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Can using polymer-coated seed reduce the risk of poor soybean emergence in no-tillage soil?☆

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ABSTRACT

Adoption of no-tillage in the northern Corn Belt has lagged behind other regions because of slow warming and drying of soils early in the spring coupled with a short growing season. Cold, wet soil can lead to seed damage resulting in poor stand establishment. Because of slow warming and drying, no-tilled soils are typically sown later than conventionally tilled systems thus often requiring the use of early maturing crop cultivars. Temperature-activated polymer seed coatings might allow soybean [*Glycine max* (L.) Merr.] to be sown earlier than normal under no-tillage while protecting seed against damage caused by cold, wet soil and perhaps allow the use of later maturing cultivars. These ideas were tested during 2005 and 2006 in west central MN on a Barnes loam no-tilled soil previously cropped in corn (*Zea mays* L.). Polymer-coated seed of a maturity group (MG) 0 and I soybean were sown as early as possible (early- to mid-April) and at an average recommended time (mid-May) for the study site. Only in 2005 did the polymer coating significantly increase emergence ($p < 0.0001$), where maximum emergence of early sown polymer-coated seed of the MG 0 and I cultivars was 51 and 35% greater than their uncoated counterparts. Conversely, for the average sowing date in 2006, under unusually dry conditions, the polymer coating slowed seedling emergence and reduced maximum emergence, although yield was not affected. Laboratory incubations confirmed that the germination delay of soybean caused by the polymer-coating increased by decreasing initial osmotic moisture potentials. The MG I soybean out yielded the earlier maturing cultivar in both years, but sowing date did not have a significant effect either year. Results indicate that temperature-activated polymer-coated seed may reduce the risk of poor stand establishment in no-tilled soil in instances where low soil temperatures cause seed to remain in the soil for an extended time before emerging.

1. Introduction

No-tillage in cropping systems has become a relatively common practice. No-tillage or reduced tillage practices prevent soil erosion (Lal et al., 2007) and can help conserve and/or build soil carbon and reduce CO_2 emissions (Al-Kaisi and Yin, 2005; Gesch et al., 2007). Reduced tillage can also lead to greater profitability in corn–soybean rotation systems (Buman et al., 2004; Archer and Reicosky, 2009). Yet, the adoption of no-tillage in the northern Corn Belt has lagged seriously behind other regions primarily because of the slow warming and drying of soils in early spring coupled with a short growing season. In west central MN, soil can remained covered in snow until mid-April or frozen until mid-May (Sharratt, 2002). Johnson and Lowery (1985) compared soil temperatures at depths from 5 to 15 cm for different tillage systems in Wisconsin and found that soil temperatures decreased with reduced tillage. They reported that daily average temperature was as much as 5.9 °C lower in no-tilled compared to moldboard plowed soil in early May. Because no-tillage soils take longer to warm they are often sown later, thus requiring earlier maturing crop cultivars that have less yield potential than later ones (Popp et al., 2002).

Timely establishment of crops such as corn and soybean, especially in regions with short growing seasons, is critical for maximizing seed yields. Moreover, sowing as early as possible optimizes the use of full-season crop cultivars (Torbert et al., 2001). However, sowing too early when soil temperatures are not conducive for good germination can lead to poor emergence and hence stand establishment. Increasing the time that seed or seedlings

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remain in the soil prior to emergence increases the occurrences of damage leading to death or decreased seedling growth rates (Shaw, 1977; Gesch and Archer, 2005). Sparse or uneven plant stands can reduce yields in crops such as corn (*Zea mays* L.) (Nafziger et al., 1991; Ford and Hicks, 1992), although soybean tends to be less affected (Egli, 1993) due to its yield plasticity (Egli, 1988). The optimum temperature range for soybean seed germination is about 25–35 °C with 10 and 40 °C being the lower and upper limits, respectively (Hatfield and Egli, 1974). Soil moisture in addition to temperature can be an important determinant of soybean emergence. As demonstrated by Helms et al. (1996), low soil water content at sowing for an extended period can significantly reduce soybean emergence, which is exacerbated by temperature stress.

A temperature-activated polymer coating has been developed for corn and soybean seed that offers the potential to allow for earlier than normal sowing and has been promoted for use in no-tillage systems (Hicks et al., 1996; Lessiter, 2000). Archer and Gesch (2003) reported that the use of polymer-coated seed for early sowing in MN could increase farm profits through reducing yield-loss due to late planting and increasing crop yields by the use of longer season cultivars. The seed coating is designed to restrict water entry by interaction of hydrophilic surface groups on the polymer until a critical temperature is reached, upon which these hydrophilic chains break-down and allow water to pass through the coating (Hicks et al., 1996). Thus, this technology could potentially protect seeds against damaged caused by extended exposure to cold wet soils allowing for early sowing (Watts, 1974; Zaychuk and Enders, 2001). Indeed, Gesch and Archer (2005) found that temperature-activated polymer-coated corn in west central MN could be sown as much as 4–5 weeks earlier than average without significantly sacrificing stand establishment. However, because the polymer coating delays germination and emergence, it may have negative consequences on plant stands, especially for soybean, if sown too late into warm soil (Sharratt and Gesch, 2008).

The objective of this study was to determine the effect of a temperature-activated polymer coating on emergence and yield of soybean sown as early as possible and at an average time in a no-tilled soil; and secondarily, to determine the potential to extend the maturity group (MG) of soybean grown for the region using ultra-early sown polymer-coated seed. In west central MN the average or normal time for sowing soybean is mid-May.

