 13.7-m long by 4.6-m wide. Each site was rainfed. Pest management and P and K applications at each site followed Iowa State University Extension recommendations (Abendroth et al., 2009; Mallarino et al., 2013). Nitrogen applications were made at 168 kg N ha^{-1}.

2.3 | Experimental treatment and data collection

Seven consecutive corn ears were hand harvested in 7 d intervals for six to eight harvest dates starting when grain moisture was at 227 to 317 g kg^{-1} (22.7–31.7%), depending on site-year. Ear collection was targeted to start at PM around 300 g kg^{-1} moisture and end at mechanical harvest near 150 g kg^{-1} moisture. However, we were unable to start ear collection at our target grain moisture for several hybrids of all 4 site-years due to rainfall events during PM (Table 1, Figure 1). There were eight rows per plot and ears were collected from a row adjacent to the center four yield rows.

The mechanical harvest yield rows were the center four rows. After collecting the first sample, seven consecutive ears were skipped before collecting the next set of ears for subsequent sampling. The harvest dates ranged from 13 September to 2 November in 2016 and 9 September to 13 November in 2017. The first harvest date with grain moisture for each site-year is listed in Table 1. At each harvest date, preharvest ear loss due to stalk lodging was estimated by evaluating 100 stalks with ears adjacent to the harvest area and assumed 1% preharvest ear loss was equal to one ear within 30 cm of the ground. Among the seven sampled ears from each harvest date, two ears were selected randomly, hand shelled, and tested for grain moisture and test weight at harvest. The remaining five ears were dried, hand shelled, weighed, and tested for grain moisture. Grain moisture was determined using the AM5200 (Perten, Sweden) and GAC2500 (DICKEY-john, Auburn, IL) moisture meters, which are calibrated by the USDA Agricultural Marketing Service. Each grain sample was analyzed three times per meter and the grain moisture was determined as the average of the six tests. Individual kernel weight was determined from weighing and drying 1000 kernels. Kernel weight was adjusted to 150 g kg^{-} moisture. Grain composition, such as protein, oil, and starch, was determined with an Infratec 1241 (Foss Analytics, Denmark) analyzer calibrated at the Iowa State University Grain Quality Laboratory. The calibrations [identified as CN201301(2,3,4)] apply to the Foss Infratec transmission analyzers. The calibration process was described by Rippke et al. (1996) and was subsequently the basis for the standard method of the American Association of Cereal Chemistry (AACC, 1999).

2.4 | Statistical analysis

All variables were analyzed separately by site-year due to having different corn hybrid at each site-year. Grain moisture and test weight were regressed against day of year using a linear-plateau model with the NLIN procedure of SAS (v9.4, SAS Inst., Cary, NC). To characterize the relationship between grain moisture content and test weight, test weight was regressed against moisture content using the MIXED procedure of SAS that considered corn hybrid as fixed effect and planting dates and replication as random effect. Although the planting dates were included in our experiment to get different in-field dry down environments for each hybrid, we found no effect of planting date on any measured variable and therefore, we used planting date as random variable in our statistical model. The same MIXED procedure was used to separately regress kernel weight, ear drop due to stalk lodging, and grain protein, oil, and starch concentrations against the day of year. All the MIXED models were initially run with both linear and quadratic terms of moisture content for test weight or day of year separately for kernel weight, ear drop due to stalk lodging, and grain protein, oil, and starch concentrations and their interaction with corn hybrid. Each MIXED model for each dependent variable was refined by eliminating the most complex nonsignificant model terms at the 0.10 probability level until the simplest model with all the significant ($P < 0.10$) model terms was obtained. The linear model for each dependent variable was selected only when the quadratic model was not significant ($P > 0.10$). The studentized residual distribution (←3.0 and >3.0) was used for every model to identify outliers and the model was rerun by excluding the outliers when there was a problem in field or recording data.

3 | RESULTS AND DISCUSSION

3.1 | Grain moisture content and test weight

We targeted to harvest corn beginning at PM (about 300 g kg^{-1} grain moisture; Table 1). The grain moisture for the first harvest was, on average, 290 g kg^{-1} in 2016 and 288 g kg^{-1} in 2017 at Kanawha and 253 g kg^{-1} in 2016 and 275 g kg^{-1} in 2017 at Crawfordsville. Regardless of hybrid and site-year, grain moisture decreased linearly with harvest dates from PM and plateaued near harvest maturity (Figure 1). However, the rate of decline and plateau moisture content for each site-year varied with hybrid. Hybrids with the longest RM generally had higher grain moisture across harvest dates and reached the plateau moisture level later than other hybrids. Grain moisture content declined, on average, at 4.66 g kg^{-1} d^{-1} in 2016 and 3.61 g kg^{-1} d^{-1} in 2017 at Kanawha and 4.61 g kg^{-1} d^{-1} in 2016 and 3.31 g kg^{-1} d^{-1} in 2017 at Crawfordsville. The mean grain moisture when dry down stopped in Kanawha was at 180 and 188 g kg^{-1} in 2016 and 2017, respectively, and in Crawfordsville was at 153 and 165 g kg^{-1} in 2016 and 2017, respectively (Table 2). This occurred in mid- to late October in Kanawha and early- to mid-October in Crawfordsville.

