CORN PLANTING STRATEGIES IN THE UNITED STATES CORN BELT

BY

ERIC GABRIEL CORONEL

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Crop Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

Doctoral Committee:

Professor Germán Bollero, Chair
Assistant Professor Fabián Fernández, University of Minnesota
Associate Professor María Villamil
Associate Professor DoKyoung Lee

ABSTRACT

In Illinois, corn (*Zea mays* L.) producers aim to start planting operations in mid-April. Early planting allows for the use of longer-season corn varieties, which tend to yield more than shorter-season varieties. However, constraints to early planting in the U.S. Corn Belt include excessive soil moisture and low temperatures in April. Corn producers often wait for soils to dry and for temperatures to increase before starting planting operations. Meeting the potential for high corn yield requires a successful planting operation and crop establishment. Chapter 1 presents research about challenges in no-till, continuous corn production due to large amounts of corn residue, which may interfere with planting operations and contributes to keeping soils cooler and wetter, delaying field operations. A practice in Illinois is to apply post-harvest nitrogen (N) fertilizer to accelerate residue decomposition. A 2-yr study in Illinois investigated corn residue treated with liquid ammonium sulfate (AMS) and urea-ammonium nitrate (UAN) broadcast-applied post-harvest. Treatments receiving fall N applications did not show greater residue decomposition as measured by stalk strength, and carbon-to-nitrogen (C/N) ratios were not reduced compared to an untreated control. Weather conditions and the residue's initial quality likely drove the decomposition rate of corn residues. Soil ammonium and nitrate data indicated that some of the N fertilizer applied in early and mid-fall was lost. Results indicated that applying post-harvest N fertilizer to enhance corn residue decomposition is not warranted. Chapters 2 and 3 present research about the application of variable seeding depth of corn as a way to improve yield. Sufficient soil moisture is crucial for corn germination and emergence; however, within-field soil moisture varies with topography. As a result, corn seeding depth should vary with soil moisture gradients to reach optimal moisture. Using relative elevation data, landscape (LSP) zones were delineated to partition soil moisture variability into dry, transitional, and wet LSP zones. The corn yield response to shallow, standard, and deep seeding depths in dry, transitional, and wet LSP zones was tested. It was hypothesized that shallow seeding in wet LSP zones and deep seeding in dry LSP zones would result in higher yield than the standard seeding depth. Chapter 2 describes the experiment where field-long strips were planted in 17 commercial fields in 2014 and 2015 at shallow, standard, and deep seeding depths. Corn was machine-harvested. Across years, the LSP zones were a significant predictor of the yield response in 7 fields. Two fields showed no response to seeding depth, 7 fields yielded similarly for the shallow and standard seeding depths, 4 fields yielded similarly for the deep and standard seeding depths, while 4 fields responded positively to combinations of shallow, standard, and deep seeding depths. Chapter 3 describes the experiment where corn emergence, plant growth, and grain yield were quantified in the LSP zones, along with soil moisture. Two fields in Illinois were planted with field-long strips in 2015 at shallow, standard, and deep seeding depths. Soil moisture was nearly twice as high in wet LSP zones than in dry LSP zones for one field. Seeds planted at shallow depths had earlier emergence and higher growth earlier in the season compared to seeds planted deeper. Shallow seeding in wet LSP zones in one field showed a more consistent emergence rate and less variability compared to the standard and deep seeding depths. However, these results did not translate into significant grain yield differences. The LSP zones had greater influence on grain yield than seeding depths. The data in the appendix showed considerable plant-to-plant variability from adjacent corn plants sampled within-row. This is particularly interesting as corn seeds are assumed to have nearly identical genetics, and except for spacing differences, the growing environment of corn plants along short distances could be assumed to be homogeneous.

Dedicated to my father, who accomplished so much with so little and whose cognitive abilities were robbed from him with so much life left to live.

ACKNOWLEDGEMENTS

I would like to recognize my doctoral committee members, Germán Bollero, Fabián Fernández, D.K. Lee, and María Villamil for the time that they have dedicated to this project. In particular, I thank Germán Bollero for taking me as a student among all his other duties. I consider myself very lucky to have been able to work under such accomplished researchers.

Many thanks to Fabián Fernández for recruiting me to come to Illinois, and to Kristin Greer, Cheri Esgar, and many undergraduate students and technicians who worked with me during my first two years in Illinois.

Thank you to Deere & Company for the two years of funding and the opportunity to learn in such a fast-paced environment. This includes Larry Hendrickson, Julian Sanchez, Sue Gray, and particularly Kevin Armstrong, with whom I shared many hours discussing research topics, objectives, and theories, in air-conditioned offices and under corn canopies.

Thank you to Agustín Alesso for the daily chats about research, R code, my many statistical questions, and for coming from Argentina to Illinois to help me make sense of the data.

Thank you to my parents, Luis Coronel and Estela Bode, who instilled in me the desire to learn, and who sacrificed everything for their four sons. Thank you to my older brothers, Luis Pablo, Mariano, and Nicolás, for their humor, encouragement, and for carrying my share of family burdens during my long absence.

Immense thanks to my childhood pen pal, English teacher, research helper, wife, and friend, Chelsea LeAnne Parker. I honestly do not know how I ever lived without her. Lastly, thank you to Isabel Robledo and Scott Parker for helping me come to study in the United States.

TABLE OF CONTENTS

CHAPTER 1: CORN RESIDUE BREAKDOWN AS AFFECTED BY POST-HARVEST SURFACE-BROADCAST NITROGEN APPLICATION IN ILLINOIS

ABSTRACT

Challenges in no-till continuous corn (*Zea mays* L.) production arise in part due to large amounts of crop residue. In Illinois, sometimes corn producers apply nitrogen (N) post-harvest to accelerate residue decomposition. There is limited research to determine the effectiveness of this practice. This 2-yr study near Urbana, IL investigated stalk strength of corn residue placed in mesh bags under a no-till, corn-on-corn system. The N treatments were liquid ammonium sulfate (AMS) (21-0-0) and urea-ammonium nitrate (UAN) (32-0-0) broadcast-applied in early, mid, and late fall at 34 kg N ha^{-1} plus a spring pre-plant application of 168 kg N ha^{-1}. Stalk strength was measured from early fall until April using a push penetrometer. Corn stalk strength of residue from the 2012 growing season was 20% lower than the 2011 growing season, possibly due to drought conditions in 2012. Treatments receiving fall N applications showed no differences in stalk strength and carbon-to-nitrogen (C/N) ratios compared to the untreated control. Weather conditions and the residue's initial quality likely drove the decomposition rate of corn residues left on the soil surface. Grain yield was improved by N fertilizer application compared to an untreated control although there were no significant differences for grain yield among the N fertilizer application timings. Soil ammonium and nitrate concentrations showed that some of the N fertilizer applied in early and mid-fall was likely lost. Results indicated that applying N fertilizer in the fall to enhance corn residue decomposition is not warranted.

Abbreviations: AMS, ammonium sulfate; UAN, urea-ammonium nitrate; C/N, carbon-to-nitrogen ratio.

INTRODUCTION

No-till is one of several conservation tillage practices for corn production (Swan et al., 1996; Buman et al., 2004). This practice has become more common over time in the Midwest, for a variety of reasons including lower machinery requirements, cost, and labor, and reduced soil erosion and runoff, improved water infiltration, soil cover, and organic matter accumulation (Baker and Laflen, 1983; McIsaac et al., 1987; Swan et al., 1996; Phillips et al., 1997; CTIC, 2002; Zuber et al., 2015).

However, corn residue buildup on the soil surface as a result of no-till management (Mann et al., 2002) creates challenges for this cropping system (Swan et al., 1996). To name a few, delayed planting due to colder and wetter soil conditions in early spring, residue interference during planting, poor plant emergence and establishment, and reduced grain yields in comparison to conventional tillage systems (Mock and Erbach, 1977; Allmaras et al., 1991; Hill, 1998; Nowak and Pierce, 2000; Buman et al., 2004; Simmons and Nafziger, 2009).

The issue of crop residue buildup has been exacerbated by corn hybrids that exhibit greater stalk strength and lodging resistance in comparison to previous hybrids (Duvick, 1984; Dwyer and Tollenaar, 1989). As a consequence, corn stalks are commonly found standing on the field during planting in the next growing season (Nafziger, 2009a). In addition to more apparent crop integrity at the time of harvest, new hybrids produce more biomass than ever before (Dwyer and Tollenaar, 1989; Duvick, 2005; Lee and Tollenaar, 2007). Between 1940 and 2000 area-based corn biomass production has increased by 112% (Johnson et al., 2006). In general, corn biomass production is closely related to grain production. The ratio of corn residue to grain yield is in the range of 0.8/1 (Pordesimo et al., 2004) to 1/1 (Ayres and Buchele, 1971; Gupta et al., 1979; Smil, 1983). In the last two decades, corn grain yields in Illinois have increased close to 0.16 Mg ha^{-1} yr^{-1}, from 7.5 Mg ha^{-1} in 1990 to 11.3 Mg ha^{-1} in 2008 (Nafziger, 2009b). Based on the grain yield trend over the last 20 years and the grain-to-biomass ratio, it is likely that corn residue production has increased at similar rates (Johnson et al., 2006; Lorenz et al., 2010).

Residue decomposition is influenced by several factors including temperature, soil moisture, nutrient availability, and the residue's C/N ratio, lignin, and carbohydrate content. It is generally accepted that residues with a C/N ratio greater than 25 can lead to immobilization of soil N as microorganisms scavenge available soil N to decompose the crop residue (Griffin, 1972; Brady and Weil, 2008). Unlike residue from legumes, such as soybean that has a C/N ratio of 20/1, corn has a greater average C/N ratio of 40/1 and normally ranges from 28/1 to 57/1 (Mungai and Motavalli, 2006; Brady and Weil, 2008). Because of these greater C/N ratios corn residue decomposition is relatively slow, especially in no-till fields where the residue is not in close contact with the soil where microorganisms can obtain N to aid in the decomposition process. Residues with high C/N ratios can immobilize soil N for longer periods of time and deprive of N a growing crop (Schomberg and Streiner, 1999).

In addition, management practices influence residue decomposition based on the amount of residue left on the field after harvest, the size of the residue, and the distribution of the residue both on the soil surface and in the subsurface (Brown and Dickey, 1970; Parr and Papendick, 1978; Hubbard and Jordan, 1996; Ernst et al., 2002). Decomposition rates of residue left on the soil surface may be slower and more variable than residue that is incorporated into the soil. Residue left on the soil surface is subject to drying and wider temperature fluctuations (Brady and Weil, 2008) and with less chance to be in close contact with soil microorganisms. Research has shown that fungal mycelia can extend its hyphae to attack the residue left on the soil surface; however, the rate of residue decomposition of this process is slower compared to buried residues (Brady and Weil, 2008). Moreover, if the residue has a high C/N ratio the fungi may transfer N from immediate sources, such as the soil, to decrease the ratio and aid in the decomposition process (Griffin, 1972).

Due to the relationship that exists between high C/N ratios and slower rates of residue decomposition (Parr and Papendick, 1978), corn producers and agronomists have hypothesized that the application of N fertilizer on corn residue left on the soil surface could speed up the residue decomposition process in no-till cropping systems. Common N products applied by corn producers in the fall to presumably increase residue decomposition are UAN and AMS. In central Illinois, corn producers aim to reach corn physiological maturity close to two weeks before 15 October, which is the average date for the first killing frost of the fall (Nafziger, 2009b). Post-harvest N applications would likely be conducted in cooler soil temperatures that are not conducive for high microbial activity needed for residue decomposition, particularly when corn is harvested late in the season. Corn residue decomposition slows down as temperatures decrease due to reduced microbial activity (Parr and Papendick, 1978). If the applied N fertilizer is not taken up by soil microbes before microbial activity slows down there is a risk of soil N loss before the next crop is able to take up the soil N in the spring.

As the state of Illinois is part of the Gulf of Mexico Watershed Nutrient Task Force (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001), a multistate coalition with the aim to reduce nutrient loading into the Mississippi River that flows into the Gulf of Mexico, there is a responsibility to educate about fertilization strategies that are not detrimental to the environment. The goal of applying N fertilizers for plant uptake requires that all aspects of the corn production cycle be covered in terms of applying nutrients at the right place, time, and form (Ehmke, 2012; Snyder, 2012).

In a Wisconsin study, Bundy and Andraski (2002) investigated the effects of fall and spring pre-plant UAN and AMS fertilizer applications on residue decomposition and no-till corn grain yields. The authors found no effect of timing and source of N fertilizer on residue decomposition, and grain yields were not improved by fall N applications compared to similar rates of spring N applications (Bundy and Andraski, 2002). Others have suggested the application of post-harvest N fertilizer as a way to accelerate microbial decomposition of corn residue (Vanhie et al., 2015) based on results from a corn residue decomposition experiment conducted under laboratory conditions (Green et al., 1995). However, not only the applicability of laboratory results from Green et al. (1995) to actual post-harvest field conditions is debatable, but another laboratory incubation study concluded that the addition of N fertilizer to increase corn residue decomposition rates was not warranted (Al-Kaisi and Guzman, 2013). To date, limited field research has been conducted on the topic, and the potential benefits of N fertilizer applications for corn residue breakdown are largely anecdotal. Further, due to warmer fall conditions and earlier harvest times in many parts of the Midwest – including central Illinois – compared to Wisconsin, practitioners have challenged the validity of the results by Bundy and Andraski (2002).

It is hypothesized that the addition of N fertilizer could speed up the decomposition process by decreasing the C/N ratios of the corn residue, particularly for N fertilizer applications conducted in early fall. Thus, the objectives of this study are: 1) to determine the potential of post-harvest AMS or UAN fertilizer applications to lower the C/N ratio of corn residue and weaken corn stalks, and 2) to quantify the fate of the N fertilizer in the soil by the time of planting. An additional objective was to evaluate the corn grain yield response to UAN and AMS spring pre-plant N fertilizer rates.

MATERIALS AND METHODS

Study sites

A 2-yr field experiment was conducted from the fall of 2011 to the fall of 2013 at the Crop Sciences Research and Education Center near Urbana, IL. Site 1 for the 2012 growing season (40.0524° N 88.2356° W) and site 2 for the 2013 growing season (40.0612° N 88.2267° W) both consisted of Drummer (fine-silty, mixed, superactive, mesic Typic Endoaquolls) silty clay loam and Flanagan (fine, smectitic, mesic Aquic Argiudolls) silt loam soils. For the preceding growing season to our study, both sites were planted with corn hybrid Pioneer 0461XR receiving 202 kg N ha^{-1} as spring pre-plant UAN (32-0-0) (N-P-K). Corn grain yields were 10 Mg ha^{-1} in 2011 (site 1) and 8.5 Mg ha^{-1} in 2012 (site 2). For this study, corn hybrid Pioneer 35K09 was planted on 76-cm row spacing at a seeding rate of 84,000 seeds ha^{-1} on 18 May 2012 and 7 June 2013.

Treatments

Treatments included two N sources [AMS (21-0-0-24) (N-P-K-S) and UAN] applied in the fall at three timings (early, mid, and late) with 34 kg N ha^{-1} and spring pre-plant time with 34, 68, 135, and 202 kg N ha^{-1} and an unfertilized 0-N control (Table 1.1). Each of the treatments were imposed on plots of size 6 × 15 m arranged in a randomized complete block design with four replications. Both sources of N were broadcast-applied as liquids. The UAN-treated plots received an application of gypsum [(0-0-0-18) (N-P-K-S)] to equalize the sulfur content provided by the AMS source. Early, mid, and late fall application timings received 34 kg N ha^{-1} in the fall and 168 kg N ha^{-1} as spring pre-plant, for a total N rate of 202 kg ha^{-1}. Dates of N fertilizer application are listed in Table 1.2.

Corn stalk strength and C/N ratios

Corn residue was examined using the residue bag method (Falconer et al., 1933; Lunt, 1933, 1935). This method was chosen for its simplicity, replicability (Vanlauwe et al., 1997), and ability to keep residue within the plots during the relatively windy fall and winter months in central Illinois (Angel, 2009). Within 24 h after the N fertilizer applications on the corn residue, nylon-mesh bags (90 × 60 cm) were filled with approx. 500 g of field-moist residue left from the preceding growing season within each plot. At each sampling time, a residue bag was prepared and collected and sufficient bags were prepared to remove samples at each of the times of later N application treatments.

Residue bag collection dates are listed in Table 1.2. A late fall 2011 residue bag collection could not be conducted. To remove soil particles adhering to the mesh bags at the time of collection, bags containing the samples were gently spray-rinsed and immediately dried at 30°C to constant weight. Stalk strength was measured with a push penetrometer (adapted from Zuber and Grogan, 1961) to act as a surrogate for corn stalk decomposition. It was assumed that a corn stalk in a more advanced state of decomposition would be weaker than a corn stalk in an earlier stage of decomposition. Stalks were measured instead of other plant parts (i.e. leaves, cobs) because they are the most durable plant part present in no-till fields at the time of planting a new crop. Corn stalks were manually separated from the rest of the residue to record their mechanical strength using a push penetrometer (Dillon GL Digital Force Gauge, Dillon Force Measurement Products and Systems, MN) equipped with a cone tip (10 mm width) to punch a hole in the internode of the collected stalks. The penetrometer force measurements, given in m kg s^{-2}, were performed on top of a compact vise with a 2.5-cm wide and 5-cm deep clearance. All residue material was ground (Wiley Mills, Thomas Scientific, NJ) and a subsample was collected for C/N ratio analysis using dry combustion (Bremner and Mulvaney, 1982) (Leco TruSpec CHN, Leco Corp., MI).

Soil nitrogen

Soil samples were collected after planting for the control and the treatments receiving the fall-spring split N fertilizer application. The samplings were conducted on 7 June 2012 and on 9 July 2013. Three core (5-cm diameter) composite soil samples (0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm depth increments) were collected within the middle rows of each plot using a tractor-mounted hydraulic probe. The soil samples were dried at 35°C, ground to pass a 2-mm sieve (Dynacrush mill, Custom Laboratory Equipment Inc., FL), and analyzed for nitrate-N (NO_3^-) and ammonium-N (NH_4^+) using the diffusion method described in Mulvaney et al. (1997).

Grain yield

Two center rows for each plot were harvested on 25 Oct. 2012 and 15 Nov. 2013 with a two-row harvester (Almaco SPC 40, IA). Corn grain yield was corrected to 155 g kg^{-1} moisture content.

Statistical analysis

Statistical analysis was performed using the PROC MIXED procedure of SAS 9.4 (SAS Institute, 2013). Significant effects and individual contrasts were declared at $\alpha \leq 0.10$. The timing of N fertilizer application and N source were considered fixed factors while blocks were considered random. The analysis procedure for augmented factorials described in Piepho et al. (2006) was applied to test the factorial design of N source and timing of N application vs. the control treatment for grain yield, stalk strength measurements, and the C/N ratios of the corn residue. Due to the contrasting weather conditions in 2012 and 2013 it was decided to analyze each season individually.

The soil NO_3^- and NH_4^+ data, which consisted of samples taken at four consecutive depths, were analyzed using repeated measures (Littell et al., 2006). Covariance structures were selected by comparing the values for the Akaike Information Criterion (AIC) (Akaike, 1974). Fixed factors included the N source, N application timing, and depth of sampling, while blocks were considered random. Depth of sampling was considered a repeated measure. The LSMEANS procedure of SAS 9.4 was used to separate means when significant effects in the model were found (SAS Institute, 2013).

RESULTS AND DISCUSSION

Weather conditions

Weather conditions for the 2012 and 2013 growing seasons were dissimilar. Mean air temperatures during the 2011 season, in which the corn residue analyzed during 2011 to 2012 was produced, were within 1°C above and below the 30-yr normal from April to June, while temperatures in July were over 2.5°C greater than the 30-yr normal (Table 1.3). Mean air temperatures in August and September 2011 were above and below the 30-yr normal, respectively. Precipitation during the 2011 growing season was above the 30-yr normal for April and May but below the 30-yr normal from June to September, with approx. 43 mm less precipitation from April to September 2011 compared to the 30-yr normal (Table 1.3).

The 2012 growing season was characterized by greater air temperatures and lower precipitation compared to the 30-yr normal. Mean air temperatures in March, April, and May were 8, 2.3, and 5.1°C greater than the 30-yr normal, respectively (Table 1.3). These abnormally high air temperatures, coupled with precipitation approx. 140 mm lower than the 30-yr normal for the March to May period, resulted in very dry soil conditions at the time of planting on 18 May 2012. Mean air temperatures during the months of June to July were over 3.5°C greater compared to the 30-yr normal, and precipitation in June to July was approx. 170 mm below the 30-yr normal (Table 1.3). These historical weather anomalies (Mallya et al., 2013) greatly affected corn growth, development, and ultimately grain yields in the 2012 growing season.

Mean air temperatures during the 2013 growing season were below the 30-yr normal in April but above the 30-yr normal in May to June (Table 1.3). Mean air temperatures in July and August were below the 30-yr normal but above the 30-yr normal in September (Table 1.3). Precipitation was approx. 90 mm above the 30-yr normal in April, below the 30-yr normal in May, and over 50 mm above the 30-yr normal in June (Table 1.3). As a result of excess precipitation, the planting date was delayed until early June 2013 due to the lack of days suitable for field work. Precipitation during the period July to September was approx. 160 mm below the 30-yr normal (Table 1.3), although soil moisture content was likely sufficient for corn development and grain fill.

Grain yield

Plots with spring pre-plant N fertilizer application only

There was a significant main effect of N rate in both seasons ($p < 0.003$ for 2012 and 2013) and a significant main effect of N source in 2013 ($p < 0.009$). In 2012, the grain yield response to spring pre-plant N fertilizer was best described with a quadratic response (Fig. 1.1), with an optimum grain yield of 7.2 Mg ha^{-1} achieved with 134 kg N ha^{-1}. Grain yields were limited in 2012 with a low response to N because water was the limiting factor more so than the N supply. In 2013, a linear response provided the best fit for the grain yield response to spring pre-plant N fertilizer application (Fig. 1.1). The grain yield response to N was not maximized and greater grain yield could have been achieved with greater N fertilizer rates since water was not a limiting factor. In 2013, the mean grain yield was significant and greater for UAN than for AMS ($p < 0.009$, 9.5 and 8.5 Mg ha^{-1} for UAN and AMS, respectively). Grain yields for the untreated control plots were 4.9 and 7.2 Mg ha^{-1} for the 2012 and 2013 growing seasons, respectively (Fig. 1.1).

Plots with fall and spring pre-plant N fertilizer applications

There was a significant main effect of the control vs. treatment term for both seasons (p <.0001) for grain yield, indicating that grain yields were improved significantly by adding N fertilizer each season, regardless of the application timing. The benefit of adding N fertilizer was of 2.2 Mg ha^{-1} in 2012 and of 2.6 Mg ha^{-1} in 2013 (Table 1.4).

Nitrogen fertilizer applied as close to the time of planting as possible is the safest choice for a corn producer to avoid the risk of loss of fall-applied N during the fall, winter, and early spring months. For this experiment, it was expected that the plots receiving the late fall and spring pre-plant N applications would yield more than the plots receiving the early and mid-fall plus spring pre-plant N applications, and that the plots receiving the full N rate at spring pre-plant would have the highest grain yield. However, that was not observed in this study (Table 1.4). Across both seasons, grain yield response to timing of N fertilizer application was not significantly different for any application timing. This is likely due to the N fertilizer applied in the fall being only 17% of the total N applied. In addition, in the 2012 growing season the maximum yield response to N was achieved with an application rate of 134 kg ha^{-1}, thus a yield difference would not have been detected even in the complete loss of the 34 kg N ha^{-1} applied in the fall since the spring N rate was of 168 kg ha^{-1}. The lack of a significant main effect due to the timing of fall N fertilizer applications compared to the spring pre-plant N fertilizer application agrees with the results of a 3-yr study conducted in Wisconsin by Bundy and Andraski (2002), in which grain yields were not improved by fall N applications compared to similar rates of spring pre-plant N applications.

Stalk strength measurements

Applications of UAN and AMS in early fall or mid-fall 2011 did not change stalk strength at the April 2012 sampling event relative to the untreated control ($p > 0.2$, Table 1.4). Moreover, no decreasing trend over time was observed for corn stalk strength (Fig. 1.2). The April 2012 mean stalk strength for the control treatment was nearly unchanged compared to the mean stalk strength in early fall 2011 (50 and 51 m kg s^{-2}, respectively). The mean stalk strength in April 2012 for the fall N treatments were slightly lower than at the time of N application in the fall, but not significantly different from the untreated control (Fig. 1.2). Dry and warm conditions in the period of February to April 2012 were not conducive to residue decomposition and may have reduced high microbial activity needed for corn residue breakdown.

The residue analyzed during the 2012 to 2013 period was produced by a corn crop that experienced severe water stress during the droughty conditions in 2012. There was a decreasing stalk strength trend over time at about the same rate regardless of treatment (Fig. 1.3). The untreated control had a mean stalk strength of 41 m kg s^{-2} in early fall 2012 and of 17 m kg s^{-2} in April 2013, a 59% reduction (Fig. 1.3). However, none of the timing and source of N application treatments exhibited weaker corn stalks in comparison to the untreated control at the April 2013 sampling event ($p > .25$).

The stalk strength data did not provide support to the hypothesis that adding post-harvest UAN or AMS fertilizer accelerates stalk decomposition, as measured by stalk strength (Table 1.4, Fig. 1.2 and 1.3). Rather, it was likely that weather conditions determined how fast stalk strength decreased over time, as warm and moist conditions promote microbial attack of plant residues. In addition, the stalk strength of the residue produced during the 2012 growing season was around 10 m kg s^{-2} weaker than the residue from the 2011 growing season, and also showed a greater rate of stalk weakening (Fig. 1.2 and 1.3). The unusually warm and dry conditions in the early spring of 2012 likely reduced microbial decomposition of the residues produced during 2011. Similar conclusion were reached by Al-Kaisi (2014), although a different approach was taken. In Al-Kaisi (2014), corn residue breakdown as affected by post-harvest N fertilizer rates of 0, 34, and 68 kg ha^{-1} was measured as percent residue remaining in mesh bags over 12 months, and also measured by CO_2 evolution methods under laboratory conditions at temperatures of 0 and 32°C. No differences in the rate of residue breakdown were found (Al-Kaisi, 2014), even though the researchers applied twice as much post-harvest N as in this study, thus indicating that N content may not be the limiting factor but rather not enough time of warm and moist conditions. Bundy and Andraski (2002) also found that post-harvest N fertilizer applications did not significantly influence residue decomposition rates in a no-till corn system, as measured by percent residue remaining in mesh bags over time. Researchers have found that the addition of N fertilizer may not increase the rate at which residues decompose likely because no additional N was required in the first place or because the microorganisms were able to obtain sufficient N from the soil N content (Allison and Murphy, 1963; Smith and Douglas, 1968, 1971). Although these previous experiments (Allison and Murphy, 1963; Smith and Douglas, 1968, 1971) were not conducted on corn residues, the insights gained from these experiments are still applicable to corn residue decomposition.

Carbon-to-nitrogen ratios of corn residue

Typically, residue from corn plants has a C/N ratio well above 25/1 which would induce N immobilization as microorganisms scavenge for N from other sources to decompose the residues. This is seen as a negative outcome since microorganisms are known to temporarily immobilize soil N to decompose low-quality residues such as corn, and may reduce plant-available soil N to the crop or result in needing additional N fertilization to overcome this effect on crop yield (Parr and Papendick, 1978).

Mean C/N ratios of N-treated residue were between 52/1 to 87/1 (Fig. 1.4 and 1.5), and are comparable to the C/N ratios reported by others (Tarkalson et al., 2008; Al-Kaisi and Guzman, 2013). A mixed trend over time was found for the residue for the 2011 to 2012 period, in which C/N ratios increased from early fall 2011 to mid-fall 2011 followed by a decrease for the last sampling in April 2012 (Fig. 1.4).The residue for the 2012 to 2013 period showed no decreasing trend over time, and high variability was observed at each sampling event (Fig. 1.5). An analysis of variance of the last sampling event for each season (April 2012 and April 2013) was conducted. The mean C/N ratio of the control was greater and significant ($p < 0.08$) than the mean C/N ratio for the combined effect of the treatments for the 2011 to 2012 period (63/1 vs 57/1, Table 1.4). However, this significant difference had no practical application as the mean C/N was still well above 25/1.

For the residue for the 2012 to 2013 period, there were no significant main effects or interactions. At the April 2013 sampling event, the mean C/N ratio of the control was of 72/1 compared to 68/1 for the mean treatment effect (Table 1.4). These results provided no evidence to support the hypothesis that adding post-harvest UAN or AMS fertilizer decreases the C/N ratio of corn residues in field conditions. These results agree with the results from Bundy and

Andraski (2002), where it was reported that post-harvest N applications had no effect on the C/N ratios of corn residue.

Soil NH_4^+

There was a significant N source × depth interaction ($p < 0.0001$) for the analysis of soil NH_4^+ concentration in 2012, which was approx. 15 mg kg^{-1} greater in the top 15 cm of soil for AMS than for UAN (Table 1.5), regardless of N fertilizer application timing. This greater concentration of soil NH_4^+ in the top 15 cm of soil for the plots treated with AMS was likely due to the warm and dry conditions that prevailed during February to May in 2012 which could have decreased the activity levels of soil microorganisms that convert NH_4^+ to NO_3^-. In addition, the period of time between the spring N application of UAN and AMS and the soil sampling, 21 d, was likely not enough to allow for the conversion of NH_4^+ to NO_3^-.