2. Materials and methods

2.1. Cultural practices

The study was conducted during 2005 and 2006 on a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) at the Swan Lake Research Farm located 24 km northeast of Morris, Minnesota (45°35′N, 95°54′W). The experimental design was a split plot randomized complete block with four replications. The main plots were planting date and the subplots consisted of cultivar by seed coating combinations. Individual plot size was 3 m × 7.6 m. Two different maturity group (MG) soybean cultivars were used in the study. An MG 0 cultivar (Croplan Genetics RT0874), which is characteristic of what is typically grown in west central MN, and a later maturing genotype, MG I (Croplan Genetics RC1812). Both cultivars were sown as early as possible in the spring and at an average or typical time based on recommended management practices for the region, which were April 6 and May 20 in 2005 and April 18 and May 16 in 2006. Polymer-coated and uncoated seed were sown at a population of 445,000 ha^{-1} on rows spaced 76 cm apart (four rows per plot) into no-tillage soil previously cropped in corn. The corn stalks were chopped to a height of about 10–15 cm prior to sowing soybean. The coatings were thin enough that they did not affect seed size or sowing. No fertilizer was added to the soil and a post-emergence application of N-(phosphonomethyl)glycine at 1.1 kg ai ha^{-1} was made for controlling weeds.

The temperature-activated polymer coating was made and applied by Intellicoat Corporation (a division of Landec Ag, Menlo Park, CA). Before coating, all seed were treated with mixture of Rival (*N*-(trichloromethylthio)cyclohex-4-ene-1,2-dicarboximide + 2-(4′-thiazolyl)benzimidazole + pentachloronitrobenzene), and RTU-Vitavax-Thiram (5,6-dihydro-2-methyl-N-phenyl-1,4-oxathiin-3-carboxamide + tetramethylthiuram disulfide). Two different coating weights were applied to seed, one consisting of approximately 10 g polymer kg^{-1} seed, referred to as a light coat (L), and the other consisting of approximately 15 g polymer kg^{-1} seed referred to as a heavy coat (H). New seed was received and germination tested each year before sowing (germination was 92–94%).

2.2. Soil temperatures and plant measurements

Soil temperature was measured at depths of 0, 5, and 10 cm within the plant row using thermocouple arrays as described by Gesch and Archer (2005). The thermocouples were installed the same day that the earliest planting was made each year. There were two thermocouple arrays placed in each of three of the four experimental blocks for a total of six arrays. Thermocouple arrays were monitored every 60 s and 15-min averages were recorded with a data logger (CR10X, Campbell Scientific, Logan, UT). After installing the arrays, every effort was made to replace the same amount of residue to the soil surface as was there before installation.

Seedling emergence was measured in 1-m of a center row in each plot which was marked before emergence. Once seedlings began to emerge, emergence was measured daily until there was no change, and the percent emergence reported is based on the number of seed sown in 1-m of row.

Three plants from each plot were sampled at the R6 reproductive stage for measuring total dry matter accumulation, node number, and pod number per plant. Averages of the three plants per plot (i.e., treatment replication) were used for statistical analysis. Soybean was harvested for seed yield and moisture with a plot combine by taking the two center rows. Harvest dates were October 3 and October 11 for the early and average sowing dates, respectively, in 2005 and October 2 for both sowing dates in 2006.

Seed oil and protein content were determined using pulsed NMR (Bruker Minispec pc120, Bruker, The Woodlands, TX). Duplicates of 5-g of whole seed per plot were measured (duplicates were averaged). Before analysis, the instrument was calibrated with pure soybean oil and with seeds of known protein content.

2.3. Laboratory germination tests

Evidence from the field study indicated that soil moisture potential might affect the responsiveness of polymer coatings even when low temperature was not a limiting factor. This prompted us to test the effects water potential on soybean germination under non-limiting temperature. Coated and uncoated soybean seeds were incubated on filter paper (Whatman No. 3) saturated with PEG solutions to simulate water potentials of −0.05, −0.25, and −0.75 MPa (Michel and Kaufmann, 1973). Seeds were germinated in covered Petri dishes (20 seeds/treatment, three replicates) on a laboratory table in a completely random design (average daily temp = 22 °C). Seed germination was counted daily (24 h intervals). An exposed radical length of 2 mm from the seed coat or seed was used as the germination criteria. The number of new seedlings was recorded

Table 1
Monthly accumulated precipitation and mean air temperature for the 2005 and 2006 growing seasons.

Month	Precipitation (mm)				Mean air temperature (°C)		
	2005	2006	120-Yr Avg.[a]		2005	2006	120-Yr Avg.
April	63	53	58		9.8	9.7	6.5
May	76	47	75.3		12.4	15.1	13.5
June	155	28	101.0		21.0	20.2	18.9
July	82	27	93.2		22.0	23.8	21.6
August	74	27	76.0		19.6	20.9	20.4
September	118	116	58.7		17.1	14.0	15.1
Total	568	298	462	Average	17.0	17.3	16.0

[a] Based on the 120-year average monthly temperature and accumulated rainfall for the Morris, MN location. Data were collected and compiled from the University of Minnesota West Central Research and Outreach Center, approximately 24 km from the study site.

for 40 d to provide a cumulative germination percentage calculated from the formula:

$$G_i\% = \frac{\sum \text{Germinated seeds}}{20} \times 100,$$

where $G_i\%$ is the percent germination on day i count day. The $G_i\%$ was then plotted versus total thermal time of day i to normalize the replicates. Hourly laboratory temperatures were recorded with a temperature logger (UA-001-64; Onset Computer Cooperation, Bourne, MA) to facilitate thermal time calculations. Longer incubations were not conducted due to the establishment of mold on seed.