The average air temperature and rainfall pattern during the grain dry down period suggests that air temperature influenced grain moisture content, but rainfall had no or minimal effect on the dynamics of grain moisture content. Kanawha is located in the northern Iowa and Crawfordsville is in southeastern Iowa and, therefore, October air temperatures were slightly lower in Kanawha than Crawfordsville. During October, air temperature >12°C at Crawfordsville was sufficient to dry corn grain below 160 g kg^{-1} moisture and conversely, air temperature <12°C at Kanawha were responsible for grain dry down ceasing above 180 g kg^{-1}. Our results of faster grain moisture decline immediately after PM and no or slower decline toward maturity were also observed by Elmore and Roeth (1999). Similar to our results, Elmore and Abendroth (2007) and Nielsen (2018) reported

TABLE 2 Coefficients of the linear-plateau model for predicting grain moisture content (MC, g kg^{-1}) and test weight (TW, kg m^{-3}) of different corn hybrids across harvest dates (day of year, DOY) for research trials conducted at Kanawha and Crawfordsville, IA, in 2016 and 2017

		Model[a] coefficient			Join point	
					DOY	MC or TW
Site-year	Corn hybrid	Intercept	Linear	R^2	d	g kg^{-1} or kg m^{-3}
Grain moisture content						
Kanawha-2016	P9526AMX	1387.3	–4.269	0.90	284.6	172.4
	P0407AMXT	1439.5	–4.356	0.93	289.6	177.8
	P0987AMX	1751.3	–5.366	0.94	290.9	190.3
Kanawha-2017	P0157AM	1153.6	–3.303	0.86	297.4	171.4
	P0589AM	1172.6	–3.327	0.81	297.6	182.5
	P1197AM	1475.5	–4.211	0.78	300.2	211.1
Crawfordsville-2016	P0636AM	1479.5	–4.843	0.86	274.1	151.9
	P1151AM	1309.7	–4.158	0.84	277.9	154.5
	P1365AMX	1495.1	–4.843	0.90	277.0	153.7
Crawfordsville-2017	P0589AM	1089.4	–3.265	0.63	286.1	155.0
	P1197AM	1094.7	–3.195	0.60	291.1	164.5
	P1555CHR	1186.0	–3.459	0.65	291.7	176.9
Grain test weight						
Kanawha-2016	P9526AMX	–233.5	3.417	0.71	280.8	725.9
	P0407AMXT	–372.7	3.911	0.89	288.6	756.1
	P0987AMX	–288.7	3.595	0.89	293.4	766.3
Kanawha-2017	P0157AM	–25.5	2.650	0.87	297.8	763.7
	P0589AM	–279.6	3.467	0.84	297.0	749.9
	P1197AM	126.7	2.011	0.61	–[b]	–[b]
Crawfordsville-2016	P0636AM	–764.1	5.635	0.39	264.0	723.4
	P1151AM	–408.9	4.221	0.45	274.1	747.9
	P1365AMX	–1015.9	6.696	0.72	265.7	763.5
Crawfordsville-2017	P0589AM	–8.5	2.629	0.58	286.3	744.3
	P1197AM	–151.7	3.127	0.61	287.4	747.2
	P1555CHR	–65.4	2.870	0.79	296.1	784.3

[a]MC or TW = intercept + (linear slope × DOY). All models were significant at the <0.001 probability level.
[b]The plateau portion of linear-plateau model was absent within the harvest dates.

5 and 4 g kg^{-1} d^{-1}, respectively, decline of grain moisture following PM. Although southern Iowa farmers can expect more in-field dry down than northern farmers, field dry down after early- to mid-October would be very minimal.

Grain test weight increased linearly following PM with a linear-plateau trend regardless of site-year and corn hybrid (Figure 2a–2d). Like moisture content, the rate of increase and plateau test weight varied among hybrids. In general, test weight was greater for the longer RM hybrid. Test weight increased, on average, at 3.64 kg m^{-3} d^{-1} from 9 to 21 Oct. 2016 and 2.71 kg m^{-3} d^{-1} from 24 to 25 Oct. 2017 at Kanawha and 5.52 kg m^{-3} d^{-1} until 22 Sept. to 2 Oct. 2016 and 2.88 kg m^{-3} d^{-1} until 13 to 23 Oct. 2017 at Crawfordsville (Table 2). Grain test weight plateaued at approximately 726 to 766 kg m^{-3} at Kanawha and 723 to 784 kg m^{-3} at Crawfordsville except for hybrid P1197AM in 2017 at Kanawha.