For the 2013 season, there was a significant N timing × depth interaction ($p < 0.049$). Across sources, the soil NH_4^+ concentration in the top 15 cm for the late fall N fertilizer application was approx. 11 and 8 mg kg^{-1} greater than the concentration for the mid and early fall N fertilizer applications, respectively (Table 1.5). This reduced concentration of soil NH_4^+ for the early and mid-fall N fertilizer applications is likely due to greater N losses compared to the late fall N fertilizer application.

Soil NO_3^-

There was a significant N source × N application timing × depth interaction ($p < .001$) for the analysis of soil NO_3^- content in both 2012 and 2013. Of practical importance, the treatment with the highest amount of soil NO_3^- in the top 15 cm of soil in 2012 was the application of UAN in early fall (Table 1.5), with a mean soil NO_3^- content of approx. 43 mg kg^{-1}. Compared to the soil NO_3^- concentration of the mid-fall application, it is likely that the plots with N application in early fall experienced a greater conversion of soil $NH_4^+$to NO_3^-.

For the 2013 season, the plots with the late fall UAN had the highest soil NO_3^- levels in the top 15 cm of soil (Table 1.5). The plots with early and mid-fall N fertilizer applications of UAN showed a reduction of approx. 53% in soil NO_3^- levels compared to the late fall UAN application in the top 15 cm of soil, suggesting that some soil NO_3^- loss occurred for the plots with earlier N applications. This agrees with the results from previous researchers (Kitur et al., 1984; Rice and Smith, 1984). Due to the high probability for N loss, UAN fertilizer is not recommended for fall applications.

As expected for a broadcast-applied N fertilizer application, most of the variability for the soil NH_4^+ and NO_3^- concentrations in 2012 and 2013 was found in the top 15 cm of soil (Table 1.5). The soil NH_4^+ and NO_3^- concentrations at soil depths from 15 to 90 cm were comparable to those of the untreated control plots (Table 1.6).

CONCLUSION

In this experiment, there was no evidence that post-harvest UAN or AMS surface-broadcast applications results in reduced C/N ratios of the corn residue or weakened corn stalks when compared to an untreated control in a no-till, corn-on-corn cropping system. Rather, weather conditions likely drove the decomposition rate of surface residues.

The high soil NO_3^- levels in the top 15 cm of soil for the late fall UAN applications for 2013 compared to the early and mid-fall UAN applications provided some evidence that post-harvest UAN applications with the purpose of accelerating corn residue decomposition added N to the soil that was not used by soil microorganisms or taken up by the next corn crop in the following season, and was likely lost to the environment. The evidence collected by this study indicates that the practice of applying post-harvest N fertilizer to accelerate corn residue decomposition is not warranted even when post-harvest N applications are conducted as early as September. Although somewhat different methodologies were used, other researchers arrived at similar conclusions while using post-harvest N application rates twice as high than in this experiment (Bundy and Andraski, 2002; Al-Kaisi, 2014). Rather than applying fall N, corn producers in no-till, corn-on-corn systems with large volumes of corn residue should focus on other alternatives to reduce the amount of residues. One alternative is to use agricultural equipment capable of mechanically reducing the particle size of surface corn residue and standing corn stalks.

TABLES

Table 1.1 Nitrogen (N) fertilizer application timing, N fertilizer rate, N source, and total N rate for the fall and spring pre-plant split applications and the spring pre-plant-only applications. The N sources were urea-ammonium nitrate (UAN) and ammonium sulfate (AMS).

	N application timing and rate					
Type	Early fall	Mid fall	Late fall	Spring pre-plant	N source	Total N rate
	kg N ha^{-1}					kg N ha^{-1}
Control	0	0	0	0	None	0
Fall + spring	34	0	0	168	UAN	202
	34	0	0	168	AMS	202
	0	34	0	168	UAN	202
	0	34	0	168	AMS	202
	0	0	34	168	UAN	202
	0	0	34	168	AMS	202
Spring only	0	0	0	34	UAN	34
	0	0	0	34	AMS	34
	0	0	0	68	UAN	68
	0	0	0	68	AMS	68
	0	0	0	135	UAN	135
	0	0	0	135	AMS	135
	0	0	0	202	UAN	202
	0	0	0	202	AMS	202

Table 1.2. Dates for the nitrogen (N) fertilizer applications and the residue bag collections. A late fall N application and bag collection was not completed for the 2011-2012 period.

N fertilizer application				
Period	Fall			Spring
	Early	Mid	Late	
2011-2012	3 Oct. 2011	24 Oct. 2011	-	17 May 2012
2012-2013	28 Sept. 2012	31 Oct. 2012	15 Nov. 2012	6 June 2013

Residue bag collection				
Period	Fall			April
	Early	Mid	Late	
2011-2012	4 Oct. 2011	25 Oct. 2011	-	16 Apr. 2012
2012-2013	11 Oct. 2012	2 Nov. 2012	16 Nov. 2012	26 Apr. 2013

Table 1.3. Air temperature (°C) and precipitation (mm) departures from the 30-yr normal. Data provided by PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 9 Sept. 2016.

		Departure from 30-yr normal		
	30-yr normal†	2011	2012	2013
	°C			
Jan.	-3.7	-1.9	5.1	2.0
Feb.	-1.5	-0.4	4.1	2.4
Mar.	4.4	0.7	8.0	-3.2
Apr.	10.9	0.4	2.3	-0.7
May	16.8	-0.3	5.1	1.5
June	22.0	0.8	3.6	0.3
July	23.5	2.8	3.7	-1.6
Aug.	22.5	0.9	0.1	-1.8
Sept.	18.9	-1.2	-1.8	1.8
Oct.	12.3	0.4	-2.7	0.4
Nov.	5.7	1.9	-2.8	-1.5
Dec.	-1.4	3.3	-0.7	0.8
Apr. to Sept. avg.	19.1	0.6	2.2	-0.1
	mm			
Jan.	52	-32	21	16
Feb.	54	34	-24	25
Mar.	69	-28	-38	-21
Apr.	91	86	-57	96
May	119	5	-47	-5
June	103	-3	-67	54
July	114	-74	-104	-32
Aug.	93	-48	49	-83
Sept.	73	-9	63	-51
Oct.	82	-27	40	6
Nov.	91	23	-63	-48
Dec.	70	-6	-15	-16
Apr. to Sept. total	593.1	-43	-163	-20

† Period of 1981-2010.

Table 1.4. Mean corn yield, corn stalk strength, and corn residue carbon-to-nitrogen (C/N) ratio for the 2 × 3 augmented factorial design. Treatments received urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) N fertilizer applications in early, mid, or late fall at 34 kg ha^{-1} and at spring pre-plant at 168 kg ha^{-1} and at spring pre-plant only at an N rate of 202 kg ha^{-1}. The control received no N fertilizer.

Effect	Type	Corn yield		Stalk strength		C/N ratio	
		2012	2013	2012	2013	2012	2013
		– Mg ha^{-1} –		– m kg s^{-2} –			
Control vs. Treatments	Control	4.9a†	7.2a	50	17	63b	72
	Treatments	7.2b	9.8b	45	19	57a	68
Control vs. Source	Control	4.9	7.2	50	17	63	72
	UAN	7.3	10.1	45	19	55	70
	AMS	7.2	9.6	44	19	59	66
Control vs. Timing	Control	4.9	7.2	50	17	63	72
	Early Fall.	7.3	9.3	45	18	56	67
	Mid Fall	7.2	10.3	44	20	57	67
	Late Fall	-	9.7	-	19	-	69
	Spring	7.3	10.1	-	-	-	-

† Means within each effect, year, and column followed by the same letter are not significantly different ($p \geq 0.10$). Letters are not included when the effect was not significant in the model.

Table 1.5. Soil NH_4^+ and NO_3^- concentrations at depths of 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm for the plots that received urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) in early, mid, or late fall at 34 kg ha^{-1} and at spring pre-plant at 168 kg ha^{-1} during the 2012 and 2013 growing seasons. Soil sampling was conducted after planting.

			NH_4^+			NO_3^-		
Season	Source	Depth	Early fall	Mid fall	Late fall	Early fall	Mid fall	Late fall
		cm		mg kg^{-1}			mg kg^{-1}	
2012	AMS	0-15	33.7	25.9	-	30.3	35.7	-
		15-30	11.1	8.8	-	7.0	5.5	-
		30-60	5.9	4.4	-	3.2	2.3	-
		60-90	3.2	2.7	-	3.4	2.9	-
	UAN	0-15	16.5	14.1	-	43.8	35.8	-
		15-30	9.4	7.3	-	7.4	6.8	-
		30-60	5.8	4.5	-	4.5	3.5	-
		60-90	3.9	4.2	-	3.3	2.6	-
2013	AMS	0-15	19.2	15.7	22.4	31.0	27.2	33.4
		15-30	3.7	4.1	5.9	6.7	7.2	7.1
		30-60	3.3	2.6	3.5	7.0	7.0	7.1
		60-90	3.6	1.4	2.5	6.8	6.5	6.6
	UAN	0-15	13.8	10.7	26.3	31.7	38.3	76.0
		15-30	4.8	4.4	4.3	8.8	8.5	10.4
		30-60	4.2	4.1	3.1	9.0	8.8	8.3
		60-90	2.0	3.0	2.7	9.7	9.2	7.5

Table 1.6. Soil NH_4^+ and NO_3^- concentrations at depths of 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm for the control plots that received no N application during the 2012 and 2013 seasons. Soil sampling was conducted shortly after planting.

	NH_4^+		NO_3^-	
Depth	2012	2013	2012	2013
cm	mg kg^{-1}		mg kg^{-1}	
0-15	11.2	4.8	7.9	6.5
15-30	6.8	4.2	5.7	4.6
30-60	5.2	3.5	2.7	5.5
60-90	3.1	1.6	2.1	5.9

FIGURES

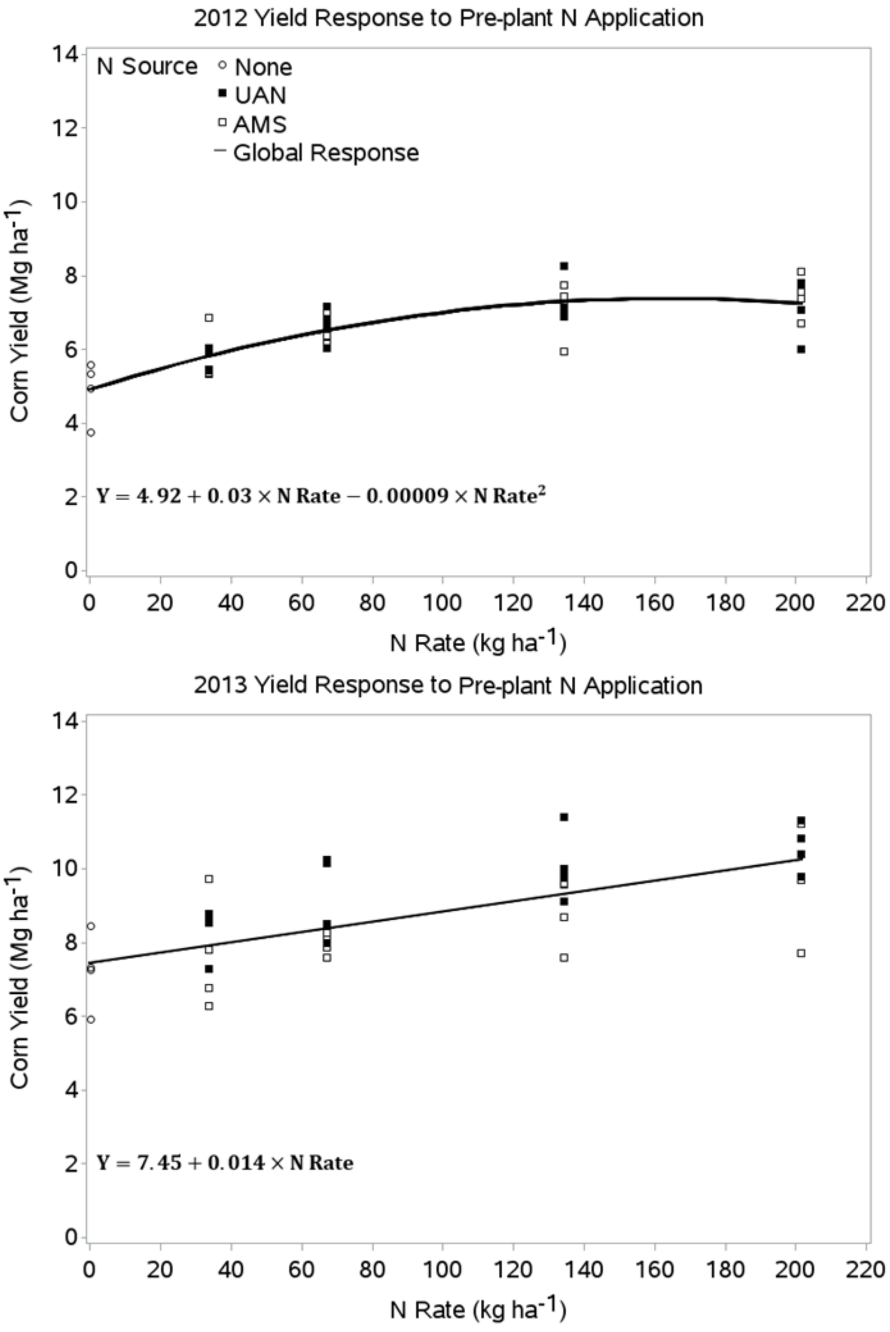


Fig. 1.1. Corn yield response to nitrogen (N) fertilizer for the plots receiving N at spring pre-plant at five N rates (0, 34, 68, 134, and 202 kg ha^{-1}) and two N fertilizer sources, urea-ammonium nitrate (UAN) and ammonium sulfate (AMS), during the 2012 and 2013 growing seasons.

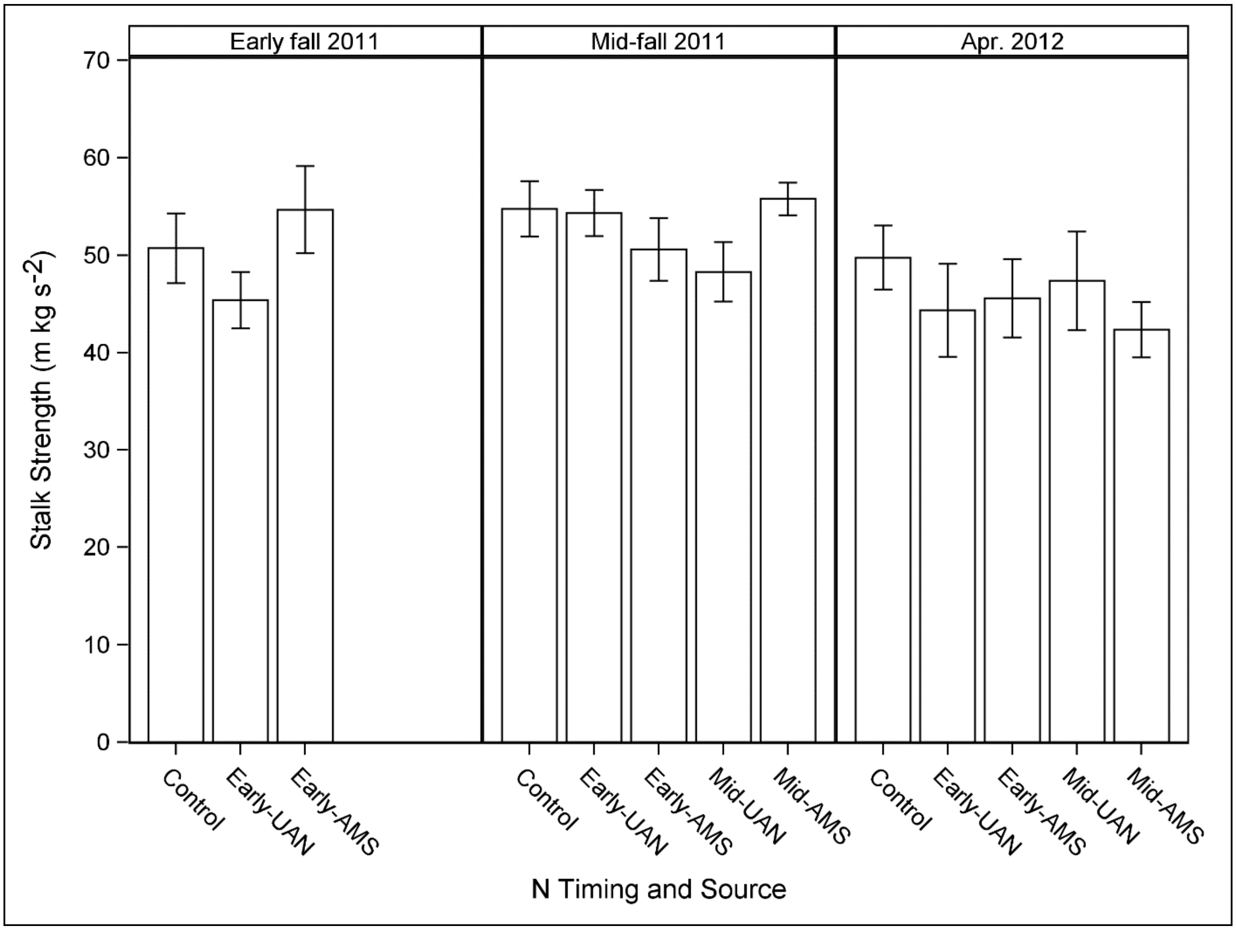


Fig. 1.2. Mean stalk strength for the corn residue bags collected in early fall, mid-fall 2011, and April 2012 for the 2011 to 2012 period as affected by urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) nitrogen (N) fertilizer applications in early or mid-fall at 34 kg N ha^{-1}. Untreated control plots were added for comparison. Data shown are the means of four replicates and the vertical bars represent the standard error.

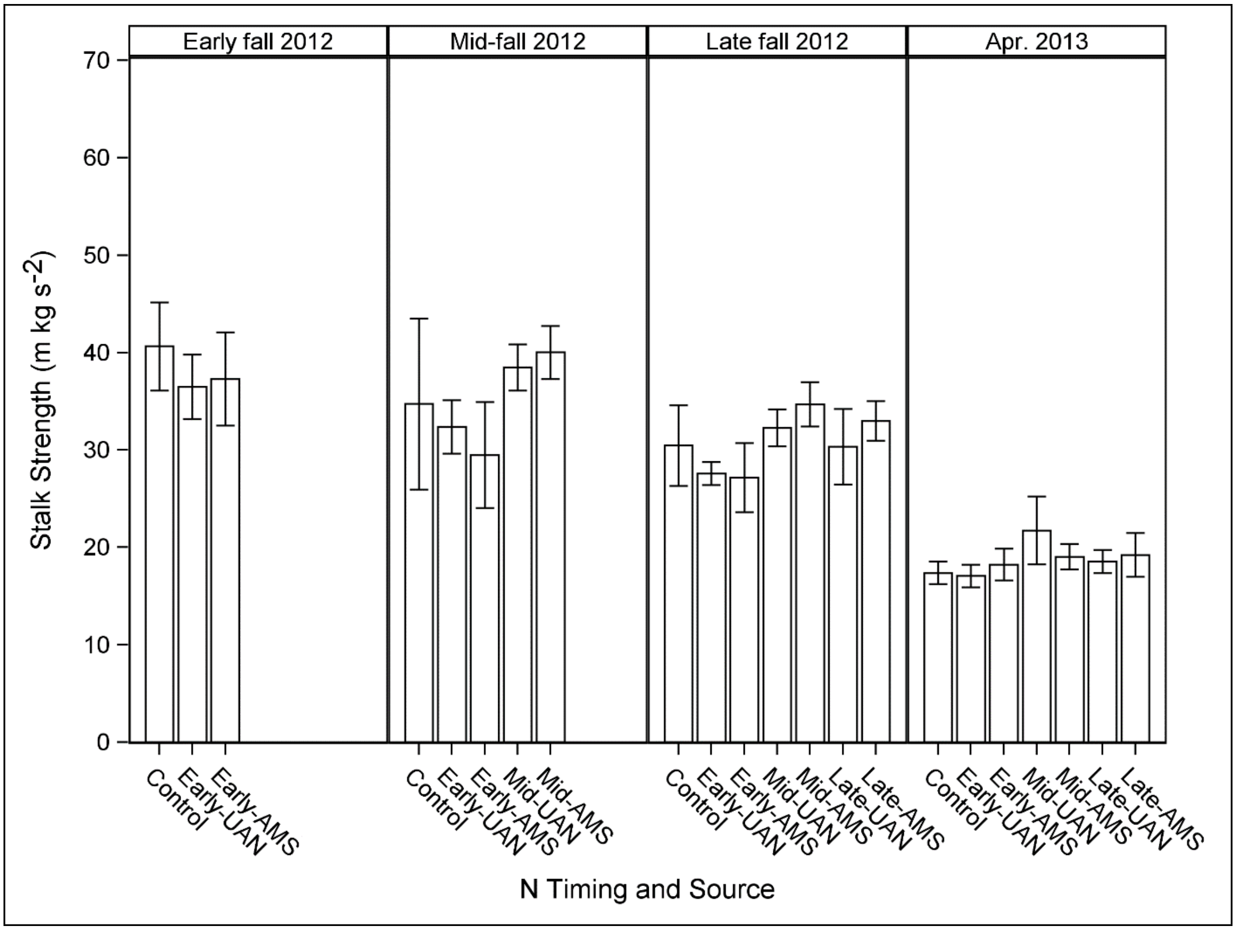


Fig. 1.3. Mean stalk strength for the corn residue bags collected in early fall, mid-fall, late fall 2012, and April 2013 for the 2012 to 2013 period as affected by urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) nitrogen (N) fertilizer applications in early fall, mid-fall, or late fall at 34 kg N ha^{-1}. Untreated control plots were added for comparison. Data shown are the means of four replicates and the vertical bars represent the standard error.

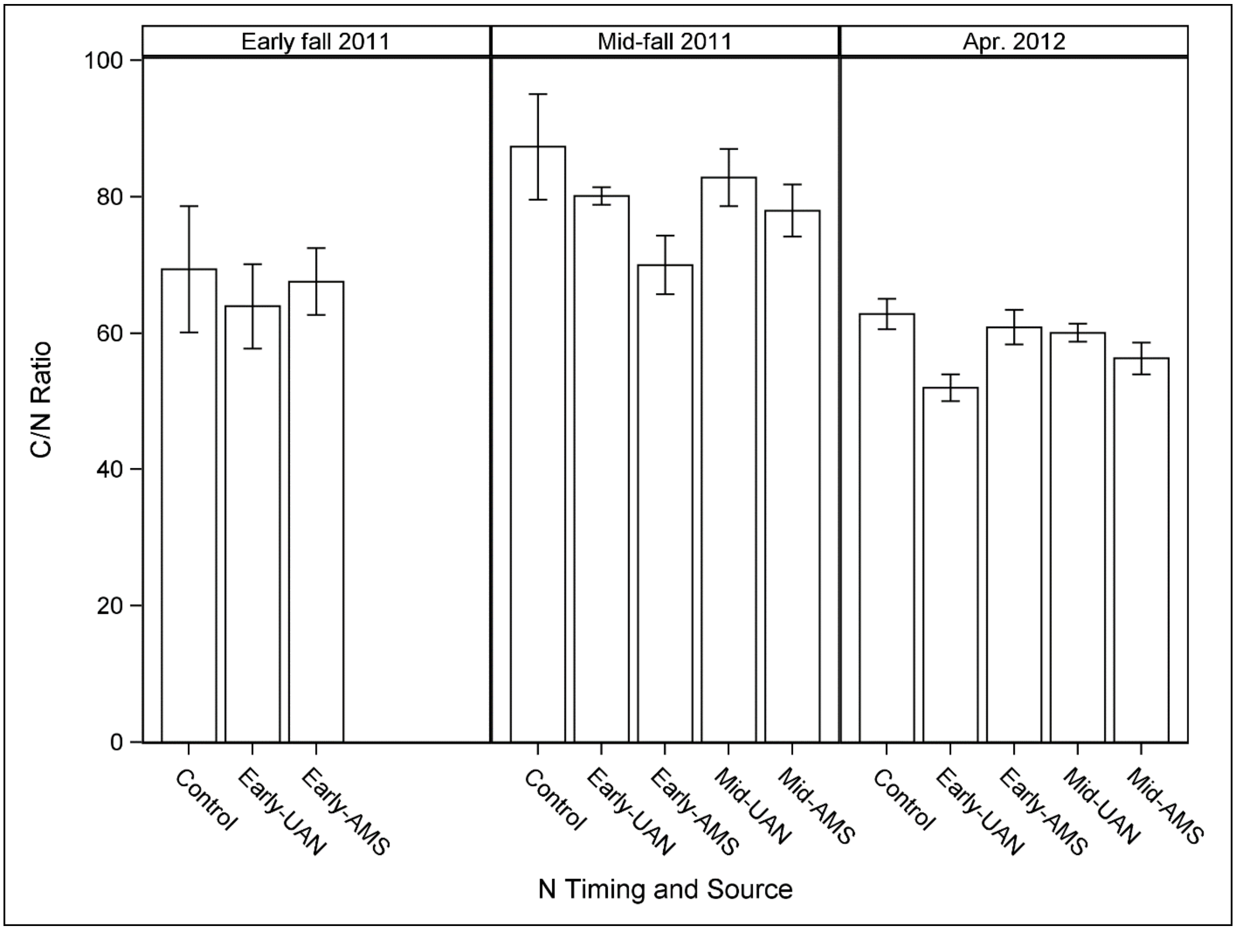


Fig. 1.4. Mean carbon-to-nitrogen (C/N) ratio for the corn residue bags collected in early fall 2011, mid-fall 2011, and April 2012 for the 2011 to 2012 period as affected by urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) nitrogen (N) fertilizer applications in early or mid-fall at 34 kg N ha^{-1}. Untreated control plots were added for comparison. Data shown are the means of four replicates and the vertical bars represent the standard error.

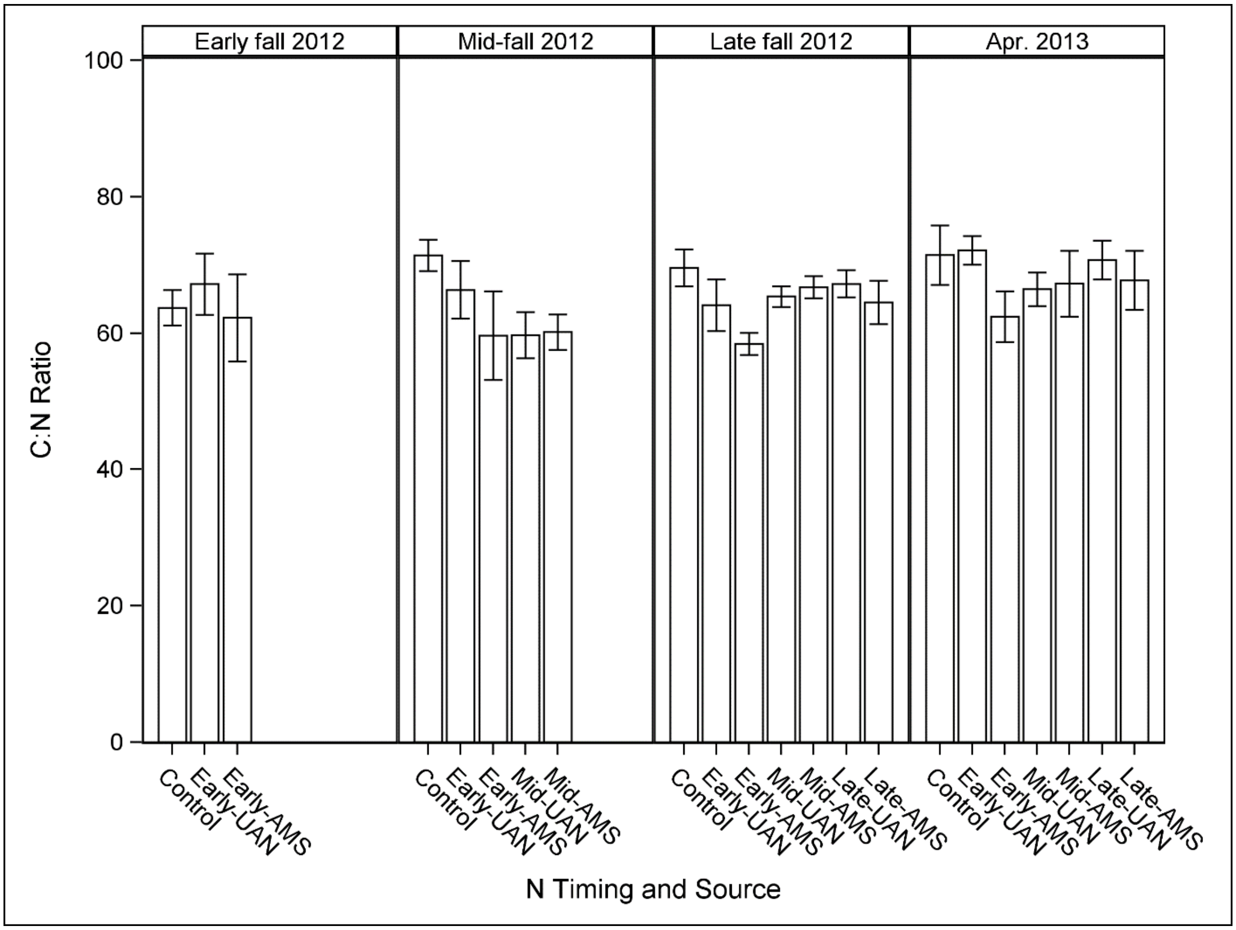


Fig. 1.5. Mean carbon-to-nitrogen (C/N) ratio for the corn residue bags collected in early fall, mid-fall, late fall 2012, and April 2013 for the 2012 to 2013 period as affected by urea-ammonium nitrate (UAN) and ammonium sulfate (AMS) nitrogen (N) fertilizer applications in early fall, mid-fall, or late fall at 34 kg N ha^{-1}. Untreated control plots were added for comparison. Data shown are the means of four replicates and the vertical bars represent the standard error.