2.4. Statistical analyses

The experimental data were analyzed by ANOVA using the Mixed Procedure of SAS (SAS for Windows 9.1, SAS Inst., Cary, NC). Seed coating (i.e., coated or uncoated), sowing date, and cultivar were treated as fixed effects, and replication and replication × sowing date were treated as random effects. Data were analyzed separately by year because the year by main (i.e., fixed) effect interactions were significant. Individual plot data of emergence and laboratory germination test data were first fit to a Boltzmann sigmoidal function using SigmaPlot (Systat Software Inc., San Jose, CA) as described by Gesch and Archer (2005) to determine the time from 10 to 90% emergence. The form of the equation was:

$$Y = \frac{A}{1 + \exp[2 \times \ln(9) \times (E_{50} - d)/B]}$$

where Y is percent emergence of seed sown, d is time in days, A is maximum emergence, E_{50} is days from sowing to 50% emergence, and B is days from 10% to 90% of maximum emergence. The 10–90% of maximum emergence data were then analyzed by ANOVA using the Mixed Procedure of SAS. Treatment mean comparisons were made by year using the Tukey Honestly Significant Difference (HSD) procedure at the $P = 0.05$ level. The laboratory germination results were compared using the 95% confidence intervals for the fitted data using SigmaPlot.

3. Results and discussion

3.1. Climate, soil temperatures, and initial emergence

Compared to the long-term average (i.e., 120-Yr average), precipitation between April and September was 106 mm above and 164 mm below average in 2005 and 2006, respectively (Table 1). The growing season of 2006 was especially dry from late May through August. The average seasonal air temperature was similar for both years and slightly higher than the 120-Yr average, but in 2006 May and July were considerably warmer than 2005 (Table 1).

A combination of early snow melt and mild spring air temperatures resulted in the first sowing on 6 April in 2005, which is relatively early for west central, MN. Nevertheless, soil temperatures in the no-till system during 2005 remained low until mid-May (Fig. 1). For instance, for the 50 mm depth at which seed was sown, the average soil temperature between 6 April and 4 May was just 8.5 °C. Soil temperatures responded similarly in 2006, although because of wetter initial field conditions in early April, largely due to greater snow pack in 2006 (866 mm in 2006 compared to 581 mm in 2005), the earliest sowing was 18 April. From initial sowing until 5 May, 3 d prior to initial plant emergence, the average 50 mm soil temperature was 10 °C (Fig. 1). For the early sowing, seed remained in the soil for up to 35 d in 2005 prior to emerging and up to 24 d in 2006. Plants began emerging 12 d and

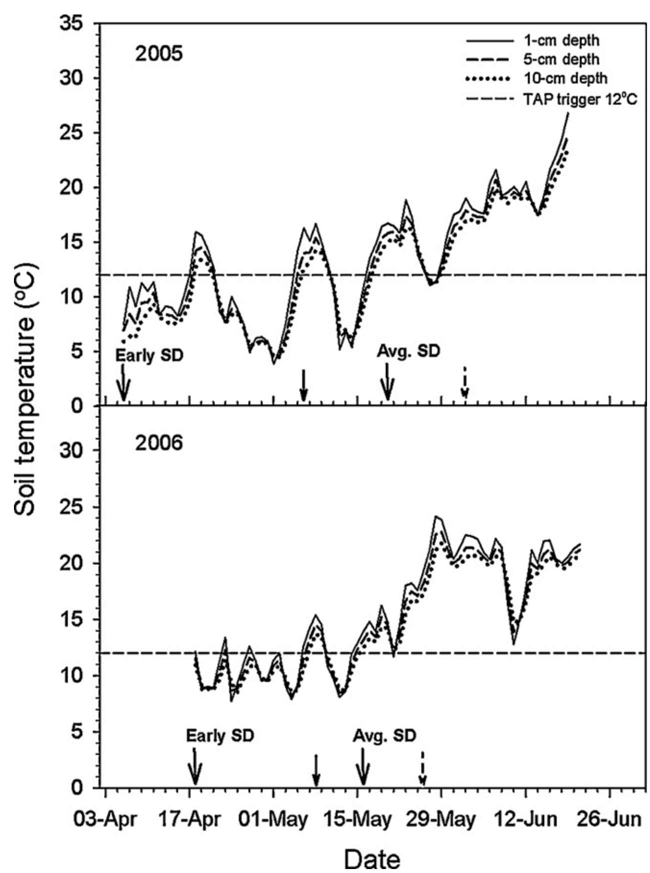

Fig. 1. Average daily soil temperature. The large arrows represent the early and average sowing dates and the small solid and dashed arrows represent when plants began to emerge for the early and average sowings, respectively. The dashed horizontal line references the temperature at which the polymer coating is designed to physically change and allow the seed to imbibed water.

Table 2
ANOVA table for the measured attributes of 10–90% emergence (10_90% Emrg), maximum emergence (MxEmrg), and seed yield (Yld), moisture (Moist), protein (Prot), and oil content.