The relationship between grain moisture and test weight was strongly correlated for every site-year and hybrid (Figure 2e–2h). Grain moisture explained 89 to 92% of the variability of grain test weight at Kanawha and 70 to 80% at Crawfordsville (Table 3). Test weight increased quadratically with a decrease of grain moisture for both 2016 and 2017 at Kanawha (Figure 2e–2f) and for 2016 at Crawfordsville (Figure 2g) and linearly for 2017 at Crawfordsville (Figure 2h). According to USDA-GIPSA (1996), the minimum allowable test weight for No. 1 yellow dent corn in the United States is 722 kg m^{-3} at 155 g kg^{-1} moisture. This standard test weight corresponded with 180 to 230 g kg^{-1} grain moisture on 1 to 15 Oct. 2016 and 205 to 235 g kg^{-1} moisture on 12 to 20 Oct. 2017 at Kanawha and 205 to 245 g kg^{-1} moisture on 18 to 23 Oct. 2016 and 185 to 245 g kg^{-1} moisture on 1 to 14 Oct. 2017 at Crawfordsville (Figure 2).

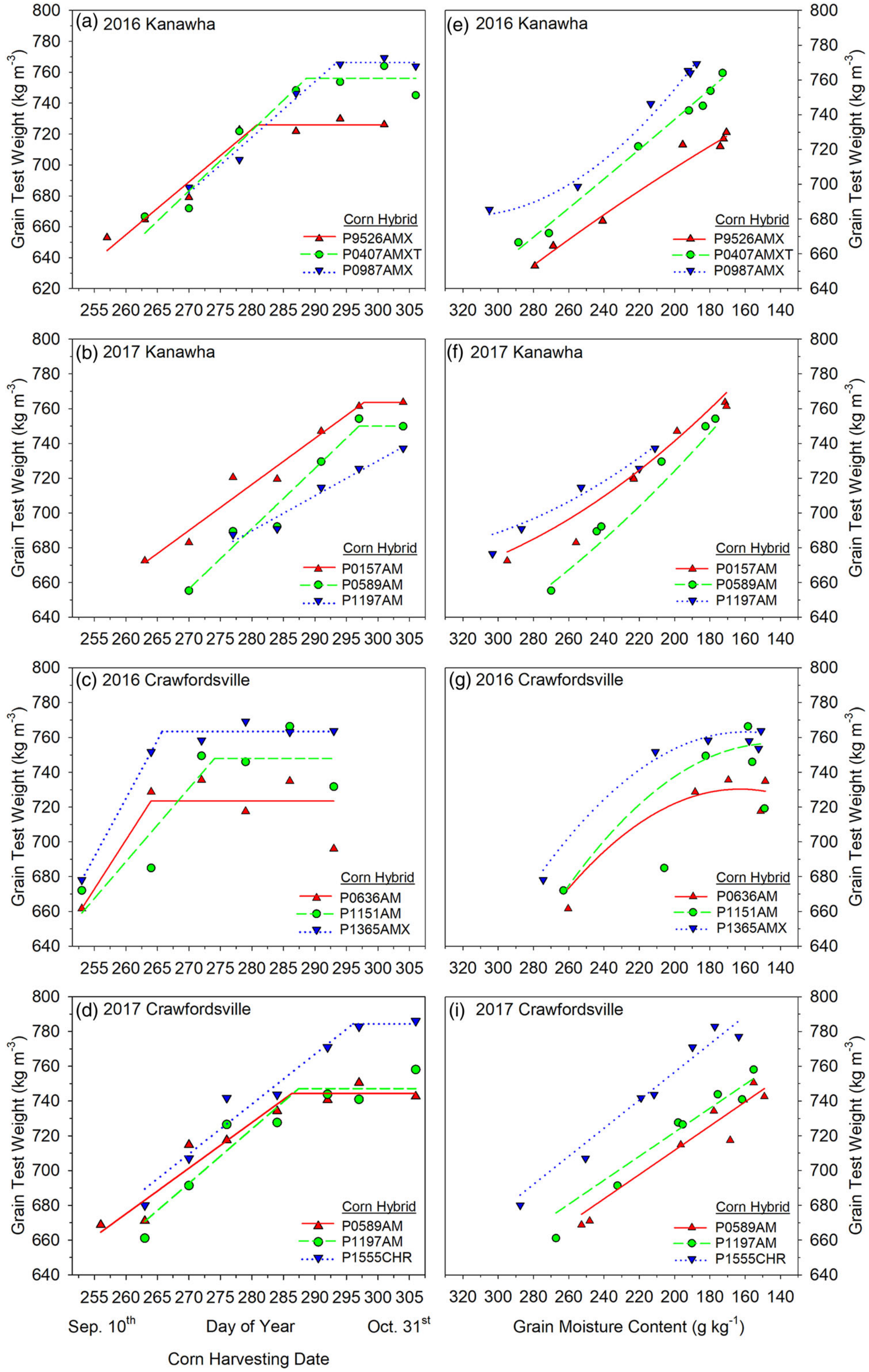

FIGURE 2 Corn (a–d) grain test weight across harvest date as predicted with linear-plateau models and (f–g) the relationship between corn grain test weight and moisture content as predicted with polynomial models for research trials conducted at Kanawha and Crawfordsville, IA, in 2016 and 2017. Coefficients of linear-plateau and polynomial models are listed in Tables 2 and 3, respectively

TABLE 3 Coefficients of the polynomial model for predicting grain test weight of different corn hybrids across grain moisture content and kernel weight, ear drop due to stalk lodging, and grain protein, oil, and starch concentrations across harvest dates for research trials conducted at Kanawha and Crawfordsville, Iowa in 2016 and 2017

		Polynomial model[a] coefficients				