REFERENCES

Akaike, H. 1974. A new look at the statistical model identification. IEEE Trans. on Automatic Control 19:716-723.

Al-Kaisi, M. 2014. Myths and facts about residue breakdown. Integrated Crop Management News. Paper 34. http://lib.dr.iastate.edu/cropnews/34 (accessed 12 July 2016).

Al-Kaisi, M.M., and J.G. Guzman. 2013. Effects of tillage and nitrogen rate on decomposition of transgenic Bt and near-isogenic non-Bt maize residue. Soil Tillage Res. 129:32-39.

Allison, F. E., and R. M. Murphy. 1963. Comparative rates of decomposition in soil of wood and bark particles of several species of pines. Soil Sci. Soc. Am. Proc. 27:309-312

Allmaras, R.R., G.W. Langdale, P.W. Unger, R.H. Dowdy, and D.M. Van Doren. 1991. Adoption of conservation tillage and associated planting systems. In: Lal, R., Pierce, F.J. (Eds.), Soil Management for Sustainability. Soil and Water Conservation Society, Ankeny, IA, pp. 53-83.

Angel, J. 2009. Average wind speed in Illinois. State Climatologist Office for Illinois. http://www.isws.illinois.edu/atmos/statecli/wind/wind.htm (accessed 9 Sept. 2016).

Ayres, G.E., and W.F. Buchele. 1971. Harvesting and storing corn plant forage. ASAE paper 71-665. ASABE, St. Joseph, MI.

Baker, J.L., and J.M. Laflen. 1983. Water quality consequences of conservation tillage: New technology is needed to improve the water quality advantages of conservation tillage. J. Soil Water Cons. 38:186-193.

Brady, N.C., and R.R. Weil. 2008. The nature and properties of soils. Prentice-Hall Inc.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen-total. In: A.L. Page et al. (eds). Methods of soil analysis, Part 2. Chemical and Microbiological Properties – Agron. Monogr. 9. p. 595-624.

Brown, P.L., and D.D. Dickey. 1970. Losses of wheat straw residue under simulated field conditions. Soil Sci. Soc. Am. J. 34:118-121.

Buman, R.A., B.A. Alesii, J.L. Hatfield, and D.L. Karlen. 2004. Profit, yield, and soil quality effects of tillage systems in corn–soybean rotations. J. Soil Water Cons. 59:260-270.

Bundy, L., and T. Andraski. 2002. Wisconsin Fertilizer Research Program and Council, Project no. 175-99.

Conservation Technology Information Center (CTIC). 2002. Economic benefits with environmental protection: no-till and conservation buffers in the Midwest. Purdue University.

Duvick, D. N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86:83-145.

Duvick, D. N. 1984. Genetic contributions to yield grains of U.S hybrid maize, 1930 to 1980. Pages 15-47 in W. R. Fehr, ed. Genetic contributions to yield gains of five major crop plants. Crop Sci. Soc. Am. Spec. Publ. 7. p. 15-47.

Dwyer, L.M., and M. Tollenaar. 1989. Genetic improvement in photosynthetic response of hybrid maize cultivars, 1959 to 1988. Can. J. Plant Sci. 69: 81-91.

Ehmke, T. 2012. 4R Nutrient management. Crops and Soil Magazine 45(5):4-10. https://www.agronomy.org/files/publications/crops-and-soils/4r-nutrient-management.pdf (accessed 6 Sept. 2016).

Ernst, O., O. Bentancur, and R. Borges. 2002. Descomposición de rastrojo de cultivos en siembra sin laboreo: trigo, maíz, soja y trigo después de maíz o de soja. (In Spanish, with English abstract.) Agrociencia 6:20-26.

Falconer, G.J., J.W. Wright, and H.W. Beall. 1933. The decomposition of certain types of fresh litter under field conditions. Am. J. Bot. 20:196-203.

Green, C.J., A.M. Blackmer, and R. Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. Soil Sci. Soc. Am. J. 59:453-459.

Griffin, D.M. 1972. Ecology of soil fungi. Syracuse: Syracuse University Press.

Gupta, S.C., C.A. Onstad, and W.E. Larson. 1979. Predicting the effects of tillage and crop residue management on soil erosion. J. Soil Water Cons. Spec. Publ. 25:7-9.

Hill, P.R. 1998. Fall strip-till systems for corn production: Results from Monsanto's Center of Excellence. 1999 No-Till Farmer Conference.

Hubbard, V.C., and D. Jordan. 1996. Nitrogen recovery by corn from nitrogen-15 labeled wheat residues and intact roots and soil. Soil Sci. Soc. Am. J. 60:1405-1410.

Johnson, J.F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622-636.

Kitur, B. K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of 15N-depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76:240-242.

Lee, E. A., and M. Tollenaar. 2007. Physiological basis of successful breeding strategies for maize grain yield. Crop Sci. 47(S3):S202- S215.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. SAS Institute Inc., Cary, NC.

Lorenz, A.J., T.J. Gustafson, J.G. Coors, and N.D. Leon. 2010. Breeding maize for a bioeconomy: a literature survey examining harvest index and stover yield and their relationship to grain yield. Crop Sci. 50:1-12.

Lunt, H.A. 1933. Effects of weathering upon composition of hardwood leaves. J. Forestry 31:43-45.

Lunt, H.A. 1935. Effects of weathering upon dry matter and composition of hardwood leaves. J. Forestry 33: 607-609.

Mallya, G., L. Zhao, X.C. Song, D. Niyogi, and R.S. Govindaraju. 2013. 2012 Midwest drought in the United States. J. Hydrol. Eng. 18:737-745.

Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion. Agric. Ecosyst. Environ. 89:149-166.

Mclsaac, G.F., J.K. Mitchell, and M.C. Hirschi. 1987. Slope steepness effects on soil loss from disturbed lands. Trans. ASAE 30:1005-1012.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action plan for reducing, mitigating, and controlling hypoxia in the Northern Gulf of Mexico. Washington (DC): Office of Wetlands, Oceans, and Watersheds, US Environmental Protection Agency.

Mock, J.J., and D.C. Erbach. 1977. Influence of conservation-tillage environments on growth and productivity of corn. Agron. J. 69:337-340.

Mulvaney, R.L., S.A. Khan, W.B. Stevens, and C.S. Mulvaney. 1997. Improved diffusion methods for determination of inorganic nitrogen in soil extracts and water. Biol. Fert. Soils 24:413-420.

Mungai, N.W., and P.P. Motavalli. 2006. Litter quality effects on soil carbon and nitrogen dynamics in temperate alley cropping systems. Appl. Soil Ecol. 31:32-42.

Nafziger, E.D. 2009a. Handling untilled fields of cornstalks. University of Illinois Extension. The Bulletin no. 25. http://bulletin.ipm.illinois.edu/article.php?id=1257 (accessed 14 Dec. 2013).

Nafziger, E.D. 2009b. Corn. Illinois Agronomy Handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign, pg. 91-112.

Nowak, P., and F.J. Pierce. 2000. Iowa residue management survey 2000: Report to the Iowa Residue Management Partnership.

Parr, J.F., and R.I. Papendick. 1978. Factors affecting the decomposition of crop residues by microorganisms. pg. 100–129. In W.R. Oschwald (ed.) Crop residue management systems. ASA Spec. Publ. 31. ASA, CSSA, and SSSA, Madison, WI.

Phillips, S.R., K.R. Olson, J.C. Siemens, and S.A. Ebelhar. 1997. Economics of conservation tillage systems for CRP land in southern Illinois. J. Prod. Agric. 10:483-489.

Piepho, H.P., E.R. Williams, and M. Fleck. 2006. A note on the analysis of designed experiments with complex treatment structure. Hort. Science 41:446-452.

Pordesimo, L.O., W.C. Edens, and S. Sokhansanj. 2004. Distribution of aboveground biomass in corn stover. Biomass Bioenerg. 26:337-343.

Rice, C.W., and M.S. Smith. 1984. Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. Soil Sci. Soc. Am. J. 48:295-297.

SAS Institute. 2013. SAS Software v. 9.4. SAS Inst., Cary, NC.

Schomberg, H. H., and J.L. Steiner. 1999. Nutrient dynamics of crop residues decomposing on a fallow no-till soil surface. Soil Sci. Soc. Am. J. 63:607-613.

Simmons, F.W. and E.D. Nafziger. 2009. Soil management and tillage. Illinois Agronomy Handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign, pg. 133-142.

Smil, V. 1983. Biomass energies. New York: Plenum Press.

Smith, J.H., and C.L. Douglas. 1968. Influence of residual nitrogen on wheat straw decomposition in the field. Soil Sci. 106:456-459.

Smith, J.H., and C.L. Douglas. 1971. Wheat straw decomposition in the field. Soil Sci. Soc. Am. Proc. 35:269-272.

Snyder, C.S. 2012. Are Midwest corn farmers over-applying fertilizer N? Better Crops 96:3-4.

Swan, J.B., T.C. Kaspar, and D.C. Erbach. 1996. Seed-row residue management for corn establishment in the northern US Corn Belt. Soil Tillage Res. 40:55-72.

Tarkalson, D.D., S.D. Kachman, J.M. Knops, J.E. Thies, and C.S. Wortmann. 2008. Decomposition of Bt and non-Bt corn hybrid residues in the field. Nutr. Cycl. Agroecosys. 80:211-222.

Vanhie, M., W. Deen, J.D. Lauzon, and D.C. Hooker. 2015. Effect of increasing levels of maize (*Zea mays* L.) residue on no-till soybean (Glycine max Merr.) in Northern production regions: A review. Soil Tillage Res. 150, 201-210.

Vanlauwe, B., J. Diels, N. Sanginga, and R. Merckx. 1997. Residue quality and decomposition: an unsteady relationship? In: Cadisch, G., Giller, K.E. (Eds.), Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, pp. 157–166.

Zuber, M.S., and C.O. Grogan. 1961. A new technique for measuring stalk strength in corn. Crop Sci. 1:378-380.

Zuber, S.M., G.D. Behnke, E.D. Nafziger, and M.B. Villamil. 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron. J. 107:971-978.

CHAPTER 2: FIELD-SPECIFIC YIELD RESPONSE TO VARIABLE SEEDING DEPTH OF CORN IN THE MIDWEST

ABSTRACT

Sufficient soil moisture is crucial for corn (*Zea mays* L.) germination and emergence; however, within-field soil moisture varies with topography. Since soil moisture varies, corn seeding depth should vary with soil moisture gradients to reach optimal moisture. Using relative elevation data, landscape (LSP) zones were delineated to partition soil moisture variability into dry, transitional, and wet LSP zones. Wet LSP zones presented lower elevation and likely higher soil moisture; transitional LSP zones were relatively flat and soil moisture was likely moderate; and dry LSP zones presented higher elevation and likely drier soils. The corn yield response to shallow, standard, and deep seeding depths in dry, transitional, and wet LSP zones was tested. It was hypothesized that shallow seeding in wet LSP zones and deep seeding in dry LSP zones would result in higher yield than the standard seeding depth. Field-long strips were planted in 17 commercial fields in 2014 and 2015 at shallow, standard, and deep seeding depths. Corn was machine-harvested. Across years, the LSP zones were a significant predictor of the yield response in 7 fields. Two fields showed no response to seeding depths, 7 fields yielded similarly for the shallow and standard seeding depths, 4 fields yielded similarly for the deep and standard seeding depths, while 4 fields responded positively to combinations of shallow, standard, and deep seeding depths. The yield response to variable seeding depth of corn presented field-specificity. The yield response to variable seeding depth was likely attenuated by favorable conditions for corn planting and during the growing seasons.

Abbreviations: DEM, digital elevation model; LIDAR, light detection and ranging; LSP, landscape; TPI, Topographic Position Index.

INTRODUCTION

On corn establishment and seeding depth

In order to meet the potential for high corn yield a successful planting operation and crop establishment are required. Providing a suitable environment for the timely germination, emergence, and establishment of corn plants requires to take into account factors such as soil moisture and temperature at the seeding depth, sufficient seed-to-soil contact, and proper soil aeration (Alessi and Power, 1971; Schneider and Gupta, 1985; Benech-Arnold and Sanchez, 2004; Nielsen, 2010; Elmore et al., 2014; Shearer and Pitla, 2014).

Corn producers can only influence soil temperature at the seeding depth by choosing an appropriate time for planting (Heege, 2013), thus a crucial factor involved in corn germination and emergence is the soil moisture at the seeding depth. Research by Schneider and Gupta (1985) showed that fastest and maximum corn emergence was obtained by warm soil temperatures (20-30°C) and soil moisture at or above field capacity in a non-cloddy seedbed. Planting operations then become an act of balancing the planting to start as early as possible in the season at a seeding depth near the soil moisture field capacity of the soil but shallow enough to the soil surface to benefit from warmer temperatures.

Extension agronomists from land-grant institutions across major corn producer states in the U.S. Corn Belt agree that producers should avoid planting corn at depths shallower than 38 mm (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011), that seeding depths should range from 38 to 51 mm when soil moisture conditions are optimal (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011; Coulter, 2016), and that deeper seeding in the range from 64 to 76 mm may be necessary when dry soil conditions are present at the time of the planting operation (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011).

Soil moisture varies within a field due to the topography (Hawley et al., 1983; Hupet and Vanclooster, 2002; Choi et al., 2007). Even fields that have narrow elevation ranges and appear to be visually uniform can exhibit soil moisture gradients and localized moisture patterns (Scott et al., 2010). Fields and their soils present an intrinsic variability that results from the interaction over time and space of parent material, climate, topography, and biological activity (Burrough, 1983; Brady and Weil, 2008). Researchers have hypothesized that since soil moisture at the seeding depth is not uniform within a field then the seeding depth should also vary to plant the seeds in optimal moisture conditions in all parts of the field (Price and Gaultney, 1993; Carter and Chesson, 1996; Benech-Arnold and Sanchez, 2004; Knappenberger and Köller, 2012; Elmore et al., 2014; Heege, 2013; René-Laforest, 2015).

As machinery used in agriculture develops to take advantage of within-field variability in the form of variable rate seeding, variable rate fertilizer application, multi-hybrid planting (Pierce and Nowak, 1999; Shearer and Pitla, 2014; Hunt and Wilson, 2015), depth of tillage (Fulton et al., 1996; Gorucu et al., 2001; Khalilian et al., 2002; Abbaspour et al., 2005), among others, and advances in planting equipment performance by adding automatic row shut-off to avoid planting overlap, monitoring of seed spacing and singulation, and variable down force to provide constant depth of planting (Shearer and Pitla, 2014; Hunt and Wilson, 2015) seeding depth for corn (and other crops) is still being applied as if fields were homogeneous units with a uniform soil moisture distribution.

As of the 2016 growing season, corn producers manually adjust the seeding depth of corn for each planter row unit, which is sufficient to set a single seeding depth at the whole-field level but not convenient to make changes at the within-field level. This assumption of homogeneity of soil moisture in fields may result in system inefficiencies by planting corn seeds in excessive moisture in parts of the field and deficient soil moisture in other parts of the same field. The result of such management could be an uneven crop stand, delayed emergence, higher incidence of disease when seeds are planted in cool and moist soils (Miedema, 1982; Bradley, 2009) thereby increasing the time to emergence, and potential yield losses. Additionally, as corn seeds have become one of the largest operational expenditures for corn producers with increases of 89% in the cost per acre for corn seed since 2005 (Duffy, 2015) and seed cost as a percent of corn revenue reaching 14% in 2016 (Schnitkey, 2015), then the exploration of new technologies and practices to obtain the highest return from the investment in corn seed is reasonable.

On site management

In precision agriculture, the purpose is to manage agricultural inputs with respect to spatial variation (Atherton et al., 1999; Pierce and Nowak; 1999). The potential benefits of field-specific management have been recognized (Earl et al., 2003; Adamchuck 2004; Christy, 2008). If the seeding depth could be adjusted on-the-go within a field the understanding of the distribution of soil moisture within a field becomes crucial for the successful application of this potential technology. Although soil surveys are commonly used for identifying variation within a field (Trangmar et al., 1985), researchers have found that management zones created from soil types alone lack the resolution needed for precision agriculture (Robert, 2002; Zhu et al., 2013; Bobryk et al., 2016).

In regards to field management strategies, it is known that water availability is the most significant factor that determines crop yields (Hillel, 1990; Howell, 1990). Soil moisture during the growing season has defining influence in emergence, plant stand establishment, plant development, and grain fill. The soil moisture distribution of non-irrigated fields is largely dependent upon topography (Hanna et al., 1982) and evidence has shown that yields are related to topographic patterns (Timlin et al., 1998; Kravchenko and Bullock, 2000; Jiang and Thelen, 2004). Field areas of lower elevation receive water from areas of higher elevation; as a consequence, soil moisture content can be inversely related to relative elevation.

Previous work on seeding depth

There have been a number of studies examining potential applications of variable seeding depth on corn and other crops. Many researchers have worked in the development of sensing instrumentation or planting mechanisms to control seeding depth on-the-go (Dyck et al., 1985; Price et al., 1990; Carter and Chesson, 1993, 1996; Price and Gaultney, 1993; Weatherly and Bowers, 1997; Mastorakos et al., 2014), although at the time of this study the technology has yet to be adopted by machinery manufacturers. Gupta et al. (1988) suggested that shallower corn seeding (from 50 to 25 mm) could compensate for cooler soil temperatures in no-till cropping systems when soil moisture is sufficient at the seeding depth. A study on variable seeding depth of corn by Knappenberger and Köller (2012) found increased emergence of deeper planted corn (80-90 mm) compared to shallower planted corn over a 3-yr field study. Recent work by René-Laforest (2015), which included the testing of a soil moisture sensor, actuators, and a seeding depth decision algorithm for on-the-go changes, found positive results of seeding corn shallower in relatively wet field areas.

The aforementioned studies have been conducted on a single geographic region at a time, in small plots, or have focused on the actuation mechanism for changing seeding depth on-the-go rather than on the agronomic value of such technology. An examination of variable seeding depth across multiple growing environments and seasons could shed light about the agronomic value of variable seeding depth of corn, if any.

In this study, it is hypothesized that varying seeding depth based upon LSP zones that present soil moisture gradients may be beneficial for corn growth if adverse soil moisture conditions are found at the time of planting. Due to the short corn planting window to achieve maximum yield potential in the U.S. Midwest, corn producers may be forced to plant in fields that have areas that are drier or wetter than optimal. If management zones with soil moisture gradients can be predicted there is potential to improve crop stand establishment and ultimately yield by planting corn seeds in optimal soil moisture within all field areas. In essence, this experiment studies the application of variable seeding depth within a field to take advantage of the soil moisture variability at the seeding depth in order to find an optimum corn seeding depth in all field areas.

The objectives are: 1) create LSP zones to delineate soil moisture gradients using relative field elevation data; 2) develop statistical methods to test the within-field seeding depth treatment yield response for each field; 3) test the within-field yield response to shallow and deep seeding depths vs. a standard seeding depth and vs. each other within the LSP zones created in objective no. 1.

MATERIALS AND METHODS

Study sites and experimental layout

Seeding depth treatments were applied in 9 fields at 5 sites in 2014 and in 8 fields at 7 sites in 2015 (Table 2.1). Partnerships were created with corn producers in Iowa, Illinois, and Indiana; in addition, a field at the Crop Sciences Research and Education Center (CSREC) from the University of Illinois at Urbana-Champaign was included for the 2015 growing season. Table

2.2 provides the year, field, planting and harvest date, seeding rate, and seeding depths for each field. Table 2.3 provides information about the precipitation, dry days, mean air temperatures for the 7-d period before and after planting, mean yield, and dominant soil textures for each field. Figure 2.1 shows the spatial distribution of the sites.

In each field, a strip trial or split-planter experiment (Doerge and Gardner, 1999) was established in order to assess the corn yield response to seeding depth across different LSP zones within the field. After planting the field edges, corn producers planted 2 to 5 strips across the entire field length with the planter set up to place the seeding depth treatments. After the seeding depth treatment strips were completed the producers planted the rest of the field at their standard seeding depth. Each seeding depth treatment strip was then harvested individually. All fields were planted at 76-cm row width. Corn producers and the CSREC crew conducted all field operations, which included typical Corn Belt agronomic practices of spring tillage, fertilizer, and pesticide applications.

In order to control local variability, each seeding depth treatment (i.e. shallow or deep seeding depths) was paired to a control treatment strip planted at the corn producer’s standard seeding depth. An example of the experimental layout is shown in Fig. 2.2a.

Requirements for selection of corn producers

The selection of corn producers was based on the following criteria: 1) appropriate planting and harvesting equipment combination (i.e. 12-row planter with 12-row harvester or 16-row split-planter with 8-row harvester); 2) field planted with corn only and using a consistent corn variety within the experiment; 3) spring tillage to ensure that deeper seeding depths could be reached; 4) Real-Time Kinematic (RTK)-GPS tractor guidance to allow planting of nontreatment strips after planting the depth treatments; 5) capability to document where the seeding depth treatment strips were planted; and 6) sharing of planting and harvesting operation data.

Corn seeding depths

Corn producers determined their standard seeding depth for the field conditions at the time of planting. Shallow and deep seeding depths were set 10 to 25 mm above and below the standard seeding depth, as decided by each corn producer. Producers selected seeding depths from 25 to 43 mm for the shallow seeding depth, 41 to 58 mm for the standard seeding depth, and 61 to 76 mm for their deep seeding depth (Table 2.2).

Development of the LSP zones

To explore the effect of spatial covariates on the yield response to within-field variable seeding depth, a digital elevation model (DEM), based on high-density aerial light detection and ranging (LIDAR) data, was used to calculate the Topographic Position Index (TPI) as shown in Weiss (2001) with the QGIS System for Automated Geoscientific Analyses (SAGA) extension (QGIS Development Team, 2016). The TPI is one of many morphometric properties that can be valuable in topographic analysis (Gallant and Wilson, 2000). Researchers have applied the TPI to several disciplines, including geology (Deumlich et al., 2010), forestry (Giorgis et al., 2011), wildlife management (Pinard et al., 2012), hydrology (Francés and Lubczynski, 2011), and agriculture (Mieza et al., 2016), among many others. In essence, the TPI is a measure of relative elevation; it computes the difference between the elevation at a central point and the average elevation within a specified radius. The search radius used in this study was of 100 m. If the central point is located higher than the average surroundings then the outcome is a positive TPI value, negative TPI values are obtained when the central point is lower than the average surroundings, and TPI values near 0 are the result of relatively flat areas in the search radius around the central point.

The TPI relative elevation layer for each field was imported into the statistical software R (R Core team, 2016) and a non-hierarchical clustering procedure, k-means, was applied to create LSP zones representative of low elevation (LSP1), transitional or relatively flat elevation (LSP2), and high elevation (LSP3). A representation of the workflow to develop the LSP zones is shown in Fig. 2.3.The R code to develop the LSP zones is given in Appendix D. Working under the assumption that LSP zones of higher and lower elevation had drier and wetter soil moisture contents at the seeding depth, respectively, the yield response to shallow, standard, and deep seeding depth treatments in the LSP zones was analyzed. It was expected that shallow seeding in dry LSP zones and deep seeding in wet LSP zones would yield less than the standard seeding depth, that shallow seeding in wet LSP zones would yield more than the standard seeding depth, and that deep seeding in dry LSP zones would yield more than the standard seeding depth.

Yield data collection and pre-processing

Corn was harvested with a commercial harvester equipped with a yield mapping system and a header wide enough to harvest each seeding depth treatment strip individually. Yield monitors were calibrated and set to record yield data every 1 Hz. In order to remove yield monitor artifacts the data were pre-processed using filters for flow delay, and start and end delays as suggested by Sudduth and Drummond (2007). In addition, extreme outliers for yield were identified by using boxplots (Tukey, 1977).

Yield data processing for analysis

Due to each seeding depth treatment strip being harvested independently the resulting yield data points were not aligned. In order to get within-field paired differences between the shallow and deep seeding depth treatments vs. the standard seeding depth and vs. each other, a grid of size 5 × 5 m was overlaid along the direction of the harvest path, points within each cell grid were averaged, and the yield value assigned to the centroid of each cell. Once the points were aligned, paired differences between adjacent treatment and control points were calculated and assigned to the average coordinates of the paired points. A positive yield difference value meant that a seeding depth treatment yielded more than the adjacent control. Finally, the LSP zones were attached to each estimated yield difference based on their spatial position. The workflow employed for yield processing is shown in Fig. 2.2. The R code to calculate the paired differences is given in Appendix D.

The corn yield response to the seeding depth treatments, i.e. the paired yield differences of the shallow and deep seeding depth treatments vs. the standard seeding depth and vs. each other, was modeled to include the effect of the LSP zones as the predictor term. The model was fitted by the generalized least-squares (GLS) procedure using the nlme package (Pinheiro et al., 2016). The assumptions of independence and homoscedasticity were explored graphically and the inclusion of variance and correlation structures were tested based on log-likelihood ratio tests (Pinheiro and Bates, 2000).

RESULTS AND DISCUSSION

Weather conditions during the 2014 and 2015 growing seasons

Total monthly precipitation and mean monthly air temperatures for all sites for the 2014 and 2015 growing seasons are presented in Tables 2.4 and 2.5, respectively. In 2014, total precipitation from April to August in sites 1, 2, 3, and 7 was higher than the 30-yr normal and lower than the 30-yr normal in site 9 (Table 2.4). Mean monthly temperatures in 2014 from April to August were generally cooler than the 30-yr normal in all sites, particularly during the month of July in which all sites presented temperatures 2.4 to 2.8°C lower than the 30-yr normal (Table 2.4).

Total precipitation in 2015 from April to August was higher than the 30-yr normal in all sites (Table 2.5). In particular, 105 to 194 mm excess precipitation compared to the 30-yr normal was observed in June at sites 4, 5, 6, 8, and 9 (Table 2.5). Mean monthly temperatures in 2015 were higher than the 30-yr normal during March and April in sites 1 and 2 but lower than the 30-yr normal for the rest of the growing season (Table 2.5). Mean monthly temperatures in sites 4, 5, 6, and 8 were higher than the 30-yr normal in April and May but lower than the 30-yr normal for the rest of the growing season (Table 2.5). Lastly, mean monthly temperatures in site 9 were lower than the 30-yr normal except during May (Table 2.5).

Weather conditions before and after planting operations

Field workability conditions in both 2014 and 2015 growing seasons allowed for timely planting operations. Planting operations were completed during 19 April to 7 May in 2014 and 14 April to 1 May in 2015 (Table 2.2).

In 2014, precipitation ranges were 2 to 52 mm and 16 to 87 mm for the 7-d period before and after planting, respectively (Table 2.3). The fields that received the lowest amount of precipitation in the 7-d period before planting (IA-10 and IN-01) received precipitation of 28 mm or more in the 7-d period after planting (Table 2.3). Moreover, several fields (IA-05, IA-10, and IL-01) received small amounts of precipitation 1 d before planting but not enough to prevent planting operations (Table 2.3). All fields received precipitation within 2 d of planting, except field IN-02 in which the field received precipitation 4 d after planting (Table 2.3). Daily mean temperatures in the 7-d period before planting were under 10°C for all fields except IL-01, IN-

01, and IN-02, in which temperatures were over 10°C (Table 2.3). After the planting operations, mean air temperature increases from 1 to 9°C were observed in all fields except IL-01 in the 7-d period after planting (Table 2.3). Although mean air temperatures decreased in field IL-01 in the 7-d period after planting, the mean air temperature was still above 10°C (Table 2.3), which is considered the minimum threshold for corn growth (Nafziger, 2009; Abendroth et al., 2011).

In 2015, precipitation ranged from 5 to 25 mm and 9 to 25 mm for the 7-d period before and after planting, respectively (Table 2.3). All fields received precipitation within 5 days before planting and within 4 days after planting (Table 2.3), with fields IA-04, IA-06, IL-06, IL-10, and IL-12 receiving precipitation within 1 day after planting (Table 2.3). Mean air temperatures in fields IA-04, IA-06, IL-08, and IN-04 were under 10°C in the 7-d period before planting, but temperatures increased to over 10°C in the 7-d period after planting (Table 2.3). Mean air temperatures in fields IL-06, IL-10, and IL-12 decreased to under 10°C in the 7-d period after planting (Table 2.3).

With few exceptions, air temperatures increased in all fields after planting operations and soil moisture conditions were likely adequate in all fields to promote corn seed germination and emergence during the 2014 and 2015 growing seasons.

Yield response to shallow seeding vs. the standard seeding depth

The type of response, probability values, and yield difference estimates of the yield response to shallow seeding vs. the standard seeding depth for the field-specific analysis for the 2014 and 2015 growing seasons are summarized in Table 2.6.