Effect	df	2005					
		10_90% Emrg	MxEmrg	Yld	Moist	Prot	Oil
		P value					
CV[a]	1	0.38	0.0002	<0.0001	0.001	<0.0001	<0.0001
Coat	2	0.05	<0.0001	0.01	0.47	0.88	0.81
Date	1	<0.0001	<0.0001	0.50	0.29	0.12	0.09
CV × Coat	2	0.33	0.09	0.03	0.18	0.86	0.53
CV × Date	1	0.78	0.73	0.41	0.02	0.60	0.09
Coat × Date	2	0.13	0.001	0.002	0.96	0.35	0.69
CV × Coat × Date	2	0.11	0.26	0.0002	0.43	0.96	0.42

Effect	df	2006					
		10_90% Emrg	MxEmrg	Yld	Moist	Prot	Oil
		P value					
CV	1	0.17	0.21	<0.0001	<0.0001	0.40	0.51
Coat	2	0.09	0.04	0.39	0.20	0.30	0.22
Date	1	0.01	0.03	0.35	0.03	0.94	0.08
CV × Coat	2	0.18	0.29	0.91	0.22	0.07	0.82
CV × Date	1	0.99	0.49	0.32	<0.0001	0.12	<0.0001
Coat × Date	2	0.43	0.02	0.90	0.31	0.09	0.52
CV × Coat × Date	2	0.35	0.29	0.44	0.29	0.47	0.64

[a] For effects, CV denotes cultivar, Coat denotes uncoated and polymer-coated seed, and Date denotes sowing date.

10 d after sowing for the average sowing date in 2005 and 2006, respectively. In 2005, uncoated seed of the MG I soybean cultivar emerged 3 d and 1 d earlier than the MG 0 cultivar for the early and average sowing dates, respectively, but no cultivar difference in initial emergence occurred during 2006.

The polymer coating did consistently delay emergence of both cultivars for the early and average sowing date in both years. The delay in initial emergence ranged from 0 to 5 d compared to uncoated seed and the delay tended to be slightly greater for the heavier coating (i.e., coat H), but there was no clear trend in length of delay between sowing dates or a difference between cultivars. When averaged across sowing dates and cultivars, the delay caused by the coating was 2 and 3 d in 2005 and 2006, respectively. Sharratt and Gesch (2008) found a slightly greater delay in soybean emergence for temperature-activated polymer-coated seed that ranged from 4 to 6 d during a 3-yr study when averaged over an early and normal sowing date and across a conventional and no-tillage system. They also reported in some instances that delayed emergence was associated with poorer stand establishment, which they believe might have been due to damage of seedlings caused by exposure of hypocotyls to high soil temperatures. Similar delays in emergence have also been observed in other polymer seed coated studies (Johnson et al., 1999; Turner et al., 2006). This delay is presumably due to the time required for decomposition of the hydrophilic groups in the polymer coating (Hicks et al., 1996).

3.2. Emergence uniformity

The time to progress from 10 to 90% of maximum emergence can be used as an indicator of plant stand uniformity (Gesch and Archer, 2005). The longer seed or seedlings remain in the soil prior to reaching full emergence the more likely the plant stand is to be non-uniform (Shaw, 1977; Gesch and Archer, 2005). In both years, sowing date, and to a lesser extent polymer coating, affected time between 10 and 90% of maximum emergence, but not cultivar (Table 2). Emergence was more rapid (i.e., shorter time between 10 and 90% emergence) following the second planting (Fig. 2), which was most likely due to higher soil temperatures (Fig. 1). During 2005, early-sown seeds required 8.3 d more than those sown later to reach 90% of maximum emergence ($p < 0.0001$), while the

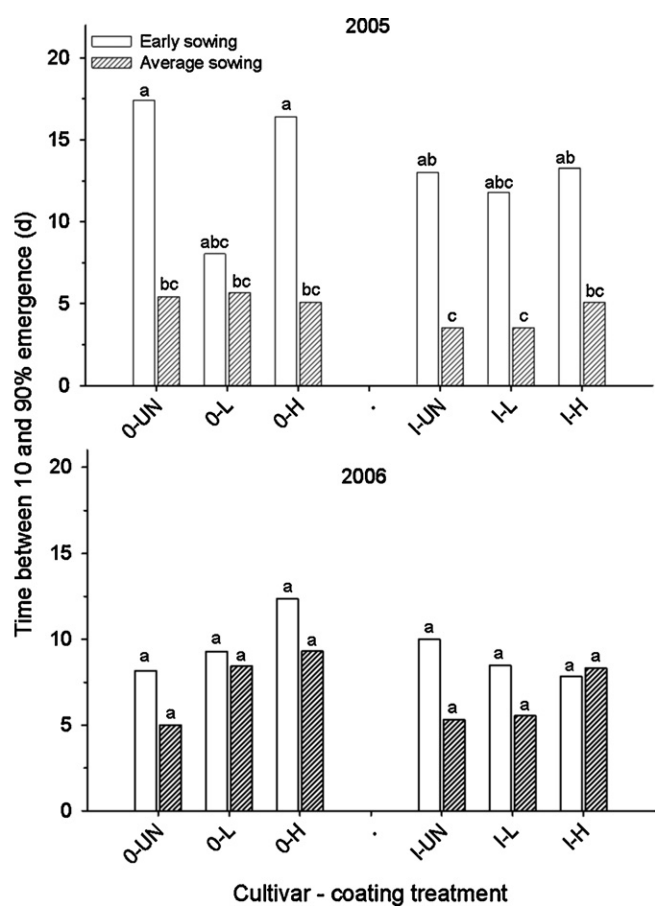

Fig. 2. The effect of the light (L) and heavy (H) polymer coatings and sowing date on the rate of emergence (i.e., time between 0 and 90% of maximum emergence) of the MG 0 (0) and MG I (I) soybean cultivars. Values represent the mean of four replicates. For each year, bars followed by the same letter are not significantly different at the $P \leq 0.05$ level.