Site-year	**Corn hybrid**	**Intercept**	**Linear**	**Quadratic**	R^2	***P*-value**
Grain test weight						
Kanawha-2016	P9526AMX	808.93	–0.3540	0.00072[b]	0.92	<0.001
	P0407AMXT	919.87	–0.9608	–0.00024[b]		
	P0987AMX	1201.97	–3.2548	–0.00509		
Kanawha-2017	P0157AM	1006.64	–1.7704	–0.00222	0.89	<0.001
	P0589AM	1006.64	–1.7704	–0.00179		
	P1197AM	1006.64	–1.7704	–0.00237		
Crawfordsville-2016	P0636AM	569.57	1.9734	0.00606	0.70	<0.001
	P1151AM	631.53	1.7408	0.00606		
	P1365AMX	608.49	1.9360	0.00606		
Crawfordsville-2017	P0589AM	851.19	–0.6977	–	0.80	<0.001
	P1197AM	860.05	–0.6901	–		
	P1555CHR	918.08	–0.8074	–		
Kernel weight						
Kanawha-2016	P9526AMX	0.32	0.0001[b]	–	0.10	0.003
	P0407AMXT	0.31	0.0001[b]	–		
	P0987AMX	0.31	0.0001[b]	–		
Kanawha-2017	P0157AM	0.29	0.0002[b]	–	0.75	<0.001
	P0589AM	0.29	0.0002[b]	–		
	P1197AM	0.37	0.0002[b]	–		
Crawfordsville-2016	P0636AM	0.30	–0.0001[b]	–	0.07	0.031
	P1151AM	0.30	–0.0001[b]	–		
	P1365AMX	0.32	–0.0001[b]	–		
Crawfordsville-2017	P0589AM	0.24	0.0002[b]	–	0.43	<0.001
	P1197AM	0.29	0.0002[b]	–		
	P1555CHR	0.26	0.0002[b]	–		
Ear drop[c]						
Kanawha-2016	P9526AMX	299.67	–2.2384	0.00419	0.56	<0.001
	P0407AMXT	310.57	–2.2807	0.00419		
	P0987AMX	270.68	–2.1361	0.00419		
Crawfordsville-2016	P0636AM	–38.06	0.1890	–	0.13	<0.001
	P1151AM	–28.01	0.1890	–		
	P1365AMX	–43.56	0.1890	–		
Crawfordsville-2017	P0589AM	121.28	–0.8919	0.00164	0.45	<0.001
	P1197AM	124.74	–0.9046	0.00164		
	P1555CHR	113.95	–0.8649	0.00164		
Grain protein concentration						
Kanawha-2016	P9526AMX	85.14	–0.0146[b]	–	0.30	<0.001
	P0407AMXT	81.09	–0.0146[b]	–		
	P0987AMX	80.27	0.0146[b]	–		
Kanawha-2017	P0157AM	548.70	–3.3264	0.00594	0.30	<0.001
	P0589AM	544.98	–3.3264	0.00594		
	P1197AM	550.38	–3.3264	0.00594		

(Continues)

TABLE 3 (Continued)