In 2014, the overall response and the response to LSP zones to shallow seeding vs. the standard seeding depth were not significant for 5 fields (IA-02, IA-05, IA-09, IL-01, and IN-01) out of the 9 fields (Table 2.6). It is possible that adequate weather conditions, particularly sufficient soil moisture, promoted corn germination and emergence at the shallow and standard seeding depths equally in all LSP zones in these fields, thus masking any differential crop establishment patterns that could have resulted in different yield outcomes should drier soil conditions after planting operations had prevailed. There was a significant overall yield response to shallow seeding vs. the standard seeding depth in two fields in 2014 (IA-08 and IA-10). Field IA-08 had estimated yield losses of 0.43 Mg ha^{-1} and field IA-10 had estimated yield gains of 0.44 Mg ha^{-1} for the yield response to shallow seeding vs. the standard seeding depth (Table 2.6). These two fields (IA-08 and IA-10) were located in site 3 (Table 2.1) and were planted 4 days apart but resulted in opposite yield outcomes. I speculate that this could have been a result of fine-textured clay soils retaining more soil moisture and warmer conditions at the time of planting and after planting in IA-10 compared to IA-08 (Table 2.3), which promoted a crop establishment that resulted in yield gains for the shallow seeding depth compared to the yield of the standard seeding depth. In addition, there was a significant effect of LSP zones in field IN-02. Yield gains were estimated in LSP1 and LSP2 zones (0.06 and 0.6 Mg ha^{-1}, respectively), while yield losses of 0.89 Mg ha^{-1} were estimated in LSP3 zones for the yield response to shallow seeding vs. the standard seeding depth in IN-02 (Table 2.6). Although precipitation before and after planting in IN-02 could be considered adequate (8 and 20 mm, respectively) (Table 2.3), I speculate that corn establishment for the shallow seeding depth was likely poor compared to the standard seeding depth in the dry LSP3 zones. In field IN-02, the soil organic matter (SOM) content in LSP3 zones was <1% while the SOM content in LSP1 and LSP2 zones was >3% (data not shown), which resulted in lower soil moisture capacity in LSP3 zones compared to the LSP1 and LSP2 zones. It is uncertain why the LSP2 zones had yield gains larger than the yield gains in LSP1 zones. The LSP1 zones were expected to yield higher for the shallow seeding vs. the standard seeding depth, particularly during moist and warm conditions after planting operations as experienced in IN-02. There were significant but negative overall and LSP zones responses in field IA-01. The overall yield loss to shallow seeding vs. the standard seeding depth was of 0.22 Mg ha^{-1}, and the LSP1 zones had the largest yield losses at 0.52 Mg ha^{-1} (Table 2.6). This runs contrary to the hypothesis that shallow seeding in the wet LSP1 zones results in yield gains compared to the yield of the standard seeding depth. It is not conclusive why such yield losses were detected in IA-01, particularly when no significant differences were found in IA-02, the other field from site 1 in 2014, which was planted only 1 d before in similar soils and experienced nearly the same weather conditions. Opposite outcomes like the ones obtained in site 1 (fields IA-01 and IA-02) provided evidence of field-specificity for the response to shallow seeding vs. the standard seeding depth, and also that there may have been variables not included in this study that influenced the response of corn to shallow seeding.

In 2015, there were no significant yield differences for the overall and the LSP zones responses for 5 fields (IA-06, IL-06, IL-08, IL-10, and IN-04) out of 8 fields (Table 2.6) for the yield response to shallow seeding vs. the standard seeding depth. Similarly to the yield response in 2014, it is probable that adequate temperatures and sufficient soil moisture conditions in the non-responsive fields prevented a yield response due to corn seeding depth alone. There was a significant but negative overall yield response to shallow seeding vs. the standard seeding depth in three fields in 2015 (IA-04, IL-11, and IL-12) (Table 2.6). The yield losses for the shallow seeding vs. the standard seeding depth were of 0.26, 1.24, and 0.29 Mg ha^{-1} for fields IA-04, IL-11, and IL-12, respectively (Table 2.6). As field IA-04 was in the lowest range of precipitation received in the 7 days after planting (only 9 mm) (Table 2.3), it is possible that the yield losses in IA-04 could have been due to relatively low soil moisture conditions at the shallow seeding depth that negatively influenced crop establishment compared to the standard seeding depth. Field IL-11 had large yield losses (> 1 Mg ha^{-1}) for the overall yield response to shallow seeding vs. the standard seeding depth (Table 2.6). These yield losses are likely the result of the shallow seeding in fine sand soils that covered extensive field areas in IL-11, resulting in poor crop establishment for the shallow seeding depth compared to the standard seeding depth. Lastly, the negative yield response to shallow seeding vs. the standard seeding depth for field IL-12 is difficult to interpret in the context of seeding depth alone. Soil moisture conditions were excellent in IL-12 with precipitation of approx. 36 mm in the 7-d period before and after planting operations (Table 2.3). It is possible, however, that weather conditions after planting operations negatively affected corn seeds at the shallow seeding depth (Table 2.3). Field IL-12 was one of the only fields in 2015 that experienced mean air temperatures under 10°C in the 7-d period after planting operations, perhaps resulting in chilling injury to the seeds at the shallow seeding depth (Miedema, 1982), which were closer to the soil surface and less buffered against temperature fluctuations. However, the other two fields with temperatures under 10°C in the 7-d period after planting operations (IL-06 and IL-10) did not share a similar outcome for the yield response to shallow seeding vs. the standard seeding depth (Table 2.6).

Yield response to deep seeding vs. the standard seeding depth

The type of response, probability values, and yield difference estimates of the yield response to deep seeding vs. the standard seeding depth for the field-specific analysis for the 2014 and 2015 growing seasons are summarized in Table 2.7.

In 2014, there were no significant yield differences in 2 fields (IA-08 and IN-02) out of 9 fields for the overall and the LSP zones yield responses to deep seeding vs. the standard seeding depth (Table 2.7). It is possible that soil moisture and temperature conditions at the deep and standard seeding depths were not different enough to result in a yield response in the non-responsive fields. There was a significant but negative overall yield response to deep seeding vs. the standard seeding depth in three fields (IA-02, IL-01, and IN-01) (Table 2.7). Yield losses of 0.29, 0.51, and 0.8 Mg ha^{-1} were estimated for fields IA-02, IL-01, and IN-01, respectively (Table 2.7). The analysis provided evidence that the standard seeding depth was preferable over the deep seeding depth in fields IA-02, IL-01, and IN-01; however, the negative yield response to deep seeding vs. the standard seeding depth is not understood in terms of the weather conditions or the soil types found in those fields. Similar to the yield response to shallow seeding vs. the standard seeding depth in site 1 during the 2014 growing season, in which the yield of the two fields in site 1 responded differently in nearly identical growing conditions, the two fields from site 9 (IN-01 and IN-02) responded differently to deep seeding vs. the standard seeding depth, even though soil types and weather conditions were similar and planting operations were completed only 2 d apart (Table 2.7). This outcome added evidence of field-specificity to the response of deep seeding vs. the standard seeding depth. I also speculate that there may have been variables not included in this study that influenced the response of corn to deep seeding. In field IL-01, there was a precipitation event (41 mm) only hours after planting operations were completed, which saturated the soils (Table 2.3). As field IL-01 was scouted during the 2014 growing season, it was observed that seedlings from the deep seeding depth emerged 4 to 6 d later than the seedlings from the standard seeding depth, and the resulting plants were less developed for much of the early season period compared to the plants from the standard seeding depth (data not shown). This differential early season growth may have negatively affected the yield response to deep seeding vs. the standard seeding depth in IL-01. There was a significant effect of LSP zones in four fields (IA-01, IA-05, IA-09, and IA-10) (Table 2.7). Field IA-01 had a significant and positive yield response of 0.26 Mg ha^{-1} to deep seeding vs. the standard seeding depth in the LSP3 zones, which supports the hypothesis that deep seeding in the dry LSP3 zones increases yield compared to the standard seeding depth. Field IA-05 had a significant but negative yield response to deep seeding vs. the standard seeding depth, with the largest yield losses estimated in the LSP1 zones. This agrees with the hypothesis that deep seeding in the wet LSP1 zones results in yield losses compared to the standard seeding depth, likely due to seed placement in cooler and wetter conditions which may result in poor crop establishment. However, field IA-05 also had yield losses in the dry LSP3 zones, which runs contrary to the hypothesis that deep seeding in the dry LSP3 zones increases yields compared to the standard seeding depth. Field IA-09 had yield losses of 0.58 Mg ha^{-1} in the LSP1 zones but yield gains of 1.15 Mg ha^{-1} in the LSP3 zones for the yield response to deep seeding vs. the standard seeding depth. This yield outcome in field IA-09 supports two of the hypothesis, that deep seeding in the wet LSP1 zones results in yield losses and that deep seeding in the dry LSP3 zones results in yield gains compared to the yield response to the standard seeding depth. The last field in 2014 that had a significant effect of LSP zones was IA-10, in which a significant and positive yield response to deep seeding vs. the standard seeding depth of 0.20 Mg ha^{-1} was estimated in the dry LSP3 zones (Table 2.7). This supports the hypothesis that deep seeding in the dry LSP3 zones increases yield compared to the yield response to the standard seeding depth.

In 2015, there were no significant overall and LSP zones yield responses to deep seeding vs. the standard seeding depth in 3 fields (IL-10, IL-11, and IL-12) out of the 8 fields (Table 2.7). No particular relationships with weather or soil types were found to help explain the non-significant differences for the yield response to deep seeding vs. the standard seeding depth. There was a significant overall yield response to deep seeding vs. the standard seeding depth in four fields (IA-06, IL-06, IL-08, and IN-04) (Table 2.7). Fields IA-06, IL-06, and IN-04 had a significant and negative yield response to deep seeding vs. the standard seeding depth, with yield losses of 0.68, 0.23, and 0.53 Mg ha^{-1}, respectively. Soil crusting was observed during scouting visits after planting operations in IA-06, IL-06, and IN-04; thus, it is possible that soil crusting caused by precipitation events shortly after planting may have negatively affected crop establishment of seeds at the deep seeding depth. Moreover, extensive field areas in field IA-06 were found with standing water due to frequent precipitation events, while mean air temperature decreases (from 13.6 to 9°C) were observed in field IL-06 in the 7-d period after planting (Table 2.3). I speculate that both conditions, standing water and cooler temperatures, likely had a more negative influence in seeds at the deep seeding depth compared to the seeds at the standard seeding depth. Field IL-08 had a significant and positive overall yield response of 0.15 Mg ha^{-1} to deep seeding vs. the standard seeding depth (Table 2.7), which was opposite of the response in field IL-06, the other field from site 5 in the 2015 growing season. The planting operation in field IL-08 was conducted 6 days later than in IL-06, and mean temperatures in the 7-d period after planting increased in IL-08 from 7.5 to 15.1°C while mean temperatures in the 7-d period after planting in IL-06 decreased from 13.6 to 9°C (Table 2.3). The contrasting weather conditions after planting operations in the fields of site 5 (IL-06 and IL-08) may explain why the yield response to deep seeding vs. the standard seeding depth was different. Lastly, field IA-04 had both significant but negative overall and LSP zones responses. The largest yield losses were estimated in the wet LSP1 zones for the yield response to deep seeding vs. the standard seeding depth (Table 2.7), which supports the hypothesis that deep seeding in the wet LSP1 zones results in yield losses compared to the yield response to the standard seeding depth. However, field IA-04 also had yield losses in the dry LSP3 zones, which runs contrary to the hypothesis that deep seeding in the dry LSP3 zones increases yields compared to the yield response to the standard seeding depth (Table 2.7).

Yield response to shallow seeding vs. deep seeding

The type of response, probability values, and yield difference estimates of the yield response to shallow seeding vs. the deep seeding depth for the field-specific analysis for the 2014 and 2015 growing seasons are summarized in Table 2.8. Four fields (IA-05, IA-06, IN-01, and IN-04) did not meet the requirement to place the shallow and deep seeding depth treatment strips adjacent to each other (as shown in Fig. 2.2a) and were therefore excluded from the analysis of the yield response to shallow seeding vs. the deep seeding depth.

In 2014, there were no significant overall and LSP zones yield responses to shallow seeding vs. the deep seeding depth in 4 fields (IA-01, IA-02, IA-08, and IA-09) out of the 7 fields (Table 2.8). The non-significant yield differences are unexpected as these 4 fields presented significant differences for the yield response to the shallow or deep seeding depth vs. the standard seeding depth (Tables 2.6, 2.7, and 2.8); moreover, large yield differences were expected for the yield response to the two seeding depths further apart. There was a significant overall yield response to shallow seeding vs. the deep seeding depth in three fields (IA-10, IL-01, and IN-02) (Table 2.8). Fields IA-10 and IL-01 had overall yield gains of 0.29 Mg ha^{-1} and 0.72 Mg ha^{-1} for the yield response to shallow seeding vs. the deep seeding depth, while field IN-02 had yield losses of 0.39 Mg ha^{-1} for the yield response to shallow seeding vs. the deep seeding depth (Table 2.8). In IA-10, the yield response to shallow seeding vs. the standard seeding depth was also significantly different and positive, thus showing a consistent pattern where shallow seeding was preferable over deeper seeding depths (Table 2.6). In field IL-01, the yield response to shallow seeding vs. the standard depth was not significant while the yield response to deep seeding vs. the standard depth was significant and negative. The significant and positive yield response to shallow seeding vs. the deep seeding depth provided evidence that yield losses were estimated as seeding depths increased. For field IN-02, the yield response to deep seeding vs. the standard depth was not significant, but significant yield losses were estimated for the response to shallow seeding vs. the deep standard depth, this time suggesting that deeper seeding depths were preferable (Tables 2.7 and 2.8). However, it is important to note that yield gains were estimated for the yield response to shallow seeding vs. the standard seeding depth when seeding shallow in the transitional LSP2 zones (Table 2.6), thus underscoring the complexity to determine an optimal seeding depth in all field areas but also that yield benefits can be obtained from the application of variable seeding depth of corn.

In 2015, there were no significant yield differences for the overall and the LSP zones yield responses to shallow seeding vs. the deep seeding depth in 5 fields (IA-04, IL-06, IL-10, IL-11, and IL-12) out of the 6 fields (Table 2.8). The lack of significant differences is surprising given the fact that some of these fields (IA-04, IL-06, IL-11, and IL-12) presented significant differences for the yield response to shallow or deep seeding vs. the standard seeding depth (Tables 2.6 and 2.7). Field IL-08 had both significant but negative overall and LSP zones yield responses to shallow seeding vs. the deep seeding depth, in which the largest losses were estimated in the LSP1 zones (Table 2.8). The outcome obtained in IL-08 runs contrary to the hypothesis that shallow seeding in wet LSP1 areas results in yield increases when compared to the yield outcome to deeper seeding depths.

In summary, the yield response to variable seeding depth of corn had a degree of field-specificity even for fields within the same site. This field-specificity, however, is a necessary condition for the application of precision agriculture technologies to be of any value to producers

(Ruffo et al., 2006). In 2014, in site 1 for field IA-01 the optimal seeding depth varied within the field; the standard seeding depth achieved the highest yield except in the dry LSP3 zones where the deep seeding depth was the optimal depth. For IA-02, the other field from site 1 in 2014, the shallow and standard seeding depths achieved similar yield outcomes regardless of LSP zones, which was also the outcome for the only field in site 2 (IA-05). For site 3 in 2014, the three fields (IA-08, IA-09, and IA-10) presented different outcomes. In IA-08, the standard and deep seeding depths achieved similar yield outcomes. In IA-09, the optimal seeding depth varied, with the shallow and standard seeding depths achieving the highest yield except for the deep seeding depth in the dry LSP3 zones. In IA-10, the optimal seeding depth was the shallow seeding depth regardless of LSP zones. In site 7 (field IL-01) the shallow and standard seeding depths achieved similar yields; this outcome was shared by IN-01 in site 9. The other field from site 9, IN-02, presented an optimal seeding depth that varied within the field. The shallow seeding depth achieved the highest yield in the LSP2 zones compared to the standard seeding depth but not to the deep seeding depth, while the standard and deep seeding depths achieved similar yields in the rest of the field regardless of LSP zones.

In 2015, field IA-04 in site 1 was particular in the sense that the yield responses to both shallow and deep seeding vs. the standard seeding depth were significant and negative (Tables 2.6 and 2.7), thus providing evidence that the standard seeding depth was the optimal depth for the entire field regardless of LSP zones. For fields IA-06, IL-06, and IN-04 in sites 2, 5, and 9, respectively, the shallow and standard seeding depths achieved similar yield outcomes regardless of LSP zones. Fields IL-11, IL-08, and IL-12 in sites 4, 5, and 8, respectively, presented similar yield outcomes for the standard and deep seeding depths regardless of LSP zones. Lastly, field IL-10 in site 6 was the only field tested during the 2014 and 2015 seasons in which there were non-significant differences for the yield response to shallow and deep seeding vs. the standard seeding depth and for the yield response to the shallow seeding vs. the deep seeding depth, suggesting that similar yield outcomes were obtained regardless of seeding depth and LSP zones (Tables 2.6, 2.7, and 2.8).

In general, the LSP zones developed and validated in this study were not a good predictor of the yield response differences to shallow, standard, and deep seeding depths. Across growing seasons, the effect of LSP zones was significant in 2 fields for the yield response to shallow seeding vs. the standard seeding depth, in 5 fields for the yield response to deep seeding vs. the standard seeding depth, and in 1 field for the yield response to shallow seeding vs. the deep seeding depth (Tables 2.6, 2.7, and 2.8). The LSP zones, based on relative elevation, may be more beneficial for other precision agriculture applications. It is possible that the soil moisture retained in the top 10 cm in which corn seeds are planted likely varies along with other gradients that were not considered in the development of the LSP zones (i.e. SOM content, slope aspect, previous crop, and residue coverage, among others).

The development of management zones for the application of precision agriculture technologies is anything but settled and a great deal of research efforts have gone into the topic (Fridgen et al., 2004; Schepers et al., 2004; Kitchen et al., 2005; Cox and Gerard, 2007; Derby et al., 2007; Ortega and Santibáñez, 2007; Thorp et al., 2008; Moshia et al., 2014; Bobryk et al., 2016, among many others). Developing management zones that stay relevant over time, cropping systems, and weather conditions is a challenging research question.

With the advent of sensing technology for agricultural machinery, particularly actuators and real-time soil moisture and temperature sensors, there has been a renewed interest in variable seeding depth of corn in the last 15 years (Adamchuk et al., 2004, 2009; Knappenberger and

Köller, 2006; Knappenberger and Köller, 2012; Mastokaros et al., 2014; René-Laforest, 2015). Some results have been encouraging for the application of variable seeding depth of corn. Barr et al. (2000) found that varying seeding depth of sweet corn from 20 to 40 mm in some field areas would have increased final plant stand, as estimated by GIS modeling. In addition, Knappenberger and Köller (2012) found that corn emergence was improved by deeper seeding depths compared to shallow and medium seeding depths. More recently, René-Laforest (2015) found a positive yield response to shallow seeding in relatively wet field areas, although inconsistent results were also obtained (i.e. yield gains of shallow seeding in relatively dry areas compared to the yield of a medium and deeper seeding depths), a result also shared by this study.

CONCLUSION

The results from this study conducted during the 2014 and 2015 growing seasons have provided an understanding of the magnitude of site-specific yield gains and losses that can be expected from the application of variable seeding depth of corn in the U.S. Corn Belt. In agreement with the literature, this study also showed the difficulty faced in developing and validating management zones. The particular challenge for this study was the development of management zones that could predict the yield response to shallow, standard, and deep seeding depths for the majority of fields.

It is likely that the yield response to the seeding depths was obscured by variables not considered in the analysis, as the yield of corn integrates varied and multifaceted biological, chemical, and physical soil properties along with weather conditions. Moreover, research has shown that as long as temperatures are above 10°C corn seeds are able to germinate and emerge successfully in diverse soil moisture conditions (Alessi and Power, 1971; Helms et al., 1997). Field conditions at the time of planting and shortly after were adequate in terms of moisture and temperature for the majority of fields (Table 2.3), thus the yield response to variable seeding depth may have been masked by adequate growing conditions.

The fact that some fields, such as IA-10 or IL-08, had a significant and positive overall yield response to shallow or deep seeding depth compared to the standard seeding depth hints at the notion that the seeding depth of many fields may not have been chosen appropriately. Moreover, fields that had no significant effect of LSP zones may be better managed with a field-average seeding depth (as they currently are) instead of a variable seeding depth.

The introduction of new planting equipment technology (Adamchuk 2004; Mastorakos et al., 2014; René-Laforest, 2015) in the near future in the form of real-time sensors of soil moisture and temperature along with seeding depth actuators, may enable corn producers to adjust seeding depth on-the-go as desired or using a closed-loop system approach where seeding depth is adjusted according to the soil moisture and temperature variability measured in real-time while planting. The control of additional parameters, such as minimum and maximum seeding depth or minimum length of soil measurements before a seeding depth change is allowed (René-Laforest, 2015), could be given to the end users of this potential technology to enable greater control of the planting operation.

Future research is needed to evaluate the corn yield response to variable seeding depth under drier soil moisture conditions. This could be achieved by extending the geographic distribution of fields to increase the chances of experiencing adverse weather conditions, by selecting locations in rainfed zones with historically low precipitation during the typical corn planting period, or by manipulating irrigation schedules and rates to simulate drier conditions in irrigated zones. In addition, field research exploring the application of real-time soil moisture and temperature sensors in planting equipment, when available by machinery manufacturers, should also be conducted to evaluate the benefits, if any, of having real-time soil data during planting operations.

The application of real-time sensors could potentially make void the need for *a priori* management zones for seeding depth as the real-time data may be more useful in terms of finding moisture and temperature gradients at a scale that cannot be resolved with current spatial modeling based on elevation alone. Even if no variable seeding depth is applied, having real-time soil moisture and temperature sensors may allow corn producers to choose a single and optimal depth for planting corn in order to achieve fastest and maximum emergence after planting a portion of the field.

TABLES

Table 2.1. Site number, U.S. state, fields per site and year, approx. site coordinates, and no. of rows (76-cm row width) of the treatment strips at each of the nine sites for the test of corn yield response to shallow, standard, and deep seeding depths during the 2014 and 2015 growing seasons.

Site	State	Field		Site coordinates (approx.)	Width treatment strips
		2014	2015		no. rows
1	Iowa	IA-01 IA-02	IA-04	42°33’ N 96°30’ W	8
2	Iowa	IA-05	IA-06	41°47’ N 95°17’ W	12
3	Iowa	IA-08 IA-09 IA-10		41°86’ N 90°62’ W	12
4	Illinois		IL-11	41°49’ N 90°15’ W	8
5	Illinois		IL-06 IL-08	40°98’ N 89°71’ W	12
6	Illinois		IL-10	40°97’ N 89°81’ W	12
7	Illinois	IL-01		40°22’ N 88°41’ W	8
8	Illinois		IL-12	40°05’ N 88°22’ W	6
9	Indiana	IN-01 IN-02	IN-04	41°41’ N 84°99’ W	12

Table 2.2. Year, field, planting and harvest date, seeding rate, and seeding depths for each of the 17 fields tested for the within-field response of corn yield to shallow, standard, and deep seeding depths during the 2014 and 2015 growing seasons.

Year	Field	Planting date	Harvest date	Seeding rate	Seeding depths		
					Shallow	Standard	Deep
				seeds ha^{-1}		mm	
2014	IA-01	20 Apr.	18 Oct.	79,000	43	58	71
2014	IA-02	19 Apr.	19 Oct.	79,000	43	58	71
2014	IA-05	6 May	2 Nov.	84,000	30	48	71
2014	IA-08	19 Apr.	26 Oct.	86,500	25	51	76
2014	IA-09	21 Apr.	16 Oct.	86,500	25	51	76
2014	IA-10	23 Apr.	23 Oct.	86,500	25	51	76
2014	IL-01	27 Apr.	11 Oct.	89,000	25	51	76
2014	IN-01	7 May	28 Oct.	79,000	32	41	64
2014	IN-02	5 May	25 Oct.	79,000	32	41	64
2015	IA-04	25 Apr.	25 Oct.	78,000	43	58	71
2015	IA-06	30 Apr.	29 Oct.	80,000	30	48	71
2015	IL-06	23 Apr.	26 Sept.	89,000	38	48	64
2015	IL-08	29 Apr.	14 Oct.	89,000	38	48	64
2015	IL-10	18 Apr.	16 Sept.	89,000	38	51	64
2015	IL-11	14 Apr.	21 Sept.	83,000	25	46	61
2015	IL-12	23 Apr.	24 Sept.	84,000	28	43	61
2015	IN-04	1 May	15 Oct.	84,000	32	41	64
				Mean	33	49	68
				SD	7	6	6

Table 2.3. Year, field, precipitation (precip.), dry days, mean temperature (temp.) for the 7-d period before planting (DBP) and after planting (DAP), mean yield, and dominant soil textures for the 17 fields tested for the within-field response of corn yield to shallow, standard, and deep seeding depths during the 2014 and 2015 season. Weather data was provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

Year	Field	Precip.		Dry days		Mean temp.		Mean yield§	Dominant soil textures
		7 DBP†	7 DAP‡	DBP	DAP	7 DBP	7 DAP		
		—— mm ——				——— °C ———		Mg ha^{-1}	
2014	IA-01	8	16	5	0	6.1	14.8	13.7	Silty Clay Loam, Loam
2014	IA-02	7	16	4	0	6.8	13.8	13.9	Silty Clay, Silty Clay Loam
2014	IA-05	11	59	1	1	9.7	17.2	13.6	Silty Clay Loam
2014	IA-08	52	20	4	2	7.7	11.5	14.6	Silty Clay Loam, Silt Loam
2014	IA-09	46	60	6	0	6.1	12.2	13.8	Clay Loam, Loam
2014	IA-10	2	87	0	0	9.4	10.5	13.5	Clay Loam, Loam
2014	IL-01	7	41	1	0	13.8	13.1	13.9	Silt Loam
2014	IN-01	2	29	4	2	11.0	18.2	11.5	Loam, Silty Clay
2014	IN-02	8	20	2	4	11.1	15.3	11.9	Silt Loam, Silty Clay
2015	IA-04	14	9	4	0	9.7	12.6	14.3	Loam, Silty Clay Loam
2015	IA-06	17	17	3	1	9.3	16.2	12.6	Silt Loam, Silty Clay Loam
2015	IL-06	12	25	1	1	13.6	9.0	13.7	Silt Loam
2015	IL-08	25	25	2	4	7.5	15.1	15.1	Silty Clay Loam, Silt Loam
2015	IL-10	7	19	4	1	12.4	11.1	13.9	Silt Loam, Silty Clay Loam
2015	IL-11	13	21	0	0	11.3	13.9	14.1	Silt Loam, Fine Sand
2015	IL-12	18	19	0	1	13.6	9.2	12.8	Silty Clay Loam, Silt Loam
2015	IN-04	5	18	5	4	7.2	16.5	13.9	Loam, Silt Loam

† DBP, days before planting.

‡ DAP, days after planting.

§ For the standard seeding depth.

Table 2.4. Monthly precipitation (precip.) and mean temperature (temp.) during the 2014 growing season at the 5 sites along with the 30-yr normals† (1981-2010). Site 1 includes fields IA-01 and IA-02. Site 2 includes field IA-05. Site 3 includes fields IA-08, IA-09, and IA-10. Site 7 includes field IL-01. Site 9 includes fields IN-01 and IN-02.

	Site 1				Site 2			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	6	15	-8.4	-6.4	4	20	-8.2	-5.7
Feb.	22	17	-8.5	-3.9	27	24	-8.8	-3.2
Mar.	10	49	-0.6	2.6	9	54	-0.3	3.0
Apr.	60	81	9.3	9.8	76	88	8.9	9.7
May	57	100	15.8	16.1	89	125	16.1	16.0
June	411	107	21.3	21.4	284	126	21.6	21.4
July	129	88	21.0	23.6	82	111	20.7	23.4
Aug.	210	81	22.1	22.5	261	95	22.0	22.3
Sept.	77	74	17.3	17.8	108	85	17.0	17.9
Oct.	39	55	11.4	10.8	115	66	11.4	11.2
Nov.	10	35	-1.3	2.6	10	44	-0.8	3.2
Dec.	34	21	-2.5	-4.8	26	31	-1.3	-4.1

	Site 3				Site 7			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	17	32	-11.2	-6.1	42	51	-7.7	-3.9
Feb.	42	36	-11.6	-3.8	72	50	-7.9	-1.7
Mar.	14	62	-1.9	2.7	42	68	0.5	4.2
Apr.	144	84	9.0	9.7	115	93	11.2	10.8
May	60	107	15.8	15.8	93	112	17.2	16.7
June	231	116	21.8	21.2	193	106	22.7	22.0
July	84	105	20.7	23.1	239	106	20.7	23.5
Aug.	58	118	22.1	22.1	88	93	22.4	22.6
Sept.	117	77	17.0	17.7	143	74	17.8	18.9
Oct.	80	74	10.4	11.0	85	81	11.9	12.1
Nov.	53	61	-1.1	3.8	53	89	0.8	5.5
Dec.	20	46	-1.2	-3.9	48	68	0.7	-1.6

† Data provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

Table 2.4 (cont.)

Site 9				
	Total precip.	30-yr normal	Mean temp.	30-yr normal
	——— mm ———		——— °C ———	
Jan.	60	53	-9.9	-4.3
Feb.	91	48	-8.3	-2.4
Mar.	35	63	-2.7	2.8
Apr.	94	88	8.9	9.7
May	114	107	15.6	15.4
June	103	99	21.4	20.8
July	37	104	20.1	22.6
Aug.	45	94	21.5	21.6
Sept.	106	85	16.9	17.7
Oct.	75	75	10.5	11.1
Nov.	66	80	1.0	4.8
Dec.	38	66	0.5	-1.8

† Data provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

Table 2.5. Monthly precipitation (precip.) and mean temperature (temp.) during the 2015 growing season at the 7 sites along with the 30-yr normals† (1981-2010). Site 1 includes field IA-04. Site 2 includes field IA-06. Site 4 includes field IL-11. Site 5 includes fields IL-06 and IL-08. Site 6 includes field IL-10. Site 8 includes field IL-12. Site 9 includes field IN-04.