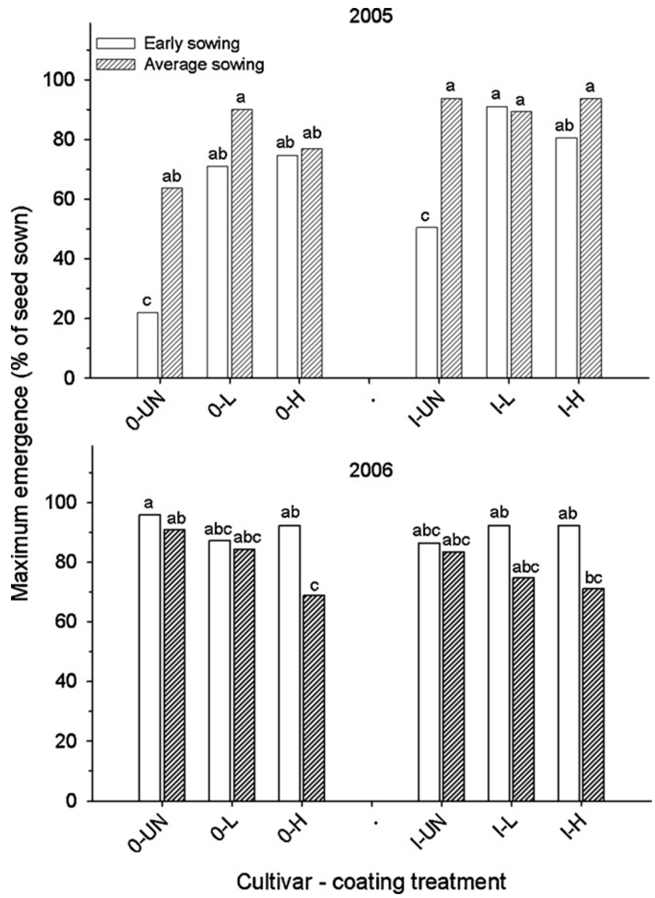

Fig. 4. The effect of the light (L) and heavy (H) polymer coatings and sowing date on maximum emergence of the MG 0 (0) and MG I (I) soybean cultivars. Values represent the mean of four replicates. For each year, bars followed by the same letter are not significantly different at the $P \leq 0.05$ level.

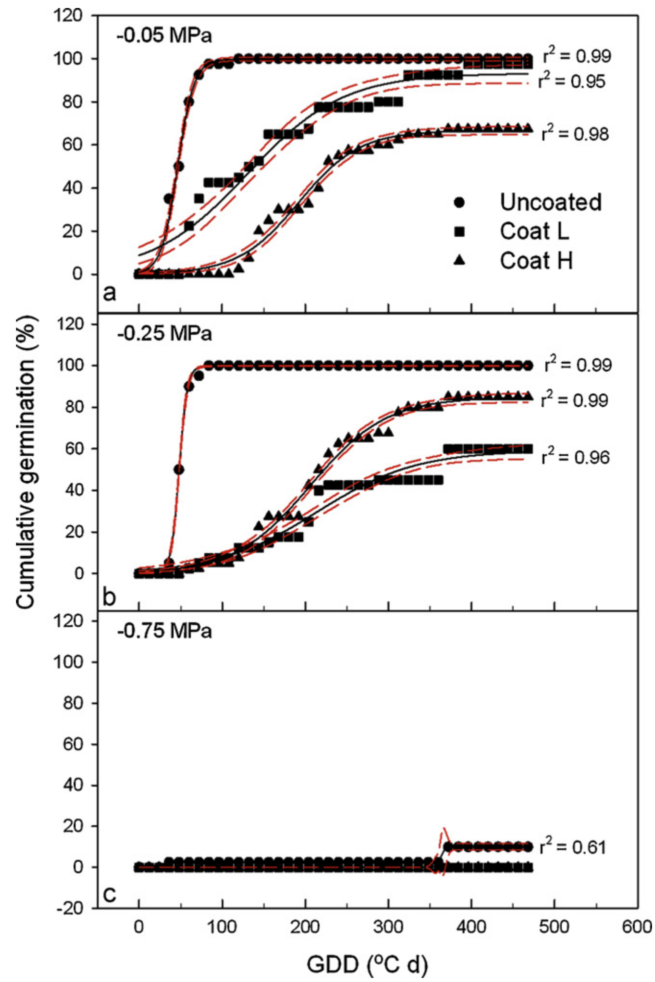

Fig. 3. Effect of osmotic moisture potential on cumulative percent germination as a function of growing degree days (base temperature of 10 °C) for the light (L) and heavy (H) polymer-coated and uncoated soybean seeds.

difference in 2006 was 2.4 d ($p = 0.01$), when averaged across both cultivars and seed coatings.

The polymer coating effect was different between years. In 2005, averaged across cultivar and sowing date, L-coated seed tended to result in a shorter delay between 10 and 90% emergence than either uncoated or H-coated seed ($p = 0.05$), but this was primarily due to differences in the early sowing (Fig. 2). This result indicates that the lighter (L) polymer coating may have protected seed from being weakened by prolonged exposure to cold, wet soil experienced during the spring of 2005, consequently leading to more vigorous seedling growth, speedier emergence, and potentially more uniform stand. This is supported by observations of Sharratt and Gesch (2008) who noted that the time between germination and emergence of soybean seed tended to be less for polymer-coated than uncoated seed when sown early and late in two different tillage systems. They suggested that the reason for this was because of more rapid development and emergence of hypocotyls from coated seed.

During 2006, although the coating effect was weak ($p = 0.09$), when averaged across sowing date and cultivar, the heavier polymer coating generally reduced the rate of 10–90% emergence by 2.4 d as compared to uncoated seed ($p = 0.03$). Gesch and Archer (2005) also reported slower emergence of polymer-coated maize seed compared to uncoated seed when both were planted at a near average time, and suggested that this could potentially lead to uneven stand establishment. The reduced rate of emergence for the H-coated seed of both cultivars and the L-coated seed of the MG 0 soybean during the second sowing date in the present study did result in uneven plant stands (field observation). This delay in progressing to 90% emergence despite relatively high soil temperatures (i.e., well above 10 °C soon after sowing), might have been related to soil moisture.