Site-year	Corn hybrid	Polynomial model[a] coefficients Intercept	Linear	Quadratic	R^2	*P*-value
Crawfordsville-2016	P0636AM	–352.79	3.1000	–0.00555	0.36	<0.001
	P1151AM	–346.50	3.1000	–0.00555		
	P1365AMX	–345.59	3.1000	–0.00555		
Crawfordsville-2017	P0589AM	–220.70[b]	2.0877	–0.00363	0.14	<0.001
	P1197AM	118.85[b]	–0.3274[b]	0.00064[b]		
	P1555CHR	–728.64	5.5974	–0.00968		
Grain oil concentration						
Kanawha-2016	P9526AMX	140.75	–0.7510	0.00130	0.82	<0.001
	P0407AMXT	147.06	–0.7510	0.00130		
	P0987AMX	146.13	–0.7510	0.00130		
Kanawha-2017	P0157AM	–	–	–	–	0.193[d]
	P0589AM	–	–	–		
	P1197AM	–	–	–		
Crawfordsville-2016	P0636AM	32.97	–0.0013[b]	–	0.57	<0.001
	P1151AM	37.63	–0.0013[b]	–		
	P1365AMX	39.16	–0.0013[b]	–		
Crawfordsville-2017	P0589AM	36.70	0.0032[b]	–	0.44	<0.001
	P1197AM	36.53	0.0032[b]	–		
	P1555CHR	39.04	0.0032[b]	–		
Grain starch concentration						
Kanawha-2016	P9526AMX	–	–	–	–	0.207[d]
	P0407AMXT	–	–	–		
	P0987AMX	–	–	–		
Kanawha-2017	P0157AM	1424.08	–4.9726	0.00886	0.29	<0.001
	P0589AM	1427.65	–4.9726	0.00886		
	P1197AM	1420.68	–4.9726	0.00886		
Crawfordsville-2016	P0636AM	293.95	3.2355	–0.00584	0.55	<0.001
	P1151AM	279.02	3.2355	–0.00584		
	P1365AMX	281.17	3.2355	–0.00584		
Crawfordsville-2017	P0589AM	1133.39	–2.7533	0.00483	0.18	0.001
	P1197AM	1162.29	–2.9353[b]	0.00509[b]		
	P1555CHR	2132.04	–9.7278	0.01698		

[a]Linear model equation, $y = z + ax$ and quadratic model equation, $y = z + ax + bx^2$; where y, grain test weight, kernel weight, and grain protein, oil, and starch concentrations; x, grain moisture content for grain test weight or day of year for kernel weight, and grain protein, oil, and starch concentrations; z, intercept; a, linear coefficient; and b, quadratic coefficient.

[b]Model coefficients are not significantly different than zero at the 0.10 probability level.

[c]No ear drop due to stalk lodging data were collected at Kanawha in 2016.

[d]The overall model is not significant at the 0.10 probability level.

Grain test weight is an important indicator of grain quality and storability. The increase of corn test weight as grain approaches maturity and grain moisture decreases during dry down in our study was in agreement with the findings of Hicks (2004) and Bern and Brumm (2009). However, Cloninger et al. (1975) found an opposite trend of test weight declined about 6.4 kg m^{-3} from 1 October to 1 December.

3.2 | Individual kernel weight and percent ear drop

Individual kernel weight was unchanged across the harvest dates regardless of site-year and hybrid, but was different among hybrids at each harvest date (Figure 3a–3d, Table 3). This difference in kernel weight among hybrids was not influenced by hybrid RM. For example, hybrid P9526AMX