	Site 1				Site 2			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	8	14	-5.2	-6.3	4	21	-4.6	-5.7
Feb.	17	17	-8.1	-3.8	26	27	-8.7	-3.3
Mar.	20	49	4.2	2.6	6	56	3.8	3.1
Apr.	71	82	10.8	9.9	94	91	10.3	9.9
May	108	101	15.2	16.1	158	128	15.3	16.3
June	125	109	21.5	21.4	175	129	21.1	21.6
July	166	89	22.8	23.6	123	114	22.5	23.6
Aug.	232	82	21.1	22.6	125	95	20.6	22.5
Sept.	151	74	20.2	17.8	152	86	20.2	17.9
Oct.	23	55	12.4	10.9	32	69	12.0	11.1
Nov.	120	35	5.3	2.6	86	45	6.0	3.2
Dec.	92	21	-1.0	-4.7	160	34	-0.1	-4.0

	Site 4				Site 5			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr average	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	33	36	-5.8	-5.3	38	43	-5.7	-4.8
Feb.	44	40	-9.8	-3.0	37	46	-9.4	-2.5
Mar.	20	61	2.0	3.5	24	66	2.0	3.7
Apr.	58	87	11.5	10.4	77	89	11.4	10.6
May	119	104	17.2	16.5	130	115	17.5	16.3
June	214	104	21.5	21.8	290	97	21.0	21.5
July	130	99	22.9	23.8	121	101	22.4	23.5
Aug.	89	110	22.0	22.8	89	97	21.3	22.5
Sept.	138	79	21.7	18.4	49	82	21.0	18.2
Oct.	56	75	12.9	11.7	42	72	12.6	11.6
Nov.	139	71	6.8	4.5	135	77	6.6	4.7
Dec.	129	51	3.4	-3.1	143	54	3.7	-2.6

† Data provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

Table 2.5 (cont.)

	Site 6				Site 8			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	39	43	-5.7	-4.9	35	51	-4.5	-3.7
Feb.	37	47	-9.4	-2.6	28	54	-7.5	-1.5
Mar.	26	66	1.9	3.6	46	69	2.0	4.4
Apr.	77	90	11.3	10.5	79	91	12.0	10.9
May	126	115	17.5	16.2	152	119	19.1	16.8
June	284	97	21.0	21.4	208	103	21.8	22.0
July	141	102	22.3	23.4	85	113	22.7	23.5
Aug.	93	96	21.2	22.4	75	93	21.7	22.5
Sept.	56	83	21.0	18.1	172	72	21.2	18.9
Oct.	43	73	12.5	11.5	29	81	13.4	12.3
Nov.	146	79	6.6	4.6	108	90	7.6	5.7
Dec.	145	55	3.6	-2.7	190	70	4.8	-1.4

	Site 9			
	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C	
Jan.	36	53	-6.9	-4.3
Feb.	25	49	-10.0	-2.4
Mar.	27	63	0.1	2.9
Apr.	65	88	9.3	9.7
May	101	108	17.3	15.4
June	204	100	20.2	20.8
July	131	103	21.1	22.7
Aug.	87	93	20.7	21.6
Sept.	62	85	19.7	17.7
Oct.	42	75	11.9	11.2
Nov.	47	79	6.5	4.8
Dec.	95	66	4.8	-1.7

† Data provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

Table 2.6. Type of response, probability values, and yield difference estimates associated with the field-specific analysis for the overall yield response and the landscape (LSP) zones yield response to shallow vs. standard seeding depth for the fields tested during the 2014 and 2015 growing seasons. Landscape zones were developed using relative elevation data and consisted of wet landscape zones (LSP1), transition or relatively flat landscape zones (LSP2), and dry landscape zones (LSP3).

Response	Field	Effect		Yield difference estimates			
		Overall	LSP	Overall	LSP1	LSP2	LSP3
		—— P value ——		—————— Mg ha^{-1} ——————			
		2014					
None	IA-02	ns†	ns	0.32	0.55	0.21	0.21
	IA-05	ns	ns	-0.63	-0.11	-0.75	-1.10
	IA-09	ns	ns	-0.08	-0.43	-0.49	0.68
	IL-01	ns	ns	0.23	0.15	0.40	0.15
	IN-01	ns	ns	-0.23	-0.72	-0.66	0.68
Overall	IA-08	0.0001	ns	-0.43	-0.23	-0.25	-0.39
	IA-10	0.0001	ns	0.44	0.59	0.48	0.25
LSP	IN-02	ns	0.0001	-0.07	0.06a	0.6a	-0.89b
Overall and LSP	IA-01	0.0042	0.0114	-0.22	-0.52a	-0.03b	-0.1b
		2015					
None	IA-06	ns	ns	-0.10	-0.25	-0.02	-0.03
	IL-06	ns	ns	-0.02	-0.19	-0.02	0.16
	IL-08	ns	ns	-0.12	-0.19	-0.13	-0.04
	IL-10	ns	ns	-0.27	-0.42	-0.48	-0.10
	IN-04	ns	ns	-0.10	-0.02	-0.01	-0.28
Overall	IA-04	0.0008	ns	-0.26	-0.27	-0.22	-0.28
	IL-11	0.0010	ns	-1.24	-0.68	-0.93	-2.11
	IL-12	0.0330	ns	-0.29	-0.11	-0.15	-0.61

† ns, not significant

Table 2.7. Type of response, probability values, and yield difference estimates associated with the field-specific analysis for the overall yield response and the landscape (LSP) zones yield response to deep vs. standard seeding depth for the fields tested during the 2014 and 2015 growing seasons. Landscape zones were developed using relative elevation data and consisted of wet landscape zones (LSP1), transition or relatively flat landscape zones (LSP2), and dry landscape zones (LSP3).

Response	Field	Effect		Yield difference estimates			
		Overall	LSP	Overall	LSP1	LSP2	LSP3
		—— P value ——		—————— Mg ha^{-1} ——————			
			2014				
None	IA-08	ns†	ns	-0.11	0.02	0.06	-0.12
	IN-02	ns	ns	-0.06	0.18	-0.11	-0.26
Overall	IA-02	0.0674	ns	-0.29	-0.19	-0.38	-0.30
	IL-01	0.0001	ns	-0.51	-0.56	-0.42	-0.54
	IN-01	0.0683	ns	-0.80	-0.50	-0.51	-1.40
LSP	IA-01	ns	0.0645	0.07	-0.08a	0.03a	0.26b
	IA-05	ns	0.0867	-0.58	-0.89a	-0.28b	-0.56ab
	IA-09	ns	0.0011	0.18	-0.58a	-0.04b	1.15ab
	IA-10	ns	0.0365	0.07	0.07a	-0.05a	0.2b
			2015				
None	IL-10	ns	ns	-0.21	-0.31	-0.31	-0.03
	IL-11	ns	ns	-0.32	0.21	-0.44	-0.73
	IL-12	ns	ns	-0.19	-0.33	-0.06	-0.18
Overall	IA-06	0.0023	ns	-0.68	-0.97	-0.39	-0.68
	IL-06	0.0638	ns	-0.23	-0.28	-0.22	-0.18
	IL-08	0.0050	ns	0.15	0.10	0.17	0.19
	IN-04	0.0046	ns	-0.53	-0.39	-0.29	-0.89
Overall and LSP	IA-04	0.0001	0.0788	-0.75	-0.75a	-0.53ab	-0.318b

† ns, not significant

Table 2.8. Type of response, probability values, and yield difference estimates associated with the field-specific analysis for the overall yield response and the landscape (LSP) zones yield response to shallow vs. deep seeding depth for the fields tested during the 2014 and 2015 growing seasons. Landscape zones were developed using relative elevation data and consisted of wet landscape zones (LSP1), transition or relatively flat landscape zones (LSP2), and dry landscape zones (LSP3).

Response	Field	Effect		Yield difference estimates			
		Overall	LSP	Overall	LSP1	LSP2	LSP3
		—— P value ——		—————— Mg ha^{-1} ——————			
		2014					
None	IA-01	ns†	ns	-0.26	-0.04	-0.40	-0.30
	IA-02	ns	ns	-0.12	-0.05	-0.12	-0.20
	IA-08	ns	ns	-0.21	-0.03	-0.05	0.13
	IA-09	ns	ns	-0.14	-0.08	0.03	-0.38
Overall	IA-10	0.0001	ns	0.29	0.29	0.19	0.37
	IL-01	0.0003	ns	0.72	0.44	0.91	0.81
	IN-02	0.0889	ns	-0.39	-0.56	-0.55	-0.06
		2015					
None	IA-04	ns	ns	0.09	0.12	0.11	0.05
	IL-06	ns	ns	0.11	-0.06	0.17	0.20
	IL-10	ns	ns	-0.01	0.06	-0.05	-0.04
	IL-11	ns	ns	-0.29	-0.36	0.05	-0.57
	IL-12	ns	ns	-0.14	-0.10	-0.16	-0.15
Overall and LSP	IL-08	0.0001	0.0073	-0.38	-0.57a	-0.39a	-0.18b

† ns, not significant

FIGURES

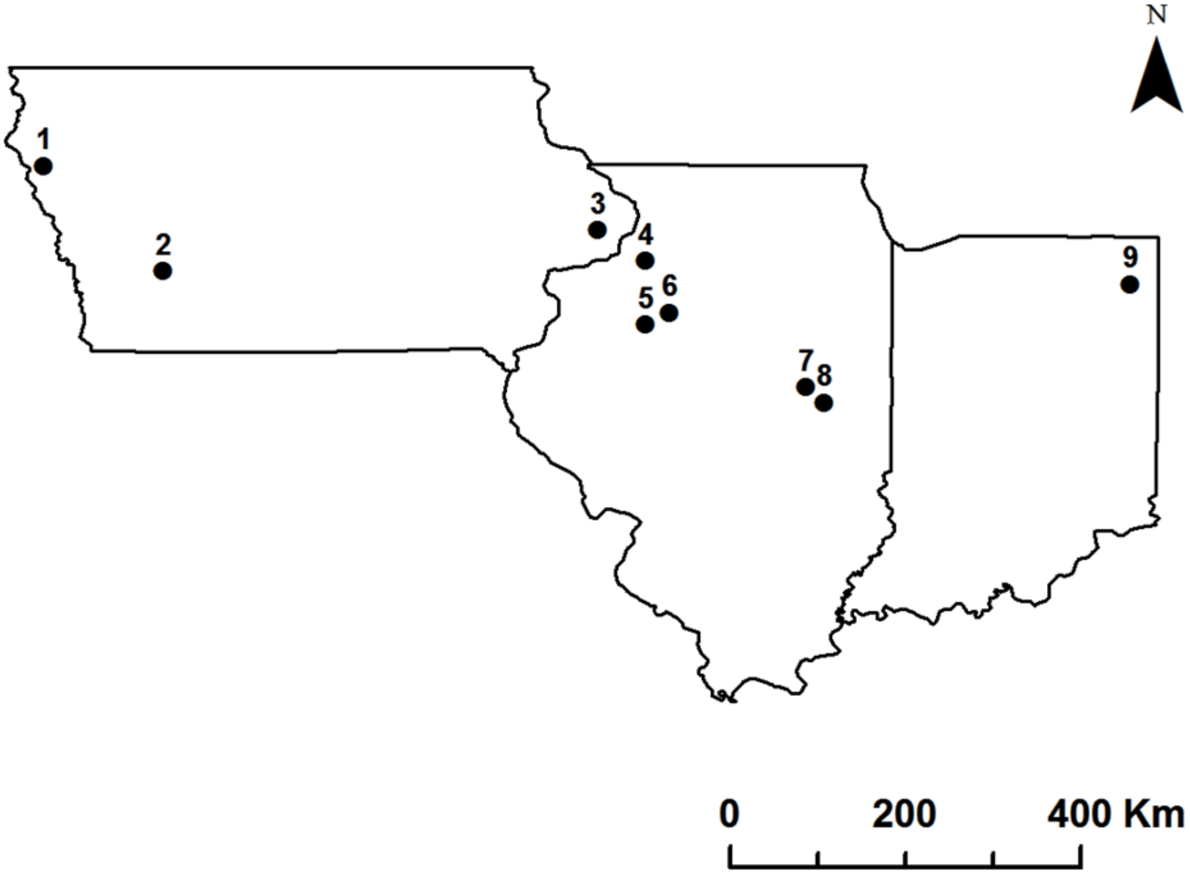


Fig. 2.1. Locations for the 9 sites in which 17 fields were tested for the within-field corn yield response to shallow, standard, and deep seeding depth during the 2014 and 2015 growing seasons in the states of Iowa, Illinois, and Indiana (left to right) in the U.S.

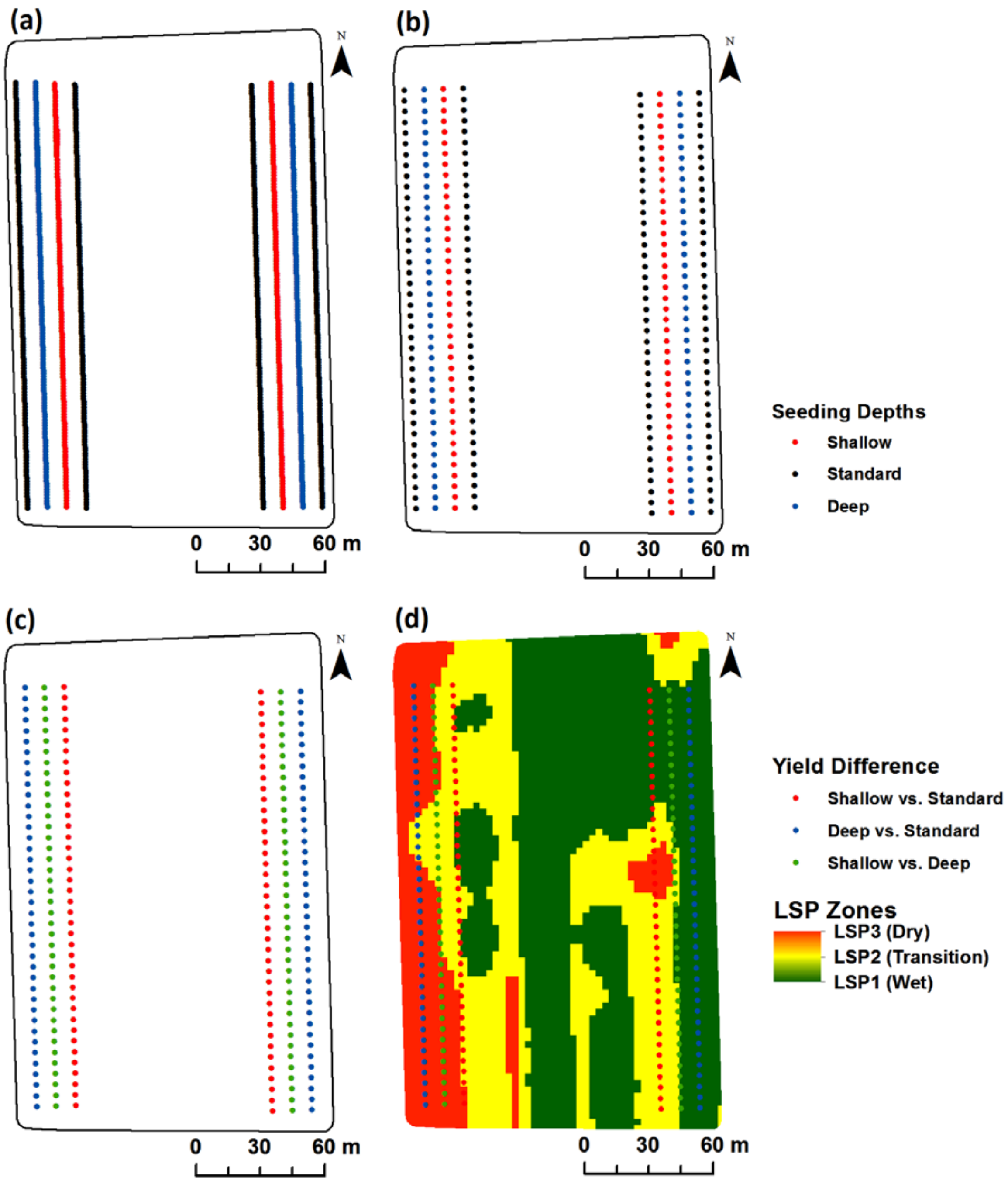


Fig. 2.2. Workflow for machine yield data processing. The raw yield data (a) were cleaned for extreme outliers and bucketed into a 5-m grid (b). Then, the yield difference was calculated for each pair of seeding depth treatment (shallow or deep) vs. the standard seeding depth and vs. each other, to the right or left of each treatment accordingly, and the location of the yield difference was recorded in the center of the pair (c). Finally, the landscape (LSP) zones were attached to each point based on the location (d), where LSP1 represents wet zones, LSP2 represents transitional zones, and LSP3 represents dry zones.

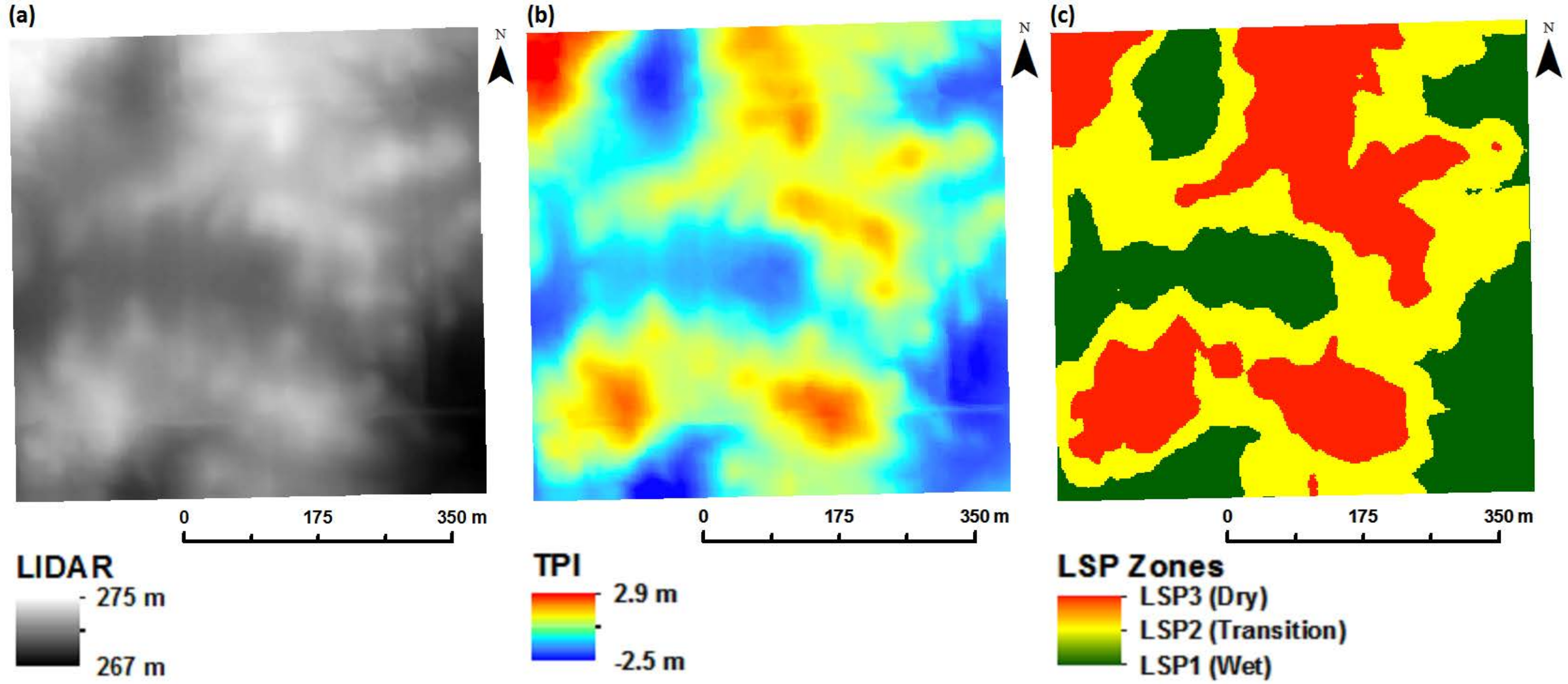


Fig. 2.3. Workflow for the development of landscape (LSP) zones for each field. Starting with light detection and ranging (LIDAR) elevation data (a), the Topographic Position Index (TPI) was computed to obtain the relative elevation layer (b). Then, the relative elevation layer was imported into a statistical software and a non-hierarchical clustering procedure (k-means) was used to delineate wet (LSP1), transitional (LSP2), and dry (LSP3) LSP zones (c). The LSP zones were developed to test the corn yield response to shallow, standard, and deep seeding within a field.

REFERENCES

Abbaspour-Gilandeh, Y., A. Khalilian, R. Alimardani, A. Keyhani, S.H. Sadati, W. Busscher, and J. Frederick. 2005. Energy savings with variable-depth tillage. Proceedings of the 27th Southern Conservation Tillage Systems Conference, Florence, South Carolina, USA. 27-29 June 2005. North Carolina Agricultural Research Service, North Carolina State University. p. 84-91.

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State University Extension, Ames, Iowa.

Adamchuk, V.I., C.R. Hempleman, and D.G. Jahraus. 2009. On-the-go capacitance sensing of soil water content. ASABE Mid-Central Conference. 4-5 Apr 2009. St. Joseph, MI.

Adamchuk, V.I., J.W. Hummel, M.T. Morgan, and S.K. Upadhyaya. 2004. On-the-go soil sensors for precision agriculture. Comput. Electron. Agric. 44:71-91.

Alessi, J., and J.F. Power. 1971. Corn emergence in relation to soil temperature and seeding depth. Agron. J. 63:717-719.

Atherton, B.C., M. Morgan, S.A. Shearer, T.S. Stombaugh, and A.D. Ward. 1999. Site-specific farming: A perspective on information needs, benefits and limitations. J. Soil Water Cons. 54:455-461.

Barr, A., M. Bennett, and J. Cardina. 2000. Geographic information systems show impact of field placement on sh2 sweet corn stand establishment. HortTechnology 10:341-350.

Benech-Arnold, R. L., and R.A. Sanchez. 2004. Handbook of seed physiology: applications to agriculture. Food Products Press.

Bobryk, C.W., D.B. Myers, N.R. Kitchen, J.F. Shanahan, K.A. Sudduth, S.T. Drummond, B. Gunzenhauser, and N.N. Gomez Raboteaux. 2016. Validating a digital soil map with corn yield data for precision agriculture decision support. Agron. J. 108:957-965.

Bradley, C.A. 2009. Managing diseases. Illinois Agronomy Handbook: 24th Edition. University of Illinois at Urbana-Champaign. Cooperative Extension Service. p. 197-207.

Brady, N.C., and R.R. Weil. 2008. Elements of the nature and properties of soils. Pearson Prentice Hall.

Burrough, P.A. 1983. Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels of soil variation. J. Soil Sci. 34:577-597.

Carter, L.M., and J.H. Chesson. 1993. A soil moisture seeking planter control. ASAE paper 93-1553.

Carter, L.M., and J.H. Chesson. 1996. Below the surface. Seed World 134:14-15.

Choi, M., J.M. Jacobs, and M.H. Cosh. 2007. Scaled spatial variability of soil moisture fields. Geophys. Res. Lett. 34 L01401.

Christy, C.D. 2008. Real-time measurement of soil attributes using on-the-go near infrared reflectance spectroscopy. Comput. Electron. Agric. 61:10-19.

Coulter, J. 2016. Corn planting decisions to establish a foundation of success. University of Minnesota Extension. http://www.extension.umn.edu/agriculture/corn/planting/corn-planting-decisions/ (accessed 1 July 2016).

Cox, M.S., and P.D. Gerard. 2007. Soil management zone determination by yield stability analysis and classification. Agron. J. 99:1357–1365.

Derby, N.E., X. Francis, M. Casey, and D.W. Franzen. 2007. Comparison of nitrogen management zone delineation methods for corn grain yield. Agron. J. 99:405–414.

Deumlich, D., R. Schmidt, and M. Sommer. 2010. A multiscale soil–landform relationship in the glacial-drift area based on digital terrain analysis and soil attributes. J. Plant Nutr. Soil Sci. 173:843–851.

Doerge, T.A., and D.L. Gardner. 1999. On-farm testing using the adjacent strip comparison method. In: P.C. Robert, R.H. Rust, W.E. Larson, editors, Precision Agriculture, ASA, CSSA, SSSA, Madison, WI. p. 603-609.

Duffy, M. 2015. The 2011 costs of crop production. Ag Decision Maker 15(2) art. 2. http://lib.dr.iastate.edu/agdm/vol15/iss2/2 (accessed 27 June 2016).

Dyck, F.B., W.K. Wu, R. Lesko. 1985. Automatic depth control for cultivators and air seeders developed under the AERD program. In: Proceedings of the Agri-Mation I. Conference and exhibition. 25–28 Feb 1985. St. Joseph. p. 265–277.

Earl, R., J.C. Taylor, G.A. Wood, I. Bradley, I.T. James, T. Waine, J.P. Welsh, R.J. Godwin, and S.M. Knight. 2003. Soil factors and their influence on within-field crop variability, part I: field observation of soil variation. Biosyst. Eng. 84:425-440.

Elmore, R., M. Al-Kaisi, and M. Hanna. 2014. Corn seeding depth: back to the basics. Integrated Crop Management News. Iowa State University Extension. https://extension.umd.edu/sites /default/files/_docs/Agronomy%20News%20May%201%202014.pdf (accessed 20 July 2014).

Francés, A.P., and M.W. Lubczynski. 2011. Topsoil thickness prediction at the catchment scale by integration of invasive sampling, surface geophysics, remote sensing and statistical modeling. J. Hydrol. 405:31–47.

Fridgen, J.J., N.R. Kitchen, K.A. Sudduth, S.T. Drummond, W.J. Wiebold, and C.W. Fraisse. 2004. Management zone analyst (MZA): Software for subfield management zone delineation. Agron. J. 96:100–108.

Fulton, J.P., L.G. Wells, S.A. Shearer, and R.I. Barnhisel. 1996. Spatial variation of soil physical properties: a precursor to precision tillage. Presented at the 1996 ASAE Annual International Meeting, paper no.96-1012. ASAE, St. Joseph, MI.

Gallant, J.C., and J.P. Wilson. 2000. Primary topographic attributes. In: J.P. Wilson and J.C. Gallant, editors, Terrain analysis: Principles and applications. Wiley, New York, pp. 51–85.

Giorgis, M., P. Tecco, A. Cingolani, D. Renison, P. Marcora, and V. Paiaro. 2011. Factors associated with woody alien species distribution in a newly invaded mountain system of central Argentina. Biological Invasions 13:1423–1434.

Gorucu, S., A. Khalilian, Y.J. Han, R.B. Dodd, F.J. Wolak, and M. Keskin. 2001. Variable depth tillage based on geo-referenced soil compaction data in Coastal Plain region of South Carolina. ASAE paper 011016. St. Joseph, MI.

Gupta, S.C., E.C. Schneider, and J.B. Swan. 1988. Planting depth and tillage interactions on corn emergence. Soil Sci. Soc. Am. J. 52:1122-1127.

Hanna, A.Y., P.W. Harlan, and D.T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. Agron J. 74:999–1004.

Hawley, M.E., T.J. Jackson, and R.H. McCuen. 1983. Surface soil moisture variation on small agricultural watersheds. J. Hydrol. 62:179-200.

Heege, H.J. 2013. Site-specific sowing. Precision in crop farming: Site specific concepts and sensing methods: Applications and results. p. 171.

Helms, T.C., E.L. Deckard, and P.A. Gregoire. 1997. Corn, sunflower, and soybean emergence influenced by soil temperature and soil water content. Agron. J. 89:59-63.

Hillel, D. 1990. Role of irrigation in agricultural systems. In B.A. Stewart and D.R. Nielsen, editors, Irrigation of agricultural crops. Agronomy monograph no. 30:5-30. ASA, CSSA, and SSSA, Madison, WI.

Howell, T. 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation. In B.A. Stewart and D.R. Nielsen, editors, Irrigation of agricultural crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI. p. 391-434.

Hunt, D., and D. Wilson. 2015. Farm power and machinery management. Waveland Press.

Hupet, F., and M. Vanclooster. 2002. Intraseasonal dynamics of soil moisture variability within a small agricultural maize cropped field. J. Hydrol. 261:86-101.

Jiang, P., and K.D. Thelen. 2004. Effect of soil and topographic properties on crop yield in a north-central corn–soybean cropping system. Agron. J. 96:252-258.

Khalilian, A., Y.J. Han, R.B. Dodd, M.J. Sullivan, S. Gorucu, and M. Keskin. 2002. A control system for variable depth tillage. ASAE paper 021209. St. Joseph, MI.

Kitchen, N.R., K.A. Sudduth, D.B. Myers, S.T. Drummond, and S.Y. Hong. 2005. Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Comput. Electron. Agric. 46:285–308.

Knappenberger, T., and K. Köller. 2006. The dynamic variation of seeding depth of corn. In Proceedings of the 8th International Conference on Precision Agriculture and other Precision Resources Management. Minneapolis, MN.

Knappenberger, T., and K. Köller. 2012. Spatial assessment of the correlation of seeding depth with emergence and yield of corn. Precis. Agric. 13:163-180.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Mastorakos, M., V. Adamchuk, F. Réne-Laforest, and C. Hemplemen. 2014. Development of a capacitance-based sensor for on-the-go soil moisture measurements. In I.C. Paltineanu, editor, Transactions of the Fourth International Symposium on Soil Water Measurement Using Capacitance, Impedance and TDT, Montreal, Quebec, Canada, 16-18 July 2014, Laurel, MD, USA. Paltin International, Inc. p. 97-106.

Miedema, P. 1982. The effects of low temperature on *Zea mays*. Adv. Agron. 35:93–128.