3.3. Soil water potential impacts on germination

Germination tests conducted under controlled-environment conditions clearly show that water potential is an important factor controlling the germination time of polymer-coated seed (Fig. 3). For instance, at 22 °C and an equivalent soil water potential of −0.05 MPa, the accumulated GDD between 10 and 90% emergence for uncoated, L-, and H-coated soybean seed was 46, 131, and 192 °C d, respectively (Fig. 3). In other words, the germination of the coated seeds was delayed by 7–12 d at this osmotic potential and was further increased to 14–18 d at lower osmotic potentials. Therefore, both polymer coat treatments resulted in higher median germination times and reduced final germination percentages at a given thermal time compared with uncoated control seeds. Additionally, this increase in germination time increases with decreasing soil moisture (Fig. 3b and c). The results here for soybean are similar to the other delayed germination observations with polymer-coated seeds of other species (Johnson et al., 1999; Willenborg et al., 2004; Turner et al., 2006).

This increase in germination time as a function of soil moisture could explain some of the differences between the years observed in the field plot study. In the present field study, 235 mm of

Table 3
Total aboveground biomass (DW) and number of nodes and pods per plant at the R6 stage for plants propagated from uncoated and polymer-coated soybean seed sown early (April 6) and at a normal time (May 20) in 2005. Values are the mean of four replicates. For a given cultivar and growth attribute, values followed by the same letter are not statistically different at the $P \leq 0.05$ level.

Cultivar	Sowing date	DW (g plant^{-1})			Nodes (plant^{-1})			Pods (plant^{-1})		
		UN	L	H	UN	L	H	UN	L	H
MG 0	Early	75.5 a	25.4 b	35.3 b	17.7 a	15.4 ab	15.6 ab	100.3 a	33.4 b	47.6 b
	Normal	33.0 b	36.5 b	29.5 b	14.9 b	15.4 ab	15.1 b	38.0 b	43.8 b	35.7 b
MG I	Early	37.2 a	33.3 ab	30.4 ab	19.1 a	18.4 a	18.1 a	47.0 a	36.1 b	31.3 b
	Normal	28.3 b	32.9 ab	28.7 b	17.6 a	18.9 a	17.6 a	33.8 b	39.6 ab	33.0 b

precipitation was received between 1 April and 10 June in 2005 compared to just 110 mm in 2006 during the same period. The 50-yr average for this period is 165 mm near the study site. Indeed, seeds sown on 16 May in 2006 that were excavated on 26 May revealed that although all uncoated and coated treatments had germinated, the development of hypocotyls of coated seed was severely restricted in some cases by lack of breakdown in the coating (supplemental data). For the excavated seeds, the moisture contents for uncoated, L-coated, and H-coated seed of the MG 0 cultivar were 770, 560, and 460 g kg^{-1}, respectively (results were similar for the MG I cultivar).

3.4. Plant stands

The effect of polymer coating on maximum emergence and hence final stand establishment differed between years. In 2005, maximum emergence, especially in the early sowing, was substantially greater for polymer-coated seed, whereas in 2006, the polymer coating either had no effect (early sowing) or led to lower emergence (average sowing) than uncoated seed (Fig. 4). For the early sowing in 2005, given that seed remained in the soil a long time before emerging (35 d), the polymer coating may have offered some form of protection against soil conditions that damaged uncoated seed leading to lower emergence (Fig. 4). For the early sowing in 2005, when averaged across both the L- and H-coated seed, maximum emergence was 51 and 35% greater than uncoated seed for the 0 and I MG cultivars, respectively. Averaged across sowing dates and seed coating in 2005, final stand establishment of the MG I cultivar was 17% greater than the MG 0 cultivar ($p < 0.001$).

In 2006, the main effects of coating and sowing date and their interaction were significant (Table 2). Averaged across all cultivar-coating treatments, maximum emergence was 12% greater for the early than the average sowing date ($p = 0.03$). Moreover, maximum emergence tended to be less for polymer-coated than uncoated seed ($p = 0.02$) in the second sowing date. Emergence for H-coated seed of the MG 0 soybean in the second sowing was 22% lower than that of its uncoated counterpart (Fig. 4). Again, this probably resulted from dry soil caused by the lack of precipitation in 2006. Helms et al. (1996) have shown that low soil water content can greatly restrict development of germinating soybean seedlings leading to poor stand establishment due to emergence and even death, and this is exacerbated by increasing soil temperatures. In our study, evidence indicates that in fact low soil water potential may have restricted the germination of polymer-coated seed and not only delayed emergence (Fig. 2) but also perhaps weakened seed causing either no germination or attrition and eventual death of developing seedling. Indeed, field observations were made of emerged seedlings with the polymer coating still attached to their cotyledons, which eventually led to death of the plant (supplemental data). Also, this behavior is evident in Fig. 3, where both the speed of germination and cumulative germination were strongly inhibited by decreasing water potential for polymer-coated seed.