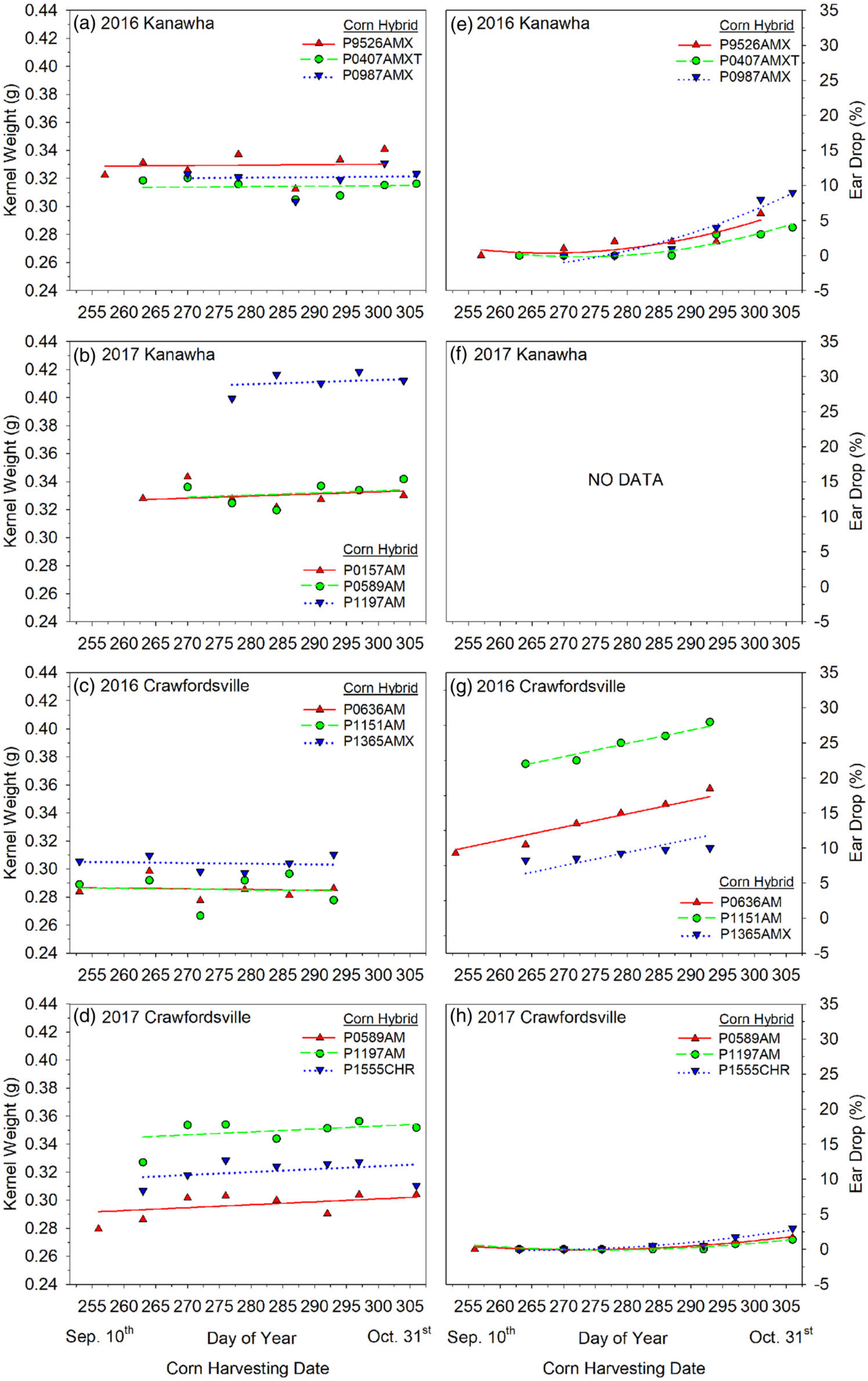

FIGURE 3 Corn (a–d) kernel weight and (e–h) ear drop due to stalk lodging across harvest date as predicted with polynomial models for research trials conducted at Kanawha and Crawfordsville, IA, in 2016 and 2017. Ear drop data were not collected at (f) Kanawha in 2017. Coefficients of polynomial models are listed in Table 3

with 95-d RM had a higher kernel weight than hybrid P0987AMX with 109-d RM in 2016 at Kanawha while hybrid P0407AMXT with 104-d RM had a lower kernel weight (Figure 3a). Kernel weight was higher for hybrids with the highest RM than other hybrids in 2017 at Kanawha and in 2016 at Crawfordsville (Figure 3b–3c, Table 1). In 2017, at Crawfordsville, corn hybrid kernel weights were in order of hybrid P1197AM (111-d RM) > hybrid P1555CHR (115-d RM) > hybrid P0589AM (105-d RM; Figure 3d). However, the actual corn yield at the final harvest was not affected by hybrid, averaging 8.20 Mg ha^{-1} at Kanawha and 11.44 Mg ha^{-1} at Crawfordsville (Baum, Archontoulis, & Licht, 2018).

Corn ear drop due to stalk lodging was affected by both harvest date and hybrid as well as their interaction depending on site-year (Figure 3e–3h, Table 3). Ear loss increased quadratically with delayed harvest in 2016 at Kanawha (Figure 3e) and in 2017 at Crawfordsville (Figure 3h) and linearly in 2016 at Crawfordsville (Figure 3g). The loss was minimal with delayed harvest over a 1-mo interval and ranged from 3 to 9% in 2016 at Kanawha and 6 to 9% in 2016 and 2 to 3% in 2017 at Crawfordsville. Ear loss was not measured in 2017 at Kanawha.

The effect of delayed harvest on corn yield and/or kernel weight has been studied by several researchers with somewhat inconsistent results. Some studies that mostly evaluated corn yield across harvest dates found significant yield loss due to delayed harvest (Allen et al., 1982; Bruns & Abbas, 2004; Hoeft et al., 2000; Lauer, 2004; Nolte et al., 1976; Thomison et al., 2011) and other studies that evaluated corn yield (Elmore & Roeth, 1999) or kernel weight (Brooking, 1990; Elmore & Roeth, 1999; Hunter et al., 1991; Knittle & Burris, 1976; Paszkiewicz et al., 1996; Pordesimo et al., 2006) found no change of corn yield or kernel weight across harvest dates. Our results were in agreement with the studies that investigated kernel weight. The no change of kernel weight across harvest dates for all hybrids but different kernel weight among hybrids for every harvest date in our study was supported by Elmore and Roeth (1999).