Mieza, M.S., W.R. Cravero, F.D. Kovac, and P.G. Bargiano. 2016. Delineation of site-specific management units for operational applications using the topographic position index in La Pampa, Argentina. Comput. Electron. Agric. 127:158-167.

Moshia, M.E., R. Khosla, L. Longchamps, R. Reich, J.G. Davis, and D.G. Westfall. 2014. Precision manure management across site-specific management zones: Grain yield and economic analysis. Agron. J. 106:2146–2156.

Nafziger, E.D. 2009. Corn. Illinois Agronomy Handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign, pg. 91-112.

Nielsen, R.L. 2010. Requirements for uniform germination and emergence of corn. Corny News Network, Purdue University.http://www.agry.purdue.edu/ext/corn/news/timeless/germemergreq.html (accessed 20 Feb. 2014).

Ortega, R.A., and O.A. Santibáñez. 2007. Determination of management zones in corn (*Zea mays* L.) based on soil fertility. Comput. Electron. Agric. 58:49–59.

Pierce, F.J., and P. Nowak. 1999. Aspects of precision agriculture. Adv. Agron. 67:1-85.

Pinard, V., C. Dussault, J.P. Ouellet, D. Fortin, and R. Courtois. 2012. Calving rate, calf survival rate, and habitat selection of forest-dwelling caribou in a highly managed landscape. J. Wildl. Manag. 76:189–199.

Pinheiro J, D. Bates, S. DebRoy, D. Sarkar, and R Core Team. 2016. nlme: linear and nonlinear mixed effects models. R package version 3.1-128. http://CRAN.R-project.org/package=nlme

Pinheiro, J.C., and D.M. Bates. 2000. Mixed effects models in S and S-Plus. Springer, New York.

Price, R.R., and L.D. Gaultney. 1993. Soil moisture sensor for predicting seed planting depth. Trans. ASAE 36:1703-1711.

Price, R.R., X. Huang, and L.D. Gaultney. 1990. Development of a soil moisture sensor. ASAE paper 90-3555. St. Joseph, MI:

Quantum GIS Development Team. 2016. Quantum GIS geographic information system. Open source geospatial foundation project.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

René-Laforest, F.F. 2015. Real-time variable control technologies for precision agriculture. Master’s thesis. McGill University, Montreal, Quebec, Canada.

Robert, P.C. 2002. Precision agriculture: A challenge for crop nutrition management. Plant Soil 47:143–149.

Ruffo, M.L., G.A. Bollero, D.S. Bullock, and D.G. Bullock. 2006. Site-specific production functions for variable rate corn nitrogen fertilization. Precis. Agric. 7:327-342.

Schepers, A.R., J.F. Shanahan, M.A. Liebig, J.S. Schepers, and S.H. Johnson. 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 96:195–203.

Schneider, E.C., and S.C. Gupta. 1985. Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. Soil Sci. Soc. Am. J. 49:415-422.

Schnitkey, G. 2015. Corn seed costs from 1995 to 2014. Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. farmdoc daily 5:214.

Scott, R.W., E.C. Krug, S.L. Burch, C.R. Mitsdarfer, and P. Nelson. 2010. Investigation of soil moisture variability under sod in east-central Illinois. Illinois State Water Survey.

Shearer, S.A., and S.K. Pitla. 2014. Precision planting and crop thinning. In Automation: The Future of Weed Control in Cropping Systems. Springer Netherlands. p. 99-124.

Sudduth, K.A., and S.T. Drummond. 2007. Yield editor: software for removing errors from crop yield maps. Agron. J. 99: 1471–1482.

Thorp, K.R., K.C. DeJonge, A.L. Kaleita, W.D. Batchelor, and J.O. Paz. 2008. Methodology for the use of DSSAT models for precision agriculture decision support. Comput. Electron. Agric. 64:276–285.

Timlin, D.J., Y. Pachepsky, V.A. Snyder, and R.B. Bryant. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Sci. Soc. Am. J. 62:764-773.

Trangmar, B.B., R.S. Yost, and G. Uehara. 1985. Application of geostatistics to spatial studies of soil properties. Adv. Agron. 38:45-94.

Tukey, J.W. 1977. Exploratory data analysis. Reading, Mass.: Addison-Wesley.

Weatherly, E.T., and C.G. Bowers Jr. 1997. Automatic depth control of a seed planter based on soil drying front sensing. Trans. ASAE 40:295-305.

Weiss, A.D. 2001. Topographic positions and landforms analysis (conference poster). ESRI International User Conference, San Diego, CA, July 9-13.

Zhu, Q., H.S. Lin, and J.A. Doolittle. 2013. Functional soil mapping for site-specific soil moisture and crop yield management. Geoderma 200:45–54.

CHAPTER 3: EMERGENCE, GROWTH, AND GRAIN YIELD RESPONSE OF CORN TO VARIABLE SEEDING DEPTH IN CONTRASTING LANDSCAPE ZONES

ABSTRACT

Corn (*Zea mays* L.) seeding depth is currently managed on a field-average basis. As soil moisture varies with topography, corn seeds are planted in suboptimal moisture in some field areas, resulting in uneven or delayed emergence and potential yield losses. This study examined corn planting at shallow, standard, and deep seeding depths in relatively dry and wet landscape (LSP) zones to quantify emergence, plant growth, and grain yield. Soil moisture in the LSP zones was also quantified. It was hypothesized that shallow seeding in wet LSP zones and deep seeding in dry LSP zones could improve emergence and yield compared to a standard seeding depth. Two fields in Illinois (IL-11 and IL-12) were planted with field-long strips in 2015 at shallow, standard, and deep seeding depths. For IL-11 and IL-12, 1,440 and 14,250 plants were measured for emergence, respectively, and 660 and 2,260 plants were hand-harvested, respectively. Soil moisture was nearly twice as high in wet LSP zones as in dry LSP zones for IL-11, while soil moisture differences were not as large in IL-12. Seeds planted at shallow depths had earlier emergence and higher growth earlier in the season compared to seeds planted deeper. Shallow seeding in wet LSP zones in IL-11 had a more consistent emergence rate and less variability compared to the standard and deep seeding depths. However, this did not translate into significant yield differences. The LSP zones and weather conditions had greater influence on yield than the seeding depths.

Abbreviations: GDD, growing degree days; GW, grain weight; LSP, landscape; PD, planting date.

INTRODUCTION

Early seedling emergence has been associated with improved plant growth and yield (Parera and Cantliffe, 1994; Verdú and Traveset, 2005; Lawles et al., 2012). The timely germination and emergence of corn plants requires to take into account factors such as soil moisture and temperature at the seeding depth, sufficient seed-to-soil contact, and proper soil aeration at the time of planting (Alessi and Power, 1971; Schneider and Gupta, 1985; Benech-Arnold and Sanchez, 2004; Nielsen, 2010; Elmore et al., 2014; Shearer and Pitla, 2014).

Producers should choose an appropriate time to start planting operations when soil temperatures are conducive to fast emergence (Heege, 2013); however, another factor involved in corn germination and emergence is soil moisture at the seeding depth. Research by Schneider and Gupta (1985) showed that fastest and maximum corn emergence was obtained by warm soil temperatures (20-30°C) and soil moisture at or above field capacity in a non-cloddy seedbed. However, these ideal conditions are rarely observed in the U.S. Corn Belt where corn producers aim to start planting operations as soon as mid-April (Sacks et al., 2010) to be able to use longer-season corn varieties that tend to yield more than shorter-season corn varieties.

Agronomists have stated that producers should avoid planting corn at depths shallower than 38 mm (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011), that seeding depths should range from 38 to 51 mm when soil moisture conditions are optimal (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011; Coulter, 2016), and that deeper seeding in the range of 64 to 76 mm may be necessary when planting in dry soil conditions (Nafziger, 2009; Nielsen, 2010; Abendroth et al., 2011).

Soil moisture varies within a field due to the topography (Hawley et al., 1983; Hupet and Vanclooster, 2002; Choi et al., 2007). Fields that present narrow elevation ranges and appear to be visually uniform have shown soil moisture gradients and localized moisture patterns (Scott et al., 2010). Fields and their soils present an intrinsic variability that results from the interaction over time and space of parent material, climate, topography, and biological activity (Burrough, 1983; Brady and Weil, 2008). Researchers have hypothesized that since soil moisture at the seeding depth is not uniform within a field then the seeding depth should also vary to place the seeds in optimal moisture conditions in all field areas (Price and Gaultney, 1993; Carter and Chesson, 1996; Benech-Arnold and Sanchez, 2004; Knappenberger and Köller, 2012; Elmore et al., 2014; Heege, 2013; René-Laforest, 2015).

As machinery used in precision agriculture develops to adapt to within-field variability, seeding depth for corn is still managed on a field-average basis. This assumption of homogeneity of soil moisture in agricultural fields may result in system inefficiencies by planting corn seeds in excessive soil moisture in parts of the field and deficient soil moisture in other parts of the same field. The result of such management could be an uneven crop stand, delayed emergence, higher incidence of disease when seeds are placed in cool and moist soils (Bradley, 2009) thereby increasing the time to emergence, and potential yield losses.

Corn seeds have become one of the largest operational expenditures for corn producers (Duffy, 2015; Schnitkey, 2015). Corn producers may benefit from the exploration of new technologies and practices to obtain the highest return from the investment in corn seed.

Managing agricultural inputs with respect to spatial variation is the defining goal of precision agriculture (Atherton et al., 1999; Pierce and Nowak; 1999). If seeding depth of corn could be adjusted on-the-go within a field the understanding of the distribution of soil moisture within a field becomes critical for the successful application of variable seeding depth. It is known that water availability is the most significant factor that determines crop yields (Hillel, 1990; Howell, 1990). Soil moisture during the growing season has influence in emergence, plant stand establishment, development, and grain fill. The soil moisture distribution of non-irrigated fields is largely dependent upon topography (Hanna et al., 1982) and evidence has shown that yields are related to topographic patterns (Timlin et al., 1998; Kravchenko and Bullock, 2000; Jiang and Thelen, 2004). Field areas of lower elevation receive water from areas of higher elevation; as a consequence, soil moisture content can potentially be inversely related to relative elevation.

Researchers have worked in the development of sensing instrumentation or seeding mechanisms to control seeding depth on-the-go for the last three decades (Dyck et al., 1985; Price et al., 1990; Carter and Chesson, 1993, 1996; Price and Gaultney, 1993; Weatherly and Bowers, 1997; Mastorakos et al., 2014), although the technology has yet to be adopted by machinery manufacturers. Gupta et al. (1988) suggested that shallower corn seeding (from 50 to 25 mm) could compensate for cooler soil temperatures in no-till cropping systems when soil moisture is sufficient in the seeding zone. A study on variable seeding depth of corn by Knappenberger and Köller (2012) found increased emergence of deeper-planted corn (80-90 mm) compared to shallow-planted corn over a three-year field study. Recent work by René-Laforest (2015), which included the testing of a soil moisture sensor, actuators, and a seeding depth decision algorithm for on-the-go changes, found positive results of seeding corn shallower in relatively wet field areas.

These previous studies have been conducted on a single geographic region at a time, in small plots, or have focused on the actuation mechanism for changing seeding depth on-the-go rather than on the agronomic value of such technology. To our knowledge, there is also limited literature in regards to the application of variable seeding depth of corn and its influence from emergence over time to physiological maturity in field conditions in the U.S. Corn Belt. An in-depth examination of corn seeding at different seeding depths, contrasting (relatively dry and wet) LSP zones, and environmental conditions could provide valuable information about corn emergence patterns, early- and late-season plant growth and development, grain yield, and the potential agronomic value of variable seeding depth of corn, if any.

It is hypothesized that varying seeding depth based upon management zones that present soil moisture gradients may be beneficial under suboptimal (excessively dry or wet) soil moisture conditions. It is hypothesized that shallow seeding in the wet LSP zones results in faster emergence and higher plant development earlier in the season, which may translate to higher grain yield and more consistent grain weight (GW) plant^{-1} compared to a standard seeding depth. In addition, it is hypothesized that when soil moisture conditions are adequate, deep seeding in the dry LSP zones results in similar or slightly delayed corn emergence compared to a standard seeding depth and with a similar grain yield outcome. Only when soil moisture is deficient, which could occur when a field receives little or no precipitation 7 to 14 d before and after planting operations, it is hypothesized that deep seeding in the dry LSP zones results in faster emergence and higher plant development earlier in the season, which may translate to higher grain yield and more consistent GW plant^{-1} compared to a standard seeding depth. It is also hypothesized that shallow seeding in the dry LSP zones and deep seeding in the wet LSP zones negatively affects corn emergence, plant development, and grain yield.

The objectives are: 1) use LSP zones to delineate soil moisture gradients for wetter and drier areas in which to set sampling zones; 2) quantify soil moisture content for the dry and wet

LSP zones at several soil depths in which corn is typically planted in the U.S. Corn Belt; 3) quantify corn emergence by LSP zones and seeding depth treatment; and 4) measure corn growth and development to physiological maturity.

MATERIALS AND METHODS

Study sites and experimental layout

One field in northwest Illinois managed in partnership with a commercial corn producer (IL-11) and one field in east-central Illinois at the Crop Sciences Research and Education Center (CSREC) at the University of Illinois at Urbana-Champaign (IL-12) were included for in-depth measurements in the 2015 growing season. These fields were part of a larger study described in Chapter 2. In IL-11 (41°49’ N 90°15’ W), predominant soil types included Oakville (mixed, mesic Typic Udipsamments) fine sand and Richwood (fine-silty, mixed, superactive, mesic Typic Argiudolls) silt loam. The soils in IL-12 (40°05’ N 88°22’ W) consisted of Drummer (fine-silty, mixed, superactive, mesic Typic Endoaquolls) silty clay loam and Flanagan (fine, smectitic, mesic Aquic Argiudolls) silt loam soils.

The study design was set up as a randomized complete block design with three replications in IL-11 and four replications in IL-12. In each field, a split-planter experiment (Doerge and Gardner, 1999) was established in order to assess the corn emergence, growth, and yield responses to shallow, standard, and deep seeding depths across contrasting LSP zones within the fields. The standard seeding depth was determined for the field conditions at the time of the planting operations, then shallow and deep seeding depths were chosen by adjusting the depth at least 15 mm above and below the standard seeding depth.

In IL-11, a 16-row planter was set up to place the treatments in a single planting date. The shallow and deep seeding depths were planted in half of the row units each, while the standard seeding depth was planted with all the row units set up at the standard seeding depth only. Each replication in IL-11 consisted of two planter passes, one for the shallow and deep seeding depths configuration and one for the standard seeding depth configuration. In IL-12, a 12-row planter was set up to plant six rows of the shallow or deep seeding depth while the other half planted at the standard seeding depth. Each replication in IL-12 consisted of two planter passes, one pass for the shallow and standard seeding depths configuration and one pass for the deep and standard seeding depths configuration. In IL-12, shallow, standard, and deep seeding depths were planted across the entire field length in three planting dates (PD1, PD2, and PD3). The addition of planting dates in IL-12 was conducted to increase the chances to capture different emergence patterns at diverse temperature and moisture conditions. Both fields were planted at 76-cm row width. The previous crops were soybean [*Glycine max* (L.) Merr.] in IL-11 and corn in IL-12. The corn producer in IL-11 and the CSREC crew in IL-12 conducted all field operations, which included typical Corn Belt agronomic practices of spring tillage, fertilizer, and pesticide applications.

Table 3.1 provides information about the planting and hand harvest dates, seeding rate, seeding depths for the shallow, standard, and deep seeding depth treatments, and no. of rows for the seeding depth treatment strips in in fields IL-11 and IL-12. Table 3.2 provides information about the precipitation, dry days, mean air temperatures for the 7-d period before and after planting, growing degree days (GDD) accumulation for the period 7 d and 14 d after planting, and for the entire season, and dominant soil textures for fields IL-11 and IL-12. Figure 3.1 shows the general location of the experimental sites. Figure 3.2 shows the distribution of the replications and sampling zones in IL-11. Figure 3.3 shows the distribution of the planting dates, replications, and sampling zones in IL-12.

Soil moisture and soil temperature monitoring

Volumetric soil moisture contents at depths of 25, 50, and 75 mm were monitored in both fields, while soil temperatures at depths of 25, 50, and 75 mm were monitored only in IL-12. Soil moisture was monitored with EC-5 sensors (Decagon Devices Inc., Pullman, WA) and soil temperature was monitored with RT-1 sensors (Decagon Devices Inc., Pullman, WA). Both EC-5 and RT-1 sensors were attached to EM-50 digital data loggers (Decagon Devices Inc., Pullman, WA) and set to record every 15 minutes. Data were downloaded weekly from the data loggers to avoid overwriting and to check for sensor performance.

In IL-11, soil moisture content was monitored in three locations for each of the dry and wet LSP zones for a total of six field locations. The soil moisture sensors were installed two days after the planting operations. In IL-12, six locations for each of the dry and wet LSP zones (12 locations total) within the field were chosen for monitoring of soil moisture while soil temperature was monitored in a single location within the field IL-12. In IL-12, soil moisture sensors were removed on 17 Apr. 2015 to prepare for the first planting date on 23 Apr. 2015 (PD1). Soil moisture sensors were placed back one day after PD1 and the soil temperature sensors were also installed. Soil sensors were kept for over 30 d after planting in IL-11 and for over 60 d after the first planting date in IL-12.

Moisture and temperature sensors were inserted horizontally at each depth (Fig. 3.4). The vertical overlap of the measurement volume of the moisture sensors across the 25-, 50-, and 75-mm depths should have been minimal, as the theoretical vertical measurement volume is of 25 to 30 mm (Cobos, 2015).

Gravimetric soil moisture contents for depths from 0 to 25, 25 to 50, and 50 to 75 mm in dry and wet LSP zones were also monitored. Five soil cores (40-mm wide and 100-mm long) in the proximity of the volumetric soil moisture sensors were extracted within a 1-m^2 area and composited by depth. The soil cores were cut on site to the specified depths and the composited soil samples for each depth were kept in airtight aluminum cans. The soil cores were taken immediately to a shop to be weighed, dried for 48 h at 60°C, and weighed again after drying. In field IL-11, gravimetric soil moisture content was measured in three sampling events (16 Apr., 20 Apr., and 30 Apr. 2015). In field IL-12, gravimetric soil moisture content was measured in four sampling events (4 Apr., 7 Apr., 11 Apr., and 17 Apr. 2015).

Verification of seeding depths

Each seeding depth was verified by destructive sampling of corn seedlings in both fields. Corn plants were dug up, soil adhered to the roots was shaken loose, and seeding depth was measured from the bottom of the seed to the soil surface, which was previously marked by a small cut in the corn stem. In IL-11, a single row within each seeding depth treatment strip was sampled twice per replication at growth stages V1 to V2. Each sample consisted of six plants, for a total of 36 plants per seeding depth treatment. In IL-12, the four replications of PD1 were sampled at each row unit of the planter at growth stages V1 to V2. Five consecutive plants per row unit were removed from a randomly placed transect within each replication, for a total of 120 plants per seeding depth treatment. The same planter depth settings used for PD1 in IL-12 were used for PD2 and PD3, thus assuming that seed placement for PD2 and PD3 was similar to the seed placement for PD1.

Corn emergence

Contrasting wetter and drier LSP zones were delineated for each field with the procedure shown in Chapter 2. Within these zones and based on the location of the replications, two areas per replication (areas representative of relatively dry and wet LSP zones) were identified for corn emergence measurements. In IL-11, a 12-m long section in a single row located in the middle of each treatment, replication, and LSP zones (dry and wet) combination was selected for seedling emergence measurements (Fig. 3.2). In IL-12, each zone was 5-m long by 18-rows wide where the shallow, standard, and deep seeding depth treatments were represented by 6 rows each (Fig. 3.3). These emergence zones resulted in approx. 1,440 plants measured in IL-11 and approx. 14,250 plants measured in IL-12 (approx. 4,750 per planting date).

After each planting event, the fields were scouted daily for emerged seedlings and emergence was recorded once the first seedling was found. In IL-12, two scouting days in PD1 and one scouting day in PD2 were omitted due to adverse weather conditions. The scouting visits were typically performed from 9 AM to 1 PM. The emergence measurements for all zones were continued until no more new plants were found. In IL-11, each emerging plant within the measurement zones was given a unique code to be able to track it from emergence to physiological maturity, while on IL-12 plants were identified from the plant growth stage measurement to physiological maturity. As a consequence, more detailed information was collected for the emergence patterns in IL-11. Corn emergence was expressed as a percent based on the theoretical plant population.

Plant growth

To explore the effect of the different seeding depths on plant development, measurements of plant growth stage, plant height (for IL-12 only), and stalk diameter were taken. Plant growth stage was measured with the leaf collar method (Ritchie et al., 1996). Plant height was measured from the ground to the uppermost, fully-developed collar. Stalk diameter was measured at the middle of the first elongated internode in the direction of largest stalk width using a digital caliper (No. 147 Digital Caliper, General Tools & Instruments, New York, NY). In IL-11, the same row section delimited for corn emergence was used to measure plant growth stage once at growth stages V5 to V6, and stalk diameters were recorded at stages R2 to R3. In IL-12, a single row from the corn emergence zones was selected from the middle rows within each seeding depth treatment, replication, and LSP zones combination that were used for corn emergence. Plant growth stage and height were taken once at growth stages V6 to V10 and stalk diameters were recorded at stages R2 to R3.

Growing degree days (GDD) were calculated using the National Oceanic and Atmospheric Administration (NOAA) 86/50 method described by Barger (1969) and also explained by Abendroth et al. (2011); the GDD were accumulated from the date of planting to the date of hand harvest.

Per-plant grain weight

In IL-11, the inner 6 m of the 12-m row sections measured for emergence, plant growth stage, and stalk diameter were hand harvested shortly after physiological maturity. Approximately 660 plants were hand harvested. The 6-m row sections that were hand harvested in IL-11 had a theoretical plant population of 39 plants row^{-1}. In IL-12, the same plants in the rows that were measured for emergence, plant growth stage, plant height, and stalk diameter were hand harvested shortly after physiological maturity. Approximately 2,260 plants were hand harvested (close to 754 plants per planting date). The sampled rows in IL-12 had a length of 5 m and a theoretical plant population of 33 plants row^{-1}. For both fields, the corn ears were individually bagged and labeled in the field before being taken to a shop to be dried. One at a time, the corn ears were mechanically threshed (Swanson Machine Co., Champaign, IL) and the GW plant^{-1} recorded, while grain moisture was measured (Seedburo Equipment Co., Des Plaines, IL) and composited for each sampled row. Grain weight was adjusted to a moisture content of 155 g kg^{-1}.

Statistical analysis

The data for cumulative corn seedling emergence were analyzed with SAS 9.4 (SAS Institute, 2013). A mixed model analysis using repeated measures was used, as seen in Madsen et al. (2012). Covariance structures were selected by comparing the values for the Akaike Information Criterion (AIC) (Akaike, 1974). Fixed factors included both the seeding depth treatments and the LSP zones, while blocks were considered random. Days after planting were considered a repeated measure. The LSMEANS procedure of SAS was used to separate means when significant effects in the model were found (SAS Institute, 2013).

The response of days to emergence (IL-11 only), plant counts, plant growth stage, plant height (IL-12 only), stalk diameter, and GW $plant^{-1}$ was modeled to include the fixed effects of the seeding depth treatments and LSP zones. The models were fitted with an analysis of variance using the PROC MIXED procedure of SAS 9.4 (SAS Institute, 2013). Blocks were designated as random, while seeding depth treatments and LSP zones were considered fixed factors. The assumptions of independence and homoscedasticity were explored graphically and the inclusion of variance and correlation structures were tested based on log-likelihood ratio tests (Pinheiro and Bates, 2000) with R (R Core Team, 2016). A significance level of $p \leq 0.10$ was selected for all models.

Fields IL-11 and IL-12 were analyzed individually. For IL-12, the three planting dates were analyzed separately. It was expected that grain yield would decrease with each passing planting date in IL-12; however, there was no interest in knowing the grain yield differences among the three planting dates nor their interactions with other factors in the model. Rather, the interest of this study was the main effect of seeding depth in terms of plant emergence, plant growth and development, and GW in the dry and wet LSP zones as influenced by weather patterns at each planting date.

RESULTS AND DISCUSSION

Weather conditions during 2015

Total monthly precipitation and mean monthly temperatures for fields IL-11 and IL-12 during 2015 along with the 30-yr normals are presented in Table 3.3. In IL-11, precipitation in April and August was lower than the 30-yr normal (Table 3.3). Precipitation during the months from May to July and September was higher than the 30-yr normal. The mean monthly temperatures in April, May, and September were higher than the 30-yr normal while temperatures in June to July were lower than the 30-yr normal. In IL-12, precipitation during April, July and August was lower than the 30-yr normal and higher than the 30-yr normal in May, June, and September. The corn seeds in field IL-12 planted in the third planting date (PD3) were particularly affected in some waterlogged field areas due to over 100 mm of excess precipitation in June compared to the 30-yr normal. The mean temperatures in April, May, and September were higher than the 30-yr normal and lower from June to August than the 30-yr normal.

Weather conditions before and after planting operations

Precipitation in field IL-11 was of 13 and 21 mm in the 7-d period before and after planting, respectively (Table 3.2). Field IL-11 received a small amount of precipitation 1 d before planting but not enough to prevent planting operations; moreover, field IL-11 received precipitation within 4 d after planting (Table 3.2). Mean air temperatures in field IL-11 were over 10°C in the 7-d period before and after planting (Table 3.2). In field IL-12, precipitation was adequate to excessive for all planting dates. The PD3 in IL-12 received the largest amount of precipitation in the 7-d period before and after planting (130 mm) (Table 3.2). Mean air temperatures for PD1 in IL-12 were under 10°C in the 7-d period after planting, while air temperatures for PD2 and PD3 were over 10°C in the 7-d period before and after planting (Table 3.2).

Field IL-11

In field IL-11, the seeds from the shallow seeding depth had more placement variability (CV = 34.3) followed by the seeds from the deep seeding depth (CV = 23.2), while the seeds from the standard seeding depth had the lowest seed placement variability (CV = 18.1) (Fig. 3.5). Additionally, the seeds from the deep seeding depth showed the widest range of seed placement (Fig. 3.5).

The mean daily volumetric soil moisture contents as measured by soil moisture sensors for the dry and wet LSP zones at depths of 25, 50, and 75 mm along with precipitation events are shown in Fig. 3.6, 3.7, and 3.8, respectively. As expected, soil moisture increased with depth. The effect of LSP zones on soil moisture content was noticeable for the 50- and 75-mm depths (Fig. 3.7 and 3.8) but not for the 25-mm depth (Fig. 3.6). For the mean daily soil moisture content at the 25-mm depth, no large differences were detected between the dry and wet LSP zones during the monitoring period, which was unexpected as the dry LSP zones consisted mostly of fine sand soils (Fig. 3.6). The mean daily soil moisture content in the wet LSP zones at both the 50- and 75-mm depths was markedly higher than in the dry LSP zones (Fig. 3.7 and 3.8). The soil moisture content increase from the 50-mm depth to the 75-mm depth (0.01 m^3 m^{-3} in wet LSP zones and no increase in dry LSP zones) was not as large as the increase from the 25-mm depth to the 50-mm depth (0.05 m^3 m^{-3} in wet LSP zones and 0.01 m^3 m^{-3} in dry LSP zones)

(Fig. 3.6, 3.7, and 3.8). The mean daily soil moisture content at the 50- and 75-mm depths had no overlap for the soil moisture content between the dry and wet LSP zones at each depth, even during days with precipitation events (Fig. 3.7 and 3.8). This is likely a result of the fast drainage conditions exhibited by the dry LSP zones in IL-11, which consisted mostly of fine sand soils. Across the soil moisture monitoring period, mean daily soil moisture content was consistently above 0.10 m^3 m^{-3} for the 25-mm depth, and soil moisture was consistently 0.03 to 0.05 m^3 m^{-3} higher at the 50- and 75-mm depths compared to the 25-mm depth, regardless of LSP zones (Fig. 3.6, 3.7, and 3.8). Fifteen precipitation events were recorded in IL-11 for the period shortly before the planting date and for 30 d after the planting operation. Based on the volumetric soil moisture monitoring, soil moisture conditions in IL-11 were likely sufficient for seed imbibition, germination, and emergence at all depths.

The gravimetric soil moisture contents for the three sampling events in the weeks following the planting operations in IL-11 are shown in Fig. 3.9. As shown by the volumetric soil moisture contents measured by the soil moisture sensors (Fig. 3.6-3.8), there were also differences in the gravimetric soil moisture contents by depth and by LSP zones. On average, the gravimetric soil moisture contents in the wet LSP zones were 0.087 to 0.104 kg kg^{-1} higher than in the dry LSP zones. In addition, the mean gravimetric soil moisture content increased from the 0-25-mm depth to the 25-50-mm depth but it decreased slightly from the 25-50-mm depth to the 50-75-mm depth, an unexpected finding. The mean soil moisture content increase from the 0-25-mm depth to the 25-50-mm depth was of 0.014 kg kg^{-1} in the dry LSP zones and of 0.031 kg kg^{-1} in the wet LSP zones (Fig. 3.9). The mean soil moisture content decrease from the 25-50-mm depth to the 50-75-mm depth was of 0.006 kg kg^{-1} in the dry LSP zones and of 0.009 kg kg^{-1} in the wet LSP zones (Fig. 3.9). An interesting observation was found for the 20 Apr. 2015 sampling. After a few hours of a 17-mm precipitation event, the 20 Apr. 2015 sampling had higher gravimetric soil moisture content at the 0-25- and 25-50- mm depths compared to the 50-75-mm depth, particularly in the wet LSP zones (Fig. 3.9). This is likely due to the soil not reaching field capacity yet at the time of the soil sampling event, as soil water was still draining lower into the soil profile (Campbell and Norman, 1998). Overall, the measurements of gravimetric soil moisture provided evidence that planting deeper than 50 mm likely resulted in no benefits in terms of higher and more adequate soil moisture content for germination and emergence, and it could have been detrimental due to cooler soil temperatures and the extra elongation of the mesocotyl needed to place the coleoptile near the soil surface.