With respect to the influence of the polymer coating on emergence, our results corroborate previous findings. In the present study for instance, the longer seed remained in the soil prior to emergence during early spring the greater the emergence was of coated seed compared to uncoated, which is similar to what Gesch and Archer (2005) found for polymer-coated corn seed, suggesting that the polymer coating does protect seed against injury caused by cold and wet soil. During both years of the study, sowing polymer-coated soybean of either cultivar as much as 4–5 weeks earlier than normal did not have any negative consequences on emergence. In fact, across both years of the study, early sown polymer-coated seed generally resulted in stands comparable to uncoated seed sown at an average time. However, polymer-coated seed sown into warmer soil at an average time did have negative consequences in 2006, where it caused slower emergence (Fig. 2) and lower stand establishment (Fig. 4), which is similar to the findings of Sharratt and Gesch (2008) for soybean and Turner et al. (2006) for woody species. Sharratt and Gesch (2008) reasoned that poor stand establishment may have been caused by a delay in emergence by the polymer coating resulting in exposure of emerging seedlings to lethal soil surface temperatures of 40 °C that prevented hypocotyl development. In the present study lethal or near lethal soil surface temperatures were not a factor, but rather the most likely reason for poor emergence was dry soil caused by a lack of late spring precipitation. Drier soil conditions would extend the delay in soybean germination of the polymer-coated seed (Fig. 3), as has been observed with other polymer-coated species (Willenborg et al., 2004; Turner et al., 2006).

3.5. Seed yield and moisture content

Soybean yields on average were 1.0 Mg ha^{-1} greater in 2005 than 2006 (Fig. 5), which was primarily due to differences in seasonal precipitation. The average precipitation between May and August (i.e., the primary growing season of soybean) at the study site is 346 mm. Precipitation in 2005 for this period was 41 mm above average, while it was 216 mm below average in 2006. Averaged across all treatments, the longer maturity cultivar out yielded the earlier one by 0.4 ($p < 0.0001$) and 0.7 ($p < 0.0001$) Mg ha^{-1} in 2005 and 2006, respectively. Sowing date, however, did not have a significant effect in either year (Table 2).

Only in 2005 did the polymer coating significantly influence grain yield (Table 2). For the early sowing in 2005, both the L- and H-coated seed of the MG 0 cultivar resulted in greater yields than for uncoated seed (Fig. 5). Furthermore, yields for the early sown polymer-coated MG 0 cultivar were comparable to uncoated seed sown at a normal time. The lower yield for the early sown uncoated seed was caused by the exceptionally poor stand establishment (Fig. 4). Stand establishment for uncoated seed of the MG I cultivar was also significantly less than its coated counterparts in the early sowing, but because of yield compensation there was no yield difference between coated and uncoated seed.

For both cultivars where stands for early-sown uncoated seed were low, plants compensated for low population with greater

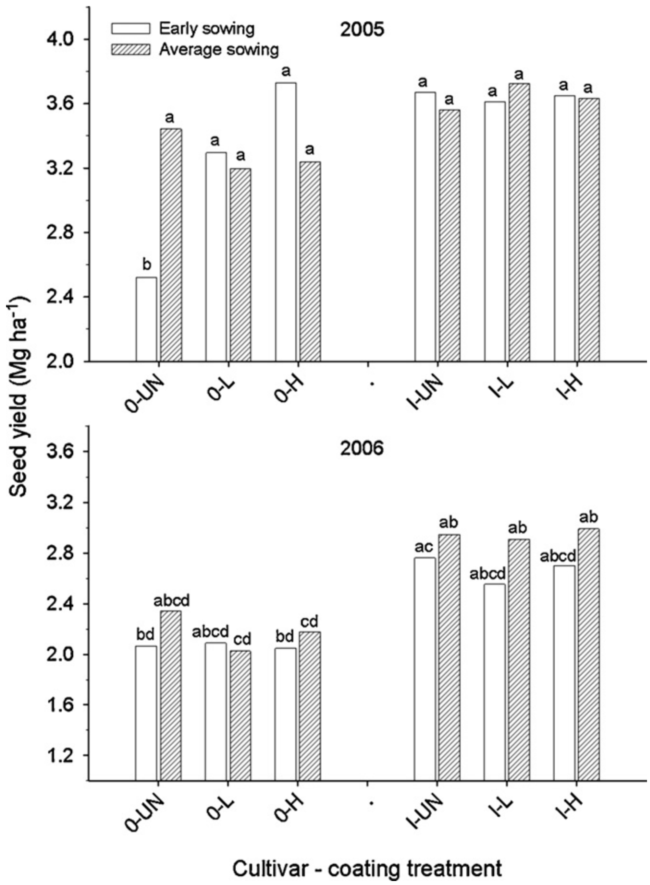

Fig. 5. Influence of the light (L) and heavy (H) polymer coatings and sowing date on seed yield of the MG 0 (0) and MG I (I) soybean cultivars. Values represent the mean of four replicates. For each year, bars followed by the same letter are not significantly different at the $P \leq 0.05$ level.