Researchers or popular press articles cited seed respiration (Finck, 1995; PFN, 1995) or stalk lodging (Allen et al., 1982, Thomison et al., 2011; Johnson et al., 1963; Nolte et al., 1976) as possible causes of yield loss, if any, due to delayed harvest. However, several researchers have proved that seed respiration is very minimal during the post maturity dry down period (Knittle & Burris, 1976; Saul & Steele, 1966; Seitz et al., 1982). Although we did not measure seed respiration, no loss of kernel dry matter content across harvest dates in our study along with several other studies (Brooking, 1990; Elmore & Roeth, 1999; Hunter et al., 1991; Knittle & Burris, 1976; Paszkiewicz et al., 1996; Pordesimo et al., 2006) signify that kernel respiration should not be a cause of corn yield loss due to delayed harvest. Stalk lodging, on the other hand, was shown to be a strong reason for yield loss due to delayed harvest and can cause up to 30% yield loss (Allen et al., 1982). Nolte et al. (1976) found approximately 5% stalk lodging wk^{-1} after mid-October in Ohio and Allen et al. (1982) found 42% greater stalk lodging at 150 g kg^{-1} grain moisture compared to 250 g kg^{-1} grain moisture. Our data indicated that ear drop to within 30 cm of the ground was increased by 7% over a month harvest window, although no measurement was attempted regarding the corn head's ability to gather these ears. Stalk lodging due to delayed harvest in our study was also dependent on genetics and environments, which was in agreement with Minyo et al. (2008) reported that corn hybrids affect maturity and stalk lodging when harvested late.

3.3 | Grain composition

Grain protein concentration was significantly influenced by both harvest dates and hybrids for all site-years (Figure 4a–4d, Table 3). Grain protein concentration for all three hybrids was unchanged across harvest dates in 2016 at Kanawha (Figure 4a). In the other site-years, protein concentration followed a quadratic trend across harvest dates with an initial decrease followed by an increase toward maturity in 2017 at Kanawha (Figure 4b) and an initial increase followed by a decrease toward maturity in 2016 (Figure 4c) and 2017 (Figure 4d) at Crawfordsville. There was no interaction effect between harvest dates and hybrids for all site-years (i.e., protein concentration was different among hybrids for every harvest date except in 2017 at Crawfordsville).

Grain oil concentration was significantly affected by harvest dates and hybrids for all site-years except at Kanawha in 2017. There was no interaction effect between harvest dates and hybrids (Figure 4e–4h, Table 3). Grain oil concentration was statistically unchanged across harvest dates regardless of response pattern (Figure 4g–4h). Grain starch concentration was not significantly influenced by either harvest date or hybrid in 2016 at Kanawha, but was affected by both the harvest date and hybrid in 2017 at Kanawha and in 2016 at Crawfordsville and by the interaction effects of harvest date and hybrid in 2017 at Crawfordsville (Figure 4i–4l, Table 3). Although grain starch concentration followed quadratic trend across harvest dates, there were slight differences in starch concentration between the first and last harvest dates.

Like kernel weight, corn hybrid RM had no influence on changes of grain quality across harvest dates. Although grain qualities responded differently across harvest dates among site-years, there was no or only slight changes of grain qualities from the first to the last harvest regardless of corn hybrid, which is expected. The reason for these different responses of grain qualities across harvest dates is unknown, but may be due to the artifact of the limited data points and/or sampling and processing errors. Literature regarding the effect