The mean air temperatures in IL-11 decreased from about 11°C before planting to 6 to 9°C after planting (Fig. 3.10); the cold weather lasted for a week. When air temperatures increased above 10°C the first seedlings started to emerge from the soil. The first week after planting accumulated 81 GDD, while the second week after planting accumulated only an additional 19 GDD for a total of 100 GDD 14 d after planting. Research has shown that corn seeds need to accumulate 90 to 125 GDD to emerge from the soil (Abendroth et al., 2011), although other factors such as suboptimal soil moisture, residue cover, and the corn variety can influence the GDD requirement for emergence (Hunter and Kannenberg, 1972; Schneider and Gupta, 1985; Swan et al., 1987).

The cumulative percent emergence for the shallow, standard, and deep seeding depths in the dry and wet LSP zones in field IL-11 is shown in Fig. 3.11. In the dry LSP zones, the first plants to emerge were plants from the shallow seeding depth and plants from a single replicate of the deep seeding depth 14 d after planting after the accumulation of 100 GDD. Higher percent emergence was observed earlier in the dry LSP zones, likely due to sufficient soil moisture and warmer soil temperatures compared to the soil conditions in the wet LSP zones. This partially supports the hypothesis that seeds from the shallow seeding depth emerge faster than the standard and deep seeding depths; however, it was not expected that the percent emergence would be higher earlier in the dry LSP zones and that plants from the deep seeding depth would be observed before plants from the standard seeding depth (Fig. 3.11). From 14 to 19 d after planting the emergence patterns of the shallow and deep seeding depths in the dry LSP zones showed high variability, as shown by standard error bars, and neither the shallow nor the deep seeding depth had a consistent emergence rate during the first few days of emergence (Fig. 3.11). This provided no support to the hypothesis that deep seeding in the dry LSP zones benefits corn emergence. Surprisingly, the plants from the standard seeding depth emerged two days later (16 d after planting) than plants from the shallow and deep seeding depths, and the plants from the standard seeding depth also showed the most consistent emergence rate in the dry LSP zones (Fig. 3.11). It is difficult to explain why plants from the standard seeding depth took longer to emerge compared to plants from the deep seeding depth. It is possible that the planter failed to consistently plant seeds at the deep seeding depth as shown by Fig. 3.5. In addition, there have been instances where soil moisture content was observed to be higher at depths close to the shallow and deep seeding depths than at the standard seeding depth (data not shown), for example after a precipitation event following several days with no precipitation; however, that was not the soil moisture pattern observed in IL-11 after planting operations (Fig. 3.6-3.8). The emergence pattern in the dry LSP zones in field IL-11 underscores the complexity found when attempting to describe a biological process such as corn emergence, which is influenced by the inherent variability found in agricultural fields, the corn variety, the weather conditions leading up to planting and in the following weeks after planting, and the consistency (or lack thereof) of the planter. In the wet LSP zones, the shallow seeding depth had a more consistent emergence rate and less variability compared to the emergence rates of the standard and deep seeding depths, as shown by standard error bars (Fig. 3.11). This partially supports the hypothesis that shallow seeding in the wet LSP zones results in faster emergence. In the wet LSP zones, it took 5 d (from 14 to 19 d after planting) for the percent emergence of the plants from the standard seeding depth to get within 15% of the percent emergence of the plants from the shallow seeding depth (Fig. 3.11); the plants from the deep seeding depth took until 20 d after planting to get within 15% of the percent emergence of the plants from the shallow seeding depth (Fig. 3.11).

For the corn emergence data, there was a main effect of LSP zones ($p = 0.086$) (Table 3.4); the mean percent emergence across all days was significantly higher for the dry LSP zones compared to the wet LSP zones (approx. 5% higher). However, final emergence at 23 d after planting was nearly the same for all seeding depths and LSP zones. Final percent emergence was 85 to 91% across seeding depths and LSP zones. There was not a significant seeding depth × LSP zones interaction for the corn emergence response (Table 3.4). For field IL-11, it took the accumulation of 174 GDD to reach about 80% emergence across both LSP zones for all seeding depths (Fig. 3.11).

Another perspective into corn emergence patterns in field IL-11 is by visualizing the percent emergence day^{-1} by seeding depths and LSP zones until emergence was completed (Fig. 3.12). The seeds from the shallow seeding depth in the dry LSP zones showed a positively skewed distribution of percent emergence day^{-1}, with approx. 25% of seeds in the dry LSP zones emerging in the first day in which seedlings were observed (Fig. 3.12). Emergence day^{-1} was then consistently from 5 to 15% day^{-1} until 21 d after planting operations, in which the emergence was nearly completed. The seeds from the standard seeding depth in the dry LSP zones presented a staggered percent emergence day^{-1} starting 16 d after planting until percent emergence peaked at approx. 30% 20 d after planting, and percent emergence day^{-1} tapered off more or less abruptly after the peak (Fig. 3.12). The seeds from the deep seeding depth showed a different pattern in the dry LSP zones compared to the shallow and standard seeding depth (Fig. 3.12). Starting 14 d after planting, the emergence in the dry LSP zones for the deep seeding depth was from 8 to 15% emergence day^{-1}, with a peak of approx. 20% emergence 20 d after planting and percent emergence gradually decreasing after 21 d after planting (Fig. 3.12). In the wet LSP zones, the seeds from the shallow seeding depth presented a staggered percent emergence day^{-1} until emergence peaked at approx. 20% 18 d after planting, and emergence gradually tapered off 18 d after planting (Fig. 3.12). The seeds from the standard seeding depth in the wet LSP zones showed very small percent emergence day^{-1} until 18 d after planting (Fig. 3.12). The percent emergence for the seeds from the standard seeding depth in the wet LSP zones was approx. 20, 35, and 30% for 18, 19, and 20 d after planting, respectively, and totaling nearly 85% emergence in just three days (Fig. 3.12). The seeds for the deep seeding depth in the wet LSP zones showed a gradual percent emergence day^{-1} starting 16 d after planting, with the greatest proportion of emergence being reached 19 to 21 d after planting (Fig. 3.12). This perspective into corn emergence patterns in IL-11 provided evidence of the potential interactions that can be observed between seeding depths and LSP zones with the goal of optimizing corn emergence at each LSP zone.

The probability values for the analysis of mean days to emergence, plant counts, growth stage, stalk diameter, and GW are shown in Table 3.5, while the mean values for the variables are shown in Table 3.6.

As the plants in IL-11 were identified since emergence, data for mean days to emergence were obtained for all sampled plants. There was a significant main effect of seeding depth (p = 0.10) (Table 3.5). On average, the seeds from the shallow seeding depth emerged 1.7 and 1.4 d faster than the seeds from the standard and deep seeding depths, respectively (Table 3.6). The estimated mean days to emergence for the plants from the standard and deep seeding depths were not significantly different from each other (Table 3.6). This again partially supports the hypothesis that seeds from the shallow seeding depth emerge faster than the standard and deep seeding depths; however, there was not a significant seeding depth × LSP zones interaction (Table 3.5). The fact that the seeds from the shallow seeding depth emerged first in the fine sand soils (which constituted most of the dry LSP zones) provided evidence that soil moisture conditions were sufficient even in the field areas predicted to be relatively drier than the rest of the field.

For the analysis of final plant counts, there were no significant main effects nor a significant seeding depth × LSP zones interaction (Table 3.5). The final plant count had a range of 35 to 37 plants row^{-1} (Table 3.6). As shown previously by the percent emergence data (Fig. 3.11), although there were differences in the cumulative emergence when seedlings were actively emerging from the soil, by the 23rd day after the planting operations in IL-11 the final plant counts were not significantly different (Table 3.6).

For the plant growth stage analysis, there was a significant main effect of seeding depth (p = 0.01) (Table 3.5). The plants from the shallow seeding depth were slightly more developed (an estimated 0.6 growth stage higher) than the plants from both the standard and deep seeding depths, which were in turn not significantly different from each other (Table 3.6). This slightly higher plant growth stage exhibited by the plants from the shallow seeding depth compared to the plants from the standard and deep seeding depths was consistent with the plants from the shallow seeding depth emerging earlier than the plants from the standard and deep seeding depths. This partially supports the hypothesis that plants from the shallow seeding depth present higher plant development earlier in the season; however, there was no significant seeding depth × LSP zones interaction (Table 3.5).

For the stalk diameters, there was a significant seeding depth × LSP zones interaction ($p = 0.008$) (Table 3.5). Of practical importance, the plants from both the shallow and standard seeding depth had higher mean stalk diameters compared to the mean stalk diameter from the plants at the deep seeding depth in the wet LSP zones (Table 3.6). This partially supports the hypothesis that deep seeding in wet LSP zones negatively affects plant growth and development compared to the plants from the shallow and standard seeding depths. Decreased plant growth due to deep seeding in wet LSP zones could be for a variety of reasons, including cooler soil conditions, reduced soil aeration deeper in the soil profile, and corn seedling diseases that thrive in cool and moist soil conditions. This also provided evidence of the importance of optimizing corn seeding depths within all field areas, as the negative impact of deep seeding in the wet LSP zones was observed throughout the growing season.

For the GW plant^{-1}, there was a significant main effect of LSP zones ($p = 0.031$) (Table 3.5). The mean GW plant^{-1} was 39 g higher for the plants in the wet LSP zones than in the dry LSP zones (Table 3.6). The lower soil moisture, and also likely lower fertility levels, in the dry LSP zones, which consisted mostly of fine sand soils, negatively impacted grain yield. It is possible that adequate soil moisture conditions after planting in IL-11 may have masked any significant effects due to seeding depth alone; the yield outcome may have been different if drier soil moisture conditions had prevailed after the planting operations. In addition, the high seed placement variability and considerable overlap among the shallow, standard, and deep seeding depths (Fig. 3.5) may have obscured seeding depth treatment effects for the variables quantified in field IL-11.

In regards to the GW plant^{-1} variability observed for each seeding depth treatment and LSP zones combination, it was assessed via descriptive statistics as shown by previous researchers (Vega and Sadras, 2003; Boomsma and Vyn, 2009; Green-Tracewicz et al., 2011; Mayer et al., 2012; Kovács and Vyn, 2014). The GW plant^{-1} distribution was highly variable for the shallow and deep seeding depths in the dry LSP zones (Fig. 3.13), exhibiting coefficients of variation (CV) of 55 and 56, respectively, and negative kurtosis and skewness (Table 3.7). The GW plant^{-1} distribution for the standard seeding depth was also negatively skewed but exhibited less than half of the CV shown by the GW plant^{-1} distribution of the shallow and deep seeding depths (CV = 25) (Fig. 3.13, Table 3.7). There was a higher incidence of low-yielding plants (plants with GW < 50 g plant^{-1}) for the shallow and deep seeding depth (approx. 16-17%) compared to the incidence of low-yielding plants from the standard seeding depth (<5%) (Fig. 3.13). On the other hand, the GW plant^{-1} distribution of the shallow, standard, and deep seeding depths in the wet LSP zones exhibited CVs within 3 units of each other, albeit the CVs were high at 38 to 41, with a well-defined peak and negative skewness (Fig. 3.13, Table 3.7). The incidence of low-yielding plants was similar across the shallow, standard, and deep seeding depths in the wet LSP zones; however, the incidence was unexpectedly high for all seeding depths (approx. 9-10% of plants) (Fig. 3.13). It is not known why the incidence of low-yield plants was as high as observed in IL-11. I speculate that the cooler weather conditions after the planting operations in IL-11 caused chilling injury to the seeds (Miedema, 1982). Nevertheless, a higher incidence of low-yielding plants for the shallow seeding depth would have been expected, since the seeds from the shallow seeding depth were closer to the soil surface and experienced the widest temperature fluctuations, but that was not observed (Fig. 3.13). The frequency distribution data for the GW plant^{-1} does not provide support to the hypothesis that deep seeding in the dry LSP zones reduces GW plant^{-1} variability, although the smaller CV shown by the GW plant^{-1} from the shallow seeding depth partially supports the hypothesis that shallow seeding in the wet LSP zones reduces GW plant^{-1} variability compared to the standard seeding depth. Moreover, the peak of the GW plant^{-1} distribution for the shallow seeding depth in the wet LSP zones was shifted towards higher GW plant^{-1} and with higher kurtosis compared to the GW plant^{-1} distribution for the standard seeding depth (Fig. 3.13, Table 3.7).

Field IL-12

From the verification of seeding depths in IL-12, it was observed that the seeds from the shallow seeding depth had more seed placement variability (CV = 17.7) compared to the standard seeding depth (CV = 13.1 and 13.8) and deep seeding depth (CV = 11.4) (Fig. 3.14 and 3.15). With few exceptions, the seed placement for each seeding depth treatment across the row units was satisfactory.

The mean daily volumetric soil moisture contents as measured by soil moisture sensors for the dry and wet LSP zones during all three planting dates at depths of 25, 50, and 75 mm along with precipitation events are shown in Fig. 3.16, 3.17, and 3.18, respectively. Predictably, soil moisture increased with depth. However, at the 25- and 50-mm depths, the dry LSP zones were wetter than the wet LSP zones, with the differences being more evident at the 25-mm depth (Fig. 3.16 and 3.17). Soil type differences may help explain the discrepancy of soil moisture content by LSP zones, since the soil in the dry LSP zones was paler in color, while the soil in the wet LSP zones was very dark in color and likely easier to heat up and lose moisture via evaporation. At the 75-mm depth, there were differences in the soil moisture content between the dry and wet LSP zones, with the wet LSP zones being wetter most of the time (Fig. 3.18). When the frequency of precipitation events increased after PD2, no differences in the mean daily soil moisture content were detected between the dry and wet LSP zones at the 75-mm depth until about a week before the PD3 (Fig. 3.18). After precipitation events within a week before and after PD3 totaling 130 mm, higher mean daily soil moisture content in the wet LSP zones was detected, likely due to slower drainage in the wet LSP zones and high soil moisture content from antecedent precipitation events (Fig. 3.18).

Between precipitation events, volumetric soil moisture at the 50-mm depth was 0.01 to 0.04 m^3 m^{-3} higher than at the 25-mm depth across LSP zones, and at the 75-mm depth the soil moisture was similar to the 50-mm depth or 0.01 to 0.04 m^3 m^{-3} higher across LSP zones (Fig. 3.16, 3.17, and 3.18). The soil moisture content differences between the 25- and 75-mm depths were in the range of 0.02 to 0.06 m^3 m^{-3} across LSP zones. Over the volumetric soil moisture monitoring period, mean daily soil moisture content was consistently near 0.10 m^3 m^{-3} or above at the 25-mm depth regardless of LSP zones (Fig. 3.16), and soil moisture content was 0.02 to 0.05 m^3 m^{-3} higher at the 50- and 75-mm depths (Fig. 3.17 and 3.18). Over 20 precipitation events were recorded before PD1 and shortly after PD3, which were more than sufficient to recharge the topsoil with water for the planting operations in IL-12.

The gravimetric soil moisture contents for the four sampling events in the weeks before the PD1 in IL-12 are shown in Fig. 3.19. The soil moisture content in the wet LSP zones was 0.018 to 0.0264 kg kg^{-1} higher than in the dry LSP zones across depths and sampling events (Fig. 3.19). In both the 4 Apr. and 7 Apr. 2015 soil moisture sampling events in field IL-12, the gravimetric soil moisture content from the 0-25-mm depth to the 25-50-mm depth presented a mean increase of 0.049 in the dry LSP zones and of 0.053 kg kg^{-1} in the wet LSP zones (Fig. 3.19). The soil moisture increase was not as pronounced from the 25-50-mm depth to the 50-75-mm depth, with a mean increase of 0.023 kg kg^{-1} in the dry LSP zones and of 0.007 kg kg^{-1} in the wet LSP zones (Fig. 3.19). From 7 Apr. to 11 Apr. 2015 there were precipitation events totaling 51 mm, which increased gravimetric soil moisture at all depths and LSP zones. The gravimetric soil moisture from the 0-25-mm depth to the 25-50-mm depth increased 0.059 kg kg^{-1} in the dry LSP zones and 0.054 kg kg^{-1} in the wet LSP zones (Fig. 3.19). However, at the 11 Apr. 2015 sampling there were virtually no soil moisture differences between the 25-50- and the 50-75-mm depths regardless of LSP zones (Fig. 3.19). On average, the gravimetric soil moisture content in the wet LSP zones was 0.026 kg kg^{-1} higher than in the dry LSP zones for the 11 Apr. 2015 sampling event (Fig. 3.19). The last gravimetric soil moisture sampling was on 17 Apr. 2015, five days before the PD1 on IL-12. There were no precipitation events between 11 Apr. and 17 Apr. 2015, which resulted on an average gravimetric soil moisture decrease of 0.043 kg kg^{-1} across all depths, with the largest soil moisture decrease being measured at the 0-25-mm depth (0.058 kg kg^{-1}), as expected for being nearest to the soil surface (Fig. 3.19). Although gravimetric soil moisture content was not quantified after PD1 in IL-12, the measurements in IL-12 provided evidence that planting deeper than 50 mm was likely not beneficial to corn seeds due to excessive soil moisture content, particularly given the frequency of precipitation events before and after each planting operation in IL-12.

The monitoring of soil temperature using sensors started one day after PD1 (Fig. 3.20). Shortly after the planting operations for PD1, a cold weather front set in and mean daily air temperatures were below 10°C for about a week (Fig. 3.20). The soil environment provided a buffer against the cold air temperatures. However, the mean soil temperatures at depths of 25, 50, and 75 mm were approx. 10°C for several days after PD1 (Fig. 3.20), which is considered the minimum temperature to promote germination and emergence for corn seeds (Nafziger, 2009; Abendroth et al., 2011). For PD2 and PD3, mean soil temperatures were near 20°C and 18°C, respectively (Fig. 3.20). Over the soil temperature monitoring period, the mean daily soil temperatures at the 50-mm depth were 0.6 to 1.9°C cooler than at the 25-mm depth, while the mean daily soil temperatures at the 75-mm depth were 1.3 to 3°C cooler than at the 25-mm depth (Fig. 3.20). These soil temperature differences at depths of 25 to 75 mm depths are not likely to result in emergence differences when corn is planted late (i.e. May corn seeding in Illinois) and temperatures are higher. However, as corn producers aim to complete corn planting operations in mid- to late April, when temperatures are historically lower, it is possible that soil temperature differences within the range of potential seeding depths chosen by corn producers could have a considerable impact on corn emergence and plant establishment, particularly if corn seeds are planted deeper in the wet LSP zones. The soil temperatures at the 25-mm depth were both the lowest and highest (Fig. 3.20); this is expected as it has been shown that soil temperature fluctuations are wider closer to the soil surface (Campbell and Norman, 1998).

The cumulative percent emergence data for the PD1 in IL-12 in the dry and wet LSP zones are shown in Fig. 3.21. For the PD1 (Fig. 3.21), which is representative of early corn planting in Illinois (Nafziger, 2009), there was a significant seeding depth × LSP zones interaction ($p < 0.001$) for the cumulative emergence response (Table 3.4). Emergence was first observed 10 d after planting in the wet LSP zones, accumulating 70 GDD by then, and continued for 17 d after planting (Fig. 3.21). Across LSP zones, corn emergence reached 80% after accumulating 156 GDD. The wet LSP zones had earlier and higher emergence for all seeding depths than the dry LSP zones (Fig. 3.21). In particular, the seeds from the deep seeding depth struggled to emerge in a timely manner in the dry LSP zones (Fig. 3.21), likely due to lower soil temperatures, the additional elongation required for the corn seeds to emerge from a deeper seeding depth, and to soil crusting that developed after frequent precipitation events. Final percent emergence 17 d after planting showed that the shallow seeding depth had lower percent emergence (85%) and was significantly different from the percent emergence of the standard (95%) and deep (93%) seeding depths in the wet LSP zones (Fig. 3.21). Moreover, the final percent emergence of the deep seeding depth 17 d after planting was lower (89%) in the dry LSP zones and significantly different from the percent emergence of the shallow (93%) and standard (95%) seeding depths (Fig. 3.21). The earlier and faster emergence presented by the plants from the shallow seeding depth partially supports the hypothesis that shallow seeding in wet LSP zones results in faster emergence. However, it was not expected that the percent emergence for the shallow seeding depth would be lower than the percent emergence for the standard and deep seeding depths (Fig. 3.21). During the daily scouting events to measure corn emergence in IL-12, it was observed that seeds from the shallow seeding depth suffered from considerable seed predation; however, seed predation was not quantified in this study. Seed predation was not observed for the seeds from the standard and deep seeding depths. The slow emergence of the seeds from the deep seeding depth in the dry LSP zones suggests that seeding depth decisions should also take into account antecedent soil moisture and not only the predicted soil moisture gradient based on relative elevation. Although it was hypothesized that deep seeding in the dry LSP zones would result in faster emergence, the results from PD1 in IL-12 did not support the hypothesis (Fig. 3.21).

For a different perspective, the percent emergence day^{-1} is shown in Fig. 3.22. The seeds from the shallow seeding in the dry LSP zones had approx. 55% emergence 12 d after planting and a gradual decline on the percent emergence day^{-1} following 13 d after planting (Fig. 3.22). The seeds from the standard and deep seeding depths in the dry LSP zones had similar emergence day^{-1}, but highest emergence was observed 13 d after planting for the seeds from the standard seeding depth and 14 d after planting for the seeds from the deep seeding depth (Fig. 3.22). In the wet LSP zones, seeds from the shallow seeding depth had less than 10% emergence 10 d after planting but approx. 75% emergence 12 d after planting (Fig. 3.22). The seeds from the standard seeding depth had approx. 55% emergence 12 d after planting, with each consecutive day declining on the percent emergence day^{-1} (Fig. 3.22). The seeds from the deep seeding depth had approx. 10% emergence 12 d after planting but maximum emergence 13 d after planting at approx. 60% emergence (Fig. 3.22). It is likely that percent emergence for 12 and 17 d after planting was overestimated due to the lack of measurements on 11 and 16 d after planting (see Materials and Methods). However, the percent emergence day^{-1} provided insights about the type of emergence rates day^{-1} that can be expected at different depths and LSP zones during early planting in the U.S. Corn Belt.

For the cumulative emergence of the second planting date (Fig. 3.23), which was representative of late corn planting in Illinois (Nafziger, 2009), there was no seeding depth × LSP zones interaction (Table 3.4). Corn emergence was observed 7 d after planting in both dry and wet LSP zones after accumulating 124 GDD, and displaying about the same level of variability for each day and seeding depth treatment, as shown by standard error bars (Fig. 3.23). Over 80% emergence was reached 9 d after planting operations after accumulating 147 GDD. Corn emergence lasted for 10 d after planting (Fig. 3.23), after accumulating 170 GDD. There were no significant differences for the final percent emergence among the shallow, standard, and deep seeding depths in the wet LSP zones (Fig. 3.23). The final percent emergence for the shallow seeding depth (95%) was significantly different and lower compared to the standard seeding depth (97%) in the dry LSP zones (Fig. 3.23). Seed predation was observed in seeds from the shallow seeding depth; however, seed predation was not quantified. Precipitation was low before planting operations for PD2, with only a 5-mm precipitation event in the 7 d leading up to PD2 (Table 3.2). However, there were precipitation events after PD2 for five consecutive days totaling 56 mm, which were likely sufficient to recharge the soil profile with water at all seeding depths (Table 3.2). The corn emergence outcomes for PD2 showed that when temperatures are over 15°C and soil moisture conditions are adequate the seeding depth of corn had no considerable impact on emergence. The emergence outcomes in PD2 did not support the hypothesis that shallow seeding in wet LSP zones or deep seeding in dry LSP zones results in faster emergence compared to the standard seeding depth.

The percent emergence day^{-1} for the PD2 in IL-12 had similar outcomes for all seeding depths in the dry and wet LSP zones (Fig. 3.24). However, it is noteworthy to point that emergence day^{-1} was higher in the first day that seedlings were observed for the seeds from the shallow seeding depth, while the seeds from the standard and deep seeding depths showed twice and thrice as higher emergence day^{-1}, respectively, 9 d after planting compared to 7 d after planting (Fig. 3.24). The percent emergence 10 d after planting was <7% for all seeding depths and LSP zones combinations (Fig. 3.24). It is likely that corn emergence 9 d after planting was overestimated due to the lack of measurements 8 d after planting (see Materials and Methods). The percent emergence day^{-1} for the PD2 in IL-12 provided evidence that under adequate soil moisture and high temperatures corn emergence was not considerably affected by seeding depth or LSP zones.

For the cumulative emergence in the third planting date (PD3) in IL-12, corn emergence started in the dry LSP zones for all seeding depths 4 d after the planting operations after accumulating 77 GDD (Fig. 3.25). Corn emergence was then observed in the wet LSP zones 5 d following planting operations and after the accumulation of 102 GDD. Approximately 80% emergence in both dry and wet LSP zones was reached 6 d after planting, accumulating 123 GDD. Corn emergence was completed in both dry and wet LSP zones 7 d after planting after accumulating 149 GDD (Fig. 3.25). There was no significant seeding depth × LSP zones interaction for PD3 (Table 3.4). For both dry and wet LSP zones, the final percent emergence for the shallow seeding depth was significantly different and lower than the percent emergence of the standard and deep seeding depths, which were not significantly different from each other (Fig. 3.25). In the dry LSP zones, final percent emergence was 90% for the shallow seeding depth, while the standard and deep seeding depths had a final percent emergence of 98 and 95%, respectively (Fig. 3.25). In the wet LSP zones, final percent emergence was 85% for the shallow seeding depth, while the standard and deep seeding depths had a final percent emergence of 97 and 95%, respectively (Fig. 3.25). Seed predation on seeds from the shallow seeding depth was observed; however, seed predation was not quantified. The observation of corn emergence starting in the dry LSP zones first provided evidence that soil moisture was sufficient at all depths and LSP zones; it is likely the seeds in wet LSP zones took longer to accumulate the GDD requirement for germination and emergence as wet soils are able to dissipate heat faster (Campbell and Norman, 1998). Although corn in Illinois would not typically be planted as late as it was for PD3 (early June), it was interesting to observe that when temperatures were over 15°C and soil moisture was adequate the seeding depth of corn had no considerable impact on emergence. It was rather the LSP zones in which corn was planted that influenced the emergence times (Fig. 3.25). The corn emergence outcomes in PD3 did not support the hypothesis that shallow seeding in wet LSP zones or deep seeding in dry LSP zones results in faster emergence compared to the standard seeding depth.

The percent emergence day^{-1} for PD3 in IL-12 showed that over 80% emergence was reached in just two days (4 and 5 d after planting) in the dry LSP zones for all three seeding depths (Fig. 3.26). Emergence did not start in the wet LSP zones until 5 d after planting, and approx. 80% of seeds emerged 5 d after planting for the shallow and standard seeding depths, while percent emergence was approx. 60% for the deep seeding depth 5 d after planting (Fig. 3.26). The seeds from the deep seeding depth also had more emergence 6 d after planting compared to the seeds from the shallow and standard seeding depths (Fig. 3.26). The influence of the wet LSP zones in delaying corn emergence for 1 d compared to the dry LSP zones was evident for the PD3 in IL-12 (Fig. 3.26).

The probability values for the analysis of the plant counts, plant growth stage, plant height, stalk diameters, and GW plant^{-1} in each of the three planting dates in IL-12 are summarized in Table 3.8, while the mean values for each variable and planting date are listed in Table 3.9.

For the final plant count for PD3 in IL-12, there was a significant main effect of LSP zones ($p = 0.082$) (Table 3.8). The wet LSP zones had a mean plant count of 30.8 vs. 32 for the dry LSP zones (Table 3.9). There was no significant seeding depth × LSP zones interaction for the plant counts at any of the three planting dates (Table 3.8). Differences between the outcome of the analysis for the percent emergence and the plant counts were expected, as the cumulative percent emergence data were based on six times as many rows measured, while the plant counts data were based on a single row selected from the six rows measured for cumulative percent emergence. It is not surprising, however, that plant counts were lower in the wet LSP zones for PD3. Most of the wet LSP zones in IL-12 had standing water due to precipitation events that totaled 220 mm in the 20 d following the planting operations for PD3 (Table 3.2), and it may have resulted in poor plant survival due to deficient soil aeration, seed disease, and cooler conditions.

For the analysis of the plant growth stage, there were significant main effects of seeding depth ($p = 0.02$) and LSP zones ($p = 0.001$) for PD1, while the main effect of LSP zones was significant for PD3 ($p < 0.0001$) (Table 3.8). There were no significant seeding depth × LSP zones interactions for any of the planting dates for the plant growth stage response (Table 3.8). The significant main effect of seeding depth in PD1 showed that the plants from the shallow and standard seeding depths were slightly more advanced (approx. 0.4 growth stage higher) in terms of plant development compared to the plants from the deeper seeding depth (Table 3.9), which partially supports the hypothesis that plants from the shallow seeding depth are more developed earlier in the season compared to plants from deeper seeding depths. The significant main effect of LSP zones in PD1 showed that the plants growing in wet LSP zones were developing faster (approx. 0.4 growth stage higher) than the plants growing in dry LSP zones, which was likely due to more water availability in the wet LSP zones (Table 3.9). The result was the opposite for PD3 in which the plants growing in dry LSP zones were developing faster (approx. 2 growth stage higher) than the plants growing in wet LSP zones (Table 3.9). This delayed growth was likely due to excessive soil moisture in the wet LSP zones resulting in limited root aeration and cooler soil temperatures.