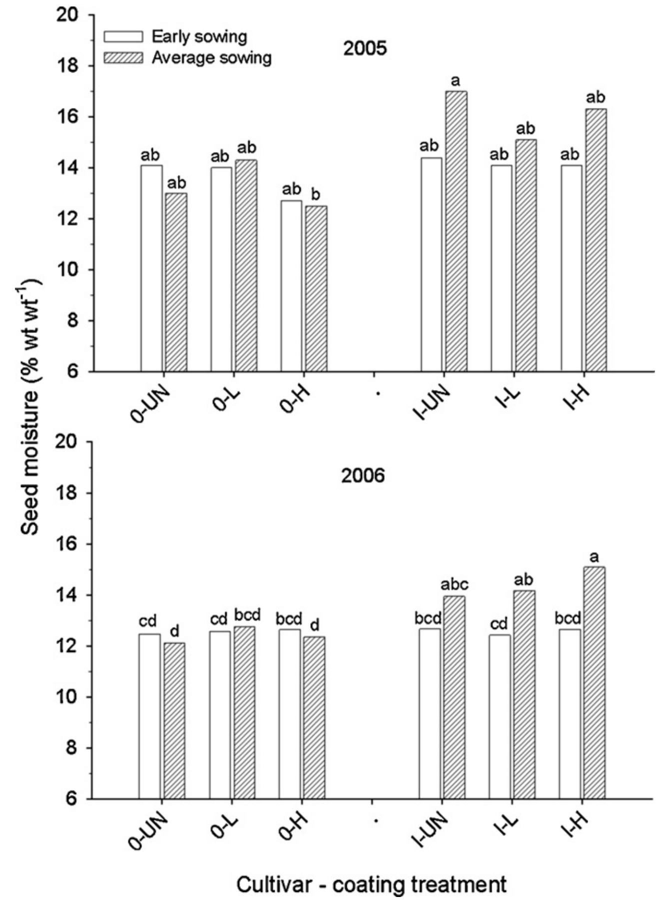

Fig. 6. Influence of the light (L) and heavy (H) polymer coatings and sowing date on seed moisture at harvest of the MG 0 (0) and MG I (I) soybean cultivars. Values represent the mean of four replicates. For each year, bars followed by the same letter are not significantly different at the $P \leq 0.05$ level.

plant growth (Table 3). Plants for the early uncoated seed of the MG 0 cultivar had more accumulated biomass and substantially more seed pods per plant than for coated seed (Table 3). The early uncoated seed of the MG I cultivar led to more pods per plant, although biomass and number of nodes per plant were not different than those of coated seed. Yield compensation in sparse soybean populations is well documented (Egli, 1988; Parvez et al., 1989; Carpenter and Board, 1997), and typically results from an increase in seed pods and hence seed yield per plant (Carpenter and Board, 1997; Ball et al., 2000), which is in agreement with our study.

The optimum seed moisture for soybean at harvest is about 13–15%. Harvesting at less than 13% can increase shattering losses,

Table 4
Seed protein and oil content for coated and uncoated soybean grown in 2005 and 2006. Values are the mean of four replications. For the given seed attribute within a year, values followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Cultivar	Sowing date	2005					
		Protein (g kg^{-1})			Oil (g kg^{-1})		
		UN	L	H	UN	L	H
MG 0	Early	356 d	364 d	359 d	211 ab	209 abc	212 a
	Average	369 bcd	366 cd	366 cd	204 abc	205 abc	207 abc
MG I	Early	389 abc	393 ab	390 abc	199 c	200 c	201 abc
	Average	397 a	393 a	395 a	201 abc	200 bc	197 c

Cultivar	Sowing date	2006					
		Protein (g kg^{-1})			Oil (g kg^{-1})		
		UN	L	H	UN	L	H
MG 0	Early	392 a	392 a	395 a	200 ab	197 ab	200 ab
	Average	388 a	395 a	384 a	202 a	196 ab	200 ab
MG I	Early	382 a	386 a	396 a	207 ab	206 ab	204 ab
	Average	390 a	389 a	393 a	191 ab	187 b	192 ab

seed splitting, and loss of market value (Hurburgh, 2008). However, storing seed for too long above 15% can result in spoilage. Only the average sowing date of the MG I cultivar in 2005 had seed moisture above 15% at harvest (Fig. 6). Averaged across coating treatments, its moisture was 16.1%, which was 2.0% greater than the early sowing ($p = 0.04$). Because of the warm, dry conditions in 2006 the plants were harvested earlier than in 2005. There was a cultivar and cultivar by sowing date effect for seed moisture in both years (Table 2), but this was only because the average sowing date for the MG I soybean tended to have greater seed moisture than either sowing date of the MG 0 cultivar. Conversely, there was no seed moisture difference between cultivars regardless of seed coating for the early sowing in both years of the study (Fig. 6). These results indicate that to maximize the maturity group of soybean grown in this region while minimizing seed moisture at harvest and thus drying costs, in most years sowing earlier than normal will be necessary.

3.6. Seed protein and oil

The polymer seed coating had no influence on seed protein or oil content in this study (Table 2). Likewise, sowing date had no significant influence on seed protein or oil content, but in 2005 there was a cultivar effect (Table 2). The MG I cultivar in 2005 averaged $29\,g\,kg^{-1}$ more seed protein than the MG 0, but on average produced $9\,g\,kg^{-1}$ less oil (Table 4). In 2006 there was a cultivar by sowing date interaction (Table 2). This was primarily because the early planted MG I seed had higher oil content ($16\,g\,kg^{-1}$; $p = 0.002$) than the average planting date (Table 4). Results demonstrated that under a higher yielding environment (i.e., 2005) that the MG I cultivar produced more protein but less oil than the MG 0 one (Table 4).

4. Conclusions

Results showed that sowing polymer-coated soybean as much as 4–5 weeks earlier than normal into no-tilled soil did not have any negative consequences on emergence, seed yield, and seed quality. During the first year of the study when seed was sown as early as 6 April and remained in the soil up to 35 d before emerging due to cold soil, the polymer coating resulted in plant stands substantially greater than those for uncoated seed. Moreover, seed yield was also greater for polymer-coated MG 0 soybean. However, results also indicated that sowing polymer-coated soybean at an average time, especially under dry conditions, could have the opposite effect, leading to poorer stands than uncoated seed. There was a yield advantage of the MG I cultivar over that of the MG 0 in both years of the study, and sowing the MG I soybean as early as possible did result in lower seed moisture content at harvest.

It is concluded that temperature-activated polymer coating can reduce the risk of poor plant stand establishment in no-tillage soils when planted very early. However, it is recommended that it should not be used if soybean is planted at a near average or later sowing date in the northern Corn Belt, where it could result in slow and/or reduced emergence.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.fcr.2011.09.005.

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