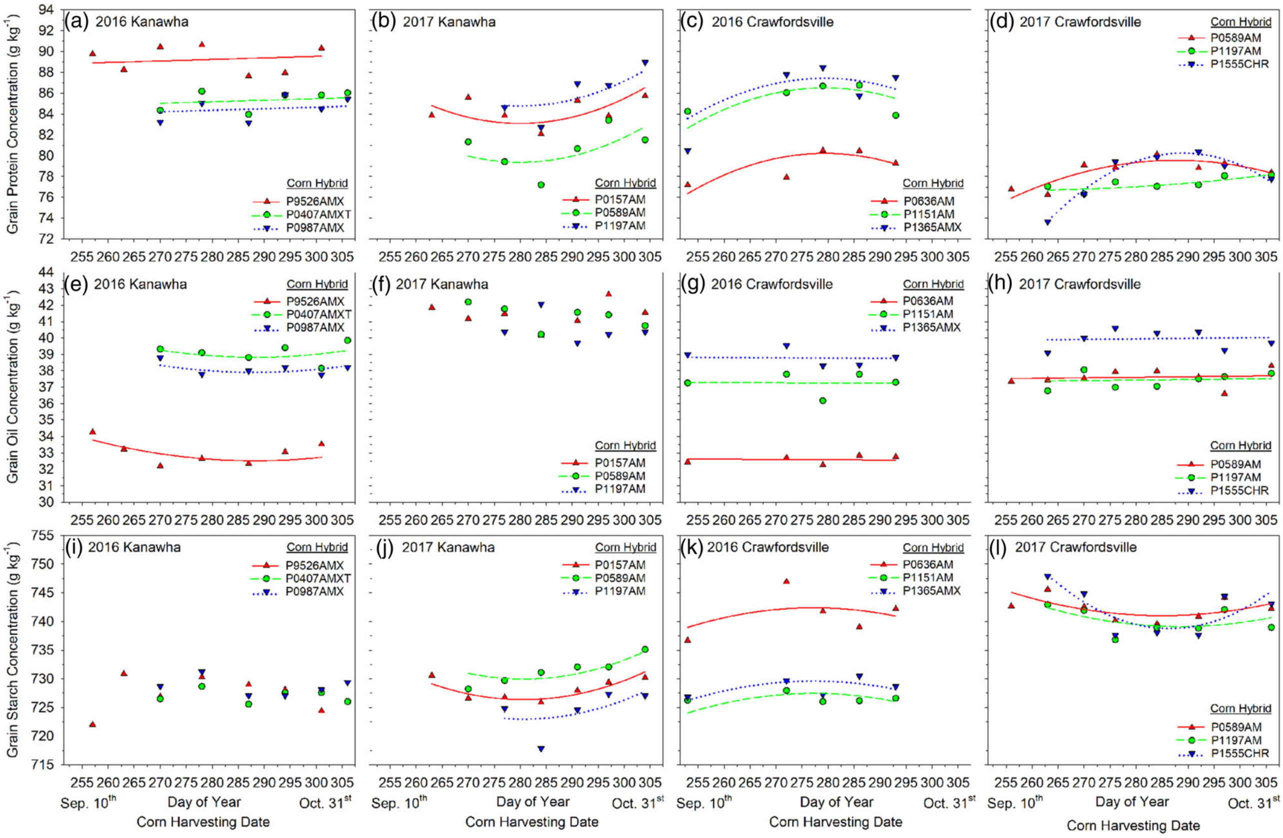

FIGURE 4 Corn grain (a–d) protein, (e–h) oil, and (i–l) starch concentrations across harvest date as predicted with polynomial models for research trials conducted at Kanawha and Crawfordsville, IA, in 2016 and 2017. Polynomial models for grain (f) oil and (i) starch concentrations across harvest date at Kanawha in 2016 and 2017, respectively are not significant at the 0.10 probability level. Coefficients of polynomial models are listed in Table 3

of harvest dates on corn grain quality are scarce. Cloninger et al. (1975) found that grain protein concentration remained unchanged but oil concentration decreased across harvest dates. They also found that both protein and oil concentrations varied among hybrids. Although we did not find any more literature related to our research for corn, literature documented that delayed harvest does not affect wheat (*Triticum aestivum* L.) protein concentration (Farrer, Weisz, Heiniger, Murphy, & Pate, 2006; Pool, Patterson, & Bode, 1958) and soybean protein and oil concentrations (Jaureguy et al., 2013). We did not find any information in the literature regarding the effect of delayed harvest on corn starch concentration.

4 | CONCLUSIONS

The response of corn dry matter content to harvest dates after PM is well documented. The dynamics of corn grain quality after PM has not yet been studied extensively. Our study provides new insight regarding the impact of post PM field dry down on grain quality along with kernel dry matter and ear losses. The results of our study were in agreement with most of the research illustrating no kernel dry matter loss after PM, but were different in showing minimal ear loss due to stalk lodging across harvest date. Our study also showed that grain composition should not be an issue of concern for delayed harvest after PM. Results support our hypothesis and suggest that corn can be harvested at any time after PM with the least possibility of any dry matter and grain composition penalties. However, harvest timing may need to begin prior to the second week of October in Iowa. This coincides with when air temperatures fall below 12°C and grain moisture content is below 170 g kg^{-1} and drying is less likely to occur. Overall, Corn Belt farmers drying their corn in-field may consider harvesting above170 g kg^{-1} grain moisture or before mid-October to avoid risk of kernel and ear losses caused by stalk lodging, ear drop, or ear shelling by the combine head.

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