There were significant main effects of seeding depth ($p = 0.002$) and LSP zones ($p < 0.0001$) for PD1 for the analysis of plant height, which was a field measurement taken concurrently with the plant growth stage (Table 3.8). The mean plant height of the shallow, standard, and deep seeding depths were significantly different from each other, with the plants from the shallow seeding depth being the tallest (mean height of 86 cm) and plants from the deep seeding depth being the shortest (mean height of 75 cm) (Table 3.9). The plants growing in wet LSP zones were significantly taller (mean height of 89 cm) than the plants from the dry LSP zones (mean height of 73 cm) (Table 3.9). There were no significant differences in plant height for PD2. In PD3, there was a significant main effect of LSP zones ($p = 0.001$) (Table 3.8), with the plants growing in dry LSP zones being significantly taller than the plants from the wet zones (mean height of 131 and 92 cm, respectively) (Table 3.9). The results of the analysis of the plant height data were very similar to the results of the analysis of the plant growth stage data, suggesting that plant height alone, a much faster field measurement, could be taken as a measure of plant growth when there is no direct interest in the plant growth stages.

For the analysis of the stalk diameters, there was a significant main effect of LSP zones in PD2 ($p = 0.073$) and PD3 ($p = 0.0002$) (Table 3.8). In both of these planting dates, the plants growing in wet LSP zones exhibited a mean diameter significantly smaller than the plants growing in dry LSP zones; mean stalk diameters were 1.2 and 4.8 smaller for PD2 and PD3, respectively, in the wet LSP zones than in the dry LSP zones (Table 3.9). This provided more evidence that season-long soil moisture conditions for PD2 and PD3 were likely excessive in the wet LSP zones, which negatively affected plant growth and development.

For the mean GW plant^{-1}, there was a significant main effect of LSP zones for all three planting dates ($p = 0.012$ for PD1, p = 0.022 for PD2, and p = 0.04 for PD3) (Table 3.8). The mean GW plant^{-1} in the dry LSP zones compared to the wet LSP zones was 23, 39, and 17 g plant^{-1} higher for PD1, PD2, and PD3, respectively (Table 3.9). The GW plant^{-1} data provided no support to the hypothesis that shallow seeding in wet LSP zones and deep seeding in dry LSP zones increases GW plant^{-1} compared to the GW plant^{-1} of the standard seeding depth. The lack of a significant seeding depth × LSP zones interaction provided evidence that the application of a shallow, standard, and deep seeding depth as a precision agriculture tool to find an optimal seeding depth of corn in all field areas was not successful in field IL-12 in the 2015 growing season. It is likely that the GW response may have been different had drier soil moisture conditions prevailed after planting operations in IL-12. The results from IL-12 provided evidence that given adequate soil moisture conditions and temperatures, the seeding depth of corn had no noticeable influence on GW. In addition, it was evident that deep seeding in predicted dry LSP areas had no quantifiable benefit when soil moisture conditions were adequate. In fact, the seeds from the deep seeding depth in PD1 had emergence delays compared to the emergence of the shallow and standard seeding depths in the dry LSP zones (Fig. 3.21).

The shape of the GW plant^{-1} distribution in IL-12 for the PD1 was similar for the shallow, standard, and deep seeding depths in both dry and wet LSP zones, with well-defined peaks and negative skewness (Fig. 3.27). However, it is noteworthy to point that in the dry LSP zones the GW plant^{-1} of the plants from the deep seeding depth presented a lower CV compared to the standard seeding depth (27 vs. 30) and higher kurtosis (Fig. 3.27, Table 3.7). This partially supports the hypothesis that deep seeding in the dry LSP zones results in less GW plant^{-1} variability compared to the standard seeding depth; however, the mean GW plant^{-1} was smaller compared to the standard seeding depth (Table 3.7). The incidence of low-yielding plants in the dry LSP zones was low (3-5%) and similar for the shallow, standard, and deep seeding depths (Fig. 3.27). In the wet LSP zones, the GW plant^{-1} for the plants from the shallow seeding depth presented the lowest CV (30) compared to the CV of the standard (38) and deep (33) seeding depths (Table 3.7). This supports the hypothesis that shallow seeding in the wet LSP zones results in less GW plant^{-1} variability compared to the standard seeding depth. The GW plant^{-1} distribution for the shallow seeding depth in the wet LSP zones also presented the highest kurtosis (Table 3.7). The incidence of low-yielding plants in the wet LSP zones was highest for the standard seeding depth (9%) compared to the shallow and deep (5% each) seeding depths. In addition, the mean GW plant^{-1} was highest for the shallow seeding depth compared to the standard seeding depth in the wet LSP zones; however, the means were not significantly different by seeding depth (Table 3.8).

For the PD2 in IL-12, differences in the GW plant^{-1} distribution were more evident by LSP zones rather than by seeding depth (Fig. 3.28); however, some observations by seeding depth treatment are still noteworthy. In the dry LSP zones, the mean GW plant^{-1} was highest for the deep seeding depth (163 g plant^{-1}), followed by the GW plant^{-1} for the shallow and standard seeding depth (161 and 154 g plant^{-1}, respectively) (Table 3.7). The CV was lowest for the plants from the shallow seeding depth (23), compared to the CV of the standard (33) and deep (26) seeding depths (Table 3.7), which does not support the hypothesis that deep seeding in the dry LSP zones results in reduced GW plant^{-1} variability. The plants from the standard seeding depth in the dry LSP zones presented the highest incidence of low-yielding plants (5%) (Fig. 3.28). In the wet LSP zones, the GW plant^{-1} was highest for the shallow seeding depth at 125 g plant^{-1} (Table 3.7), which partially supports the hypothesis that shallow seeding in the wet LSP zones results in higher yield; however, there were no significant differences by seeding depth treatment (Table 3.8). The CVs for the GW plant^{-1} in the wet LSP zones were 21 to 38 units higher than the CVs in the dry LSP zones across all seeding depth treatments (Table 3.7). In particular, the CV for the GW plant^{-1} for the deep seeding depth was the highest at 64 units (Table 3.7). Moreover, the incidence of low-yielding plants was also high for the deep seeing depth at 35%, compared to 16 and 11% incidence of low-yielding plants for the shallow and standard seeding depth, respectively (Fig. 3.28). This partially supports the hypothesis that deep seeding in wet LSP zones results in decreased yield and higher GW plant^{-1} variability. The GW plant^{-1} distribution showed negative kurtosis for all seeding depths (Table 3.7). It is likely that soil moisture was excessive in the wet LSP zones for the PD2 in IL-12, thus negatively affecting corn growth, development, and GW.

For the PD3 in IL-12, the mean GW plant^{-1} was similar for the shallow, standard, and deep seeding depths in the dry LSP zones (Fig. 3.29). The CVs for the GW plant^{-1} in the dry LSP zones ranged from 25 to 30, with the CV for the standard seeding depth being the lowest (Table 3.7). The plants from the standard seeding depth also presented the lowest incidence of low-yielding plants (1%), while the incidence of low-yielding plants was of 4 and 5% for the plants from the shallow and deep seeding depths in the dry LSP zones, respectively (Fig. 3.29). The distribution of GW plant^{-1} was negatively skewed and showed positive kurtosis for all seeding depth treatments in the dry LSP zones (Table 3.7). The GW plant^{-1} in the wet LSP zones showed CVs 12 to 15 units higher than in the dry LSP zones (Table 3.7), and incidence of low-yielding plants was the highest for the shallow seeding depth at 10% (Fig. 3.29). The mean GW plant^{-1} of the plants from the shallow seeding depth in the wet LSP zones was the lowest of the three seeding depths and also presented the highest CV (Table 3.7), which does not support the hypothesis that shallow seeding in wet LSP zones results in higher yield and reduced GW plant^{-1} variability.

CONCLUSION

The volumetric and gravimetric soil moisture data collected during the 2015 field season provided evidence that soil moisture contents in dry and wet LSP zones within a range of potential seeding depths (25-75 mm) were not uniform (Fig. 3.6-3.9 and 3.16-3.19); for field IL-11, the gravimetric soil moisture contents of the wet LSP zones were almost twice as high as in the dry LSP zones within the same field (Fig. 3.9). For field IL-12, the gravimetric soil moisture content differences between the dry and wet LSP zones were not as large (Fig. 3.19), but the differences would have been larger had drier soil moisture conditions prevailed in the 2015 growing season. The soil moisture data provided evidence that a single seeding depth for a given field can result in corn seeds being placed in soils that are either drier or wetter than optimal; however, the extent of the influence of the soil moisture variability on corn seeds within a field is likely dependent on the antecedent soil moisture conditions at the time of planting and in the following days or weeks after planting. In essence, if soil moisture and temperature conditions are adequate then corn seeds are able to germinate and emerge from the soil successfully (Helms et al., 1997). Given adequate soil moisture conditions, temperatures play a much bigger role in corn germination and emergence (Alessi and Power, 1971).

The analysis of corn emergence, plant growth and development, and GW plant^{-1} data for the three seeding depths (shallow, standard, and deep) provided interesting insights. Seeds placed at shallow depths did emerge earlier and had more advanced growth stages and increased plant heights earlier in the growing season compared to seeds placed deeper into the soil. In addition, shallow seeding in wet LSP zones in IL-11 resulted in seeds showing a more consistent emergence rate with less variability compared to the standard and deep seeding depths. However, these encouraging results from the emergence patterns, plant growth and development in both fields did not translate into significant differences for the mean GW, which had no significant seeding depth × LSP zones interaction in neither field. Rather, the LSP zones in which the plants emerged and developed along with the environmental conditions had a greater influence on GW than the seeding depths. The fact that the fields tested did not show a significant seeding depth × LSP zones interaction for the GW response provided evidence that when soil moisture is sufficient a field may be better managed with a field-average seeding depth instead of a variable seeding depth.

The delineation of the dry and wet LSP zones was effective in capturing the inherent variability observed in the two fields used in this study. The use of these LSP zones based on relative elevation may be useful to describe the growing environment of sampled plants in both on-farm and small-scale experiments. It is also suggested that the application of LSP zones could be used with relative ease as a spatial covariate whenever field conditions exhibit soil moisture gradients that may affect crop responses.

Moist but cool environmental conditions at the time of planting in IL-11 and for the first planting date in IL-12 (PD1) delayed corn emergence for 10 d or more at both fields. Low temperature stress may have affected corn seeds and the GW response may have been obscured by a stressful germination and emergence period. The two remainder planting dates in IL-12 (PD2 and PD3) were conducted in moist and warm conditions, and there were no reasons to expect reduced emergence and yield due to seeding depths alone.

Planting equipment in the near future may include real-time sensors of soil moisture and temperature along with seeding depth actuators (Adamchuk 2004; Mastorakos et al., 2014; René-Laforest, 2015). These improvements may enable farmers to adjust seeding depth on-the-go as desired or using a closed-loop system approach where seeding depth is adjusted according to soil moisture and temperature measured in real-time during the planting operations. If corn producers were able to adjust seeding depth on-the-go then corn seeds could potentially be planted in better environments in field parts with suboptimal soil moisture content.

Agronomists usually dispense the general advice to plant into moisture when soil temperatures are high enough to promote germination and emergence (Hoeft et al., 2000; Espinoza and Ross, 2004; Nafziger, 2009). However, current technology does not allow for the within-field, real-time data collection of soil moisture and temperature via the planter. It is expected that having real-time soil moisture and temperature data will translate to corn producers being able to take better and more informed decisions in regards to the seeding depth of corn.

It is not known how corn seeds would have responded to variable seeding depth under drier soil conditions, which were not encountered during the 2015 growing season in the two fields tested. Corn producers may benefit from research exploring the application of real-time soil moisture sensors attached to the planter to place corn seeds in optimal soil moisture conditions in all field areas.

Future research should also quantify how severe seed predation of shallow-planted seeds is and the depth at which seed predation is no longer a concern. A limitation of this study was the lack of soil temperature measurements in both dry and wet LSP zones, as soil temperature data were collected at a single location within field IL-12. It was evident from the emergence data for PD3 in IL-12 that the seeds placed in the dry and wet LSP zones accumulated GDD differently, resulting in a 1-d delay in emergence in the wet LSP zones. These delays could be much longer when corn is planted as early as mid-April in the U.S. Corn Belt.

TABLES

Table 3.1. Planting and hand harvest dates, seeding rates, seeding depths for the shallow, standard, and deep treatments, and no. of rows for the treatment strips in the fields IL-11 and IL-12 tested for the emergence, plant growth and development, and grain weight response to shallow, standard, and deep seeding depths during the 2015 growing season. In field IL-12, three planting dates (PD1, PD2, and PD3) were applied.

Field	Planting date	Hand harvest date	Seeding rate	Seeding depths			Width of treatments
			seeds ha^{-1}	Shallow	Standard	Deep	no. rows
				mm			
IL-11	14 Apr.	9 Sept.	83,000	25	46	61	8,16
IL-12 (PD1)	23 Apr.	14 Sept.	84,000	28	44	61	6
IL-12 (PD2)	8 May	30 Sept.	84,000	28	44	61	6
IL-12 (PD3)	4 June	15 Oct.	84,000	28	44	61	6

Table 3.2. Precipitation, dry days, mean air temperature 7 days before planting (DBP) and 7 days after planting (DAP), growing degree days (GDD) 7 DAP, 14 DAP, and for the entire season, and dominant soil textures for the two fields (IL-11 and IL-12) tested for the emergence, plant growth and development, and grain weight response to shallow, standard, and deep seeding depths. In field IL-12, three planting dates were applied (PD1, PD2, and PD3). The first planting date (PD1) was on 23 Apr. 2015, PD2 was on 8 May 2015, and PD3 was on 4 June 2015.

Year	Field	Precip.		Dry days		Mean temp.		GDD			Dominant soil textures
		7 DBP	7 DAP	DBP	DAP	7 DBP	7 DAP	7 DAP	14 DAP	Season	
		—— mm ——				—— °C ——					
2015	IL-11	13	21	0	4	11.3	13.9	81	107	2,739	Silt Loam, Fine Sand
2015	IL-12 (PD1)	18	19	0	1	13.6	9.2	40	156	2,874	Silty Clay Loam, Silt Loam
2015	IL-12 (PD2)	5	56	2	0	18.4	18.2	124	224	3,003	Silty Clay Loam, Silt Loam
2015	IL-12 (PD3)	71	59	2	4	18.3	22.4	176	356	2,722	Silty Clay Loam, Silt Loam

Table 3.3. Total monthly precipitation (precip.) and mean monthly temperatures (temp.) during the 2015 growing season in IL-11 and IL-12 along with the 30-yr normal† (1981-2010). Data provided by PRISM Climate Group, Oregon State University, URL http://prism.oregonstate.edu, created 8 Aug. 2016.

	IL-11				IL-12			
	Total precip.	30-yr normal	Mean temp.	30-yr normal	Total precip.	30-yr normal	Mean temp.	30-yr normal
	mm		°C		mm		°C	
Jan.	33	36	-5.8	-5.3	36	52	-4.5	-3.7
Feb.	45	40	-9.8	-3.0	29	54	-7.5	-1.5
Mar.	21	62	2.0	3.5	47	69	2.0	4.4
Apr.	59	88	11.5	10.4	79	91	12.0	10.9
May	119	105	17.2	16.5	152	119	19.1	16.8
June	215	104	21.5	21.8	209	103	21.8	22.0
July	130	99	22.9	23.8	86	114	22.7	23.5
Aug.	89	110	22.0	22.8	75	93	21.7	22.5
Sept.	138	79	21.7	18.4	173	73	21.2	18.9
Oct.	57	75	12.9	11.7	30	82	13.4	12.3
Nov.	139	71	6.8	4.5	108	91	7.6	5.7
Dec.	130	52	3.4	-3.1	190	70	4.8	-1.4

Table 3.4. Probability values associated with the mixed model analysis of variance for the effect of seeding depth treatments (Depth) and landscape zones (LSP) on cumulative corn emergence in field IL-11 and for each of the three planting dates (PD1, PD2, and PD3) in field IL-12.

Effect	IL-11	IL-12		
		PD1	PD2	PD3
Depth	0.187	<.001	<.001	0.011
LSP	0.086	<.001	0.537	<.001
Depth × LSP	0.553	<.001	0.913	0.723
DAP†	<.001	<.001	<.001	<.001
Depth × DAP	0.026	<.001	0.102	0.163
LSP × DAP	0.637	<.001	0.869	<.001
Depth × LSP × DAP	0.985	<.001	0.999	0.206

† DAP, days after planting (repeated measures).

Table 3.5. Probability values associated with the mixed model analysis of variance for the effect of seeding depth treatments (Depth) and landscape zones (LSP) on days to emergence (DTE), plant counts, plant growth stage, stalk diameter, and grain weight plant^{-1} for field IL-11 during the 2015 growing season.

Variable	Depth	LSP	Depth × LSP
DTE	0.10	0.140	0.457
Plant counts	0.304	0.911	0.304
Plant growth stage	0.010	0.139	0.242
Stalk diameter	0.019	<.0001	0.008
Grain weight	0.803	0.031	0.402

Table 3.6. Mean values for the effect of seeding depth treatments and landscape (LSP) zones on days to emergence (DTE), plant counts, plant growth stage, stalk diameter, and grain weight plant^{-1} for field IL-11.

Variable	Seeding depth			LSP zones	
	Shallow	Standard	Deep	Dry	Wet
	days				
DTE	17.7a	19.4b	19.1b	18.3	19.3
	plants row^{-1}				
Plant counts	35.5	37.0	37.3	36.7	36.6
	growth stage				
Plant growth stage	5.9a	5.3b	5.3b	5.6	5.4
	mm				
Stalk diameter	25.4	25.0	23.6	23.2	26.1
	g ear^{-1}				
Grain weight	158.8	166.3	153.8	140.4a	178.8b

Means with different letters within a row are significantly different ($p < 0.10$).

Table 3.7. Descriptive statistics of the influence of shallow, standard, and deep seeding depths and dry and wet landscape (LSP) zones on the grain weight plant^{-1} distribution in fields IL-11 and IL-12 tested during the 2015 growing season. Three planting dates (PD1, PD2, and PD3) were applied in field IL-12. The statistics presented include number of plants (*n*), mean, median, interquartile range (IR), coefficient of variation (CV), skewness, and kurtosis.

Planting date	LSP zones	Seeding depth	*n*	Mean	Median	IR	CV	Skewness	Kurtosis
				——— g plant^{-1} ———			%		
				Field IL-11					
-	Dry	Shallow	110	127	128	130	55	-0.14	-1.12
		Standard	110	158	157	49	25	-0.21	0.98
		Deep	110	141	161	141	56	-0.29	-1.27
	Wet	Shallow	103	192	216	59	38	-1.65	1.94
		Standard	112	174	204	69	41	-1.36	0.84
		Deep	114	170	189	74	39	-1.3	1.09
				Field IL-12					
PD1	Dry	Shallow	130	178	187	56	29	-1.49	2.94
		Standard	126	189	200	54	30	-1.69	3.33
		Deep	124	180	188	51	27	-1.58	4.43
	Wet	Shallow	122	171	181	57	30	-1.2	2.08
		Standard	127	156	169	55	38	-1.15	1.19
		Deep	121	152	162	60	33	-0.85	1.3
PD2	Dry	Shallow	127	161	164	47	23	-0.61	1.29
		Standard	132	154	155	69	33	-0.86	1.08
		Deep	127	163	168	55	26	-0.39	0.29
	Wet	Shallow	117	125	128	89	49	-0.12	-0.62
		Standard	130	115	116	68	44	-0.12	-0.1
		Deep	126	119	138	152	64	-0.33	-1.24
PD3	Dry	Shallow	123	145	148	48	29	-1	1.65
		Standard	130	142	141	40	25	-0.2	0.06
		Deep	131	140	151	50	30	-1.31	2.4
	Wet	Shallow	124	119	114	69	45	0.06	-0.3
		Standard	121	134	123	73	38	0.29	-0.35
		Deep	124	120	125	54	37	-0.27	0.24

Table 3.8. Probability values associated with the mixed model analysis of variance for the effect of seeding depth treatments (Depth) and landscape zones (LSP) on plant counts, plant growth stage, plant height, stalk diameter, and grain weight plant^{-1} for the three planting dates (PD1, PD2, and PD3) of field IL-12 during the 2015 growing season.

Variable	Planting date	Depth	LSP	Depth × LSP
Plant counts	PD1	0.541	0.306	0.519
	PD2	0.212	0.291	0.606
	PD3	0.493	0.082	0.302
Plant growth stage	PD1	0.020	0.001	0.323
	PD2	0.560	0.234	0.953
	PD3	0.619	<.0001	0.736
Plant height	PD1	0.002	<.0001	0.542
	PD2	0.426	0.115	0.880
	PD3	0.698	0.001	0.950
Stalk diameter	PD1	0.137	0.221	0.431
	PD2	0.688	0.073	0.896
	PD3	0.976	0.0002	0.869
Grain weight	PD1	0.618	0.012	0.318
	PD2	0.881	0.022	0.982
	PD3	0.595	0.040	0.594

Table 3.9. Mean values for the effect of seeding depth treatments and landscape (LSP) zones on plant counts, plant growth stage, plant height, stalk diameter, and grain weight plant^{-1} for the three planting dates (PD1, PD2, and PD3) on field IL-12.

Variable	Planting date	Seeding depth			LSP zones	
		Shallow	Standard	Deep	Dry	Wet
		plants row^{-1}				
Plant counts	PD1	31.5	31.6	30.6	31.7	30.8
	PD2	30.5	32.8	31.6	32.2	31.1
	PD3	30.9	31.4	31.9	32a	30.8b
		growth stage				
Plant growth stage	PD1	8a	7.9a	7.6b	7.6a	8b
	PD2	9.2	9.7	9.6	9.7	9.3
	PD3	9.5	9.8	9.4	10.6a	8.5b
		cm				
Plant height	PD1	86.2a	81.2b	75.1c	72.7a	89b
	PD2	140.4	153.8	152.1	156.2	141.3
	PD3	108.6	117.0	108.5	131a	92b
		mm				
Stalk diameter	PD1	25.6	24.6	25.4	25.4	24.9
	PD2	24.2	23.7	24.3	24.7a	23.5b
	PD3	21.9	22.1	21.9	24.4a	19.6b
		g plant^{-1}				
Grain weight	PD1	176	173	166	183a	160b
	PD2	144	135	143	160a	121b
	PD3	133	139	130	142a	125b

Means with different letters within a row are significantly different ($p < 0.10$).

FIGURES

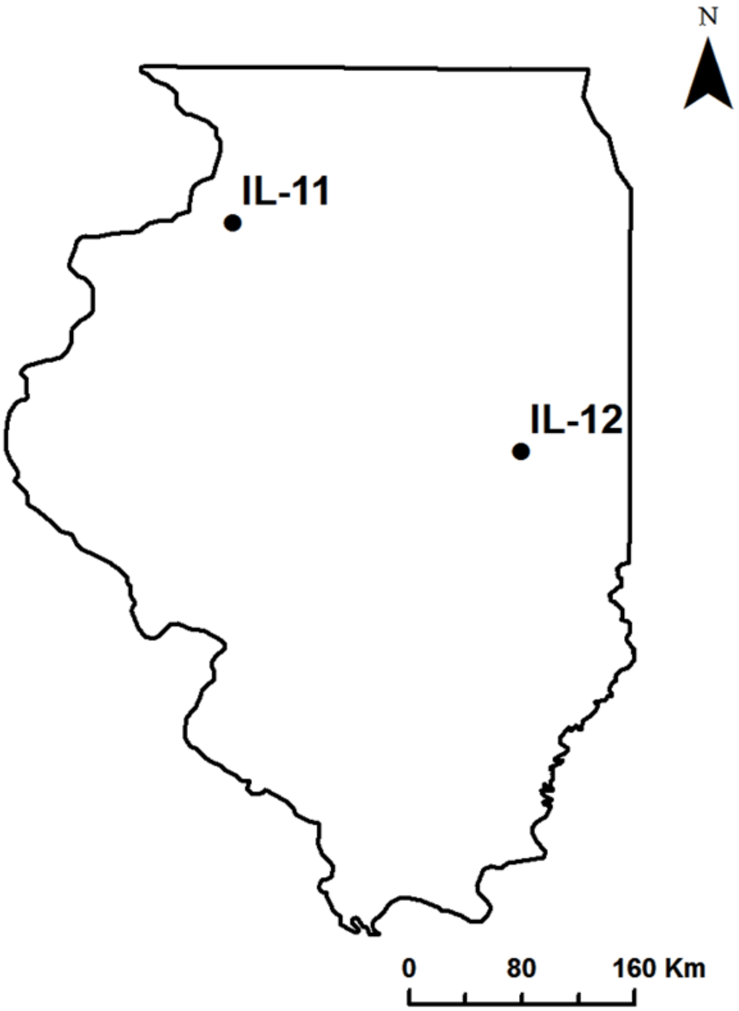


Fig. 3.1. Location of the two fields in the state of Illinois, U.S., tested for the response of corn emergence, plant growth and development, and grain weight to shallow, standard, and deep seeding depths in wet and dry landscape zones in the 2015 growing season.

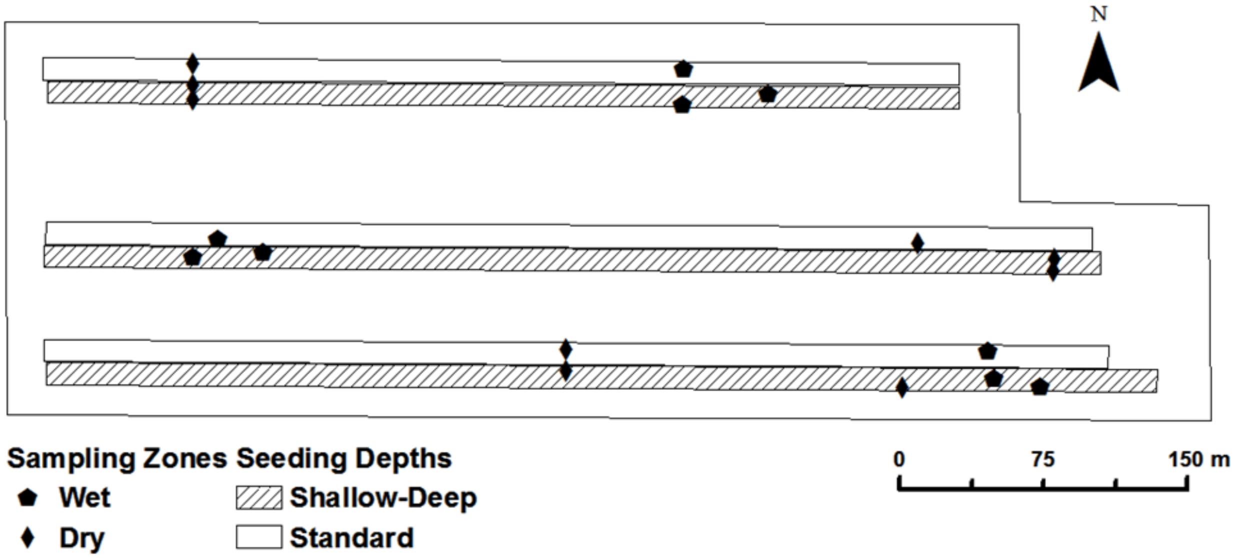


Fig. 3.2. Distribution of the replications and sampling zones in IL-11. Three replications of shallow, standard, and deep seeding depths were planted across the entire field length on 14 Apr. 2015. Each replication had the three seeding depths (shallow, standard, and deep) represented. Each replication had two sampling zones per treatment representative of relatively dry and wet areas where data were taken from emergence to physiological maturity.

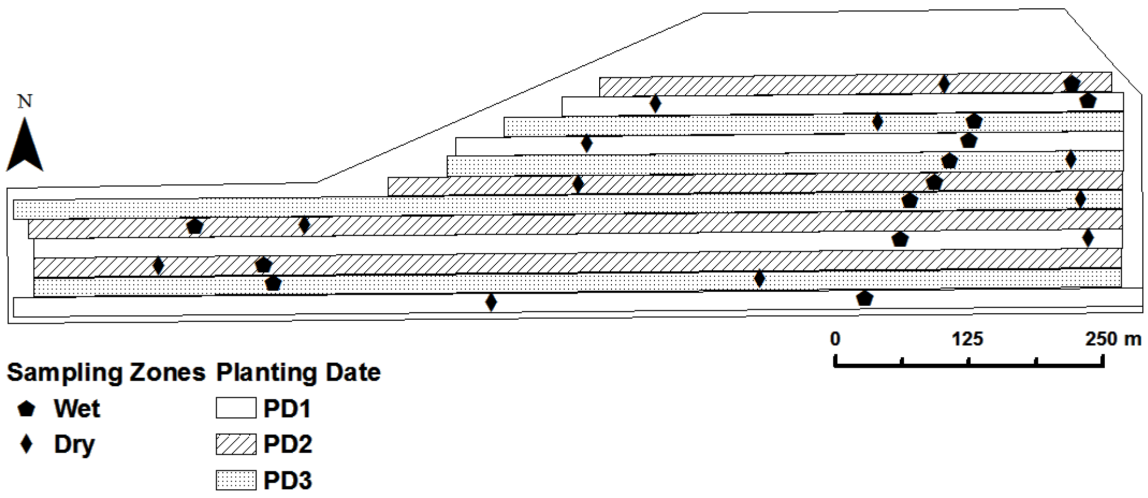


Fig. 3.3. Distribution of the planting dates, replications, and sampling zones in IL-12. Four replications of shallow, standard, and deep seeding depths were planted across the entire field length in three planting dates (PD1, PD2, and PD3). The planting dates were 23 Apr. 2015 for PD1, 8 May 2015 for PD2, and 4 June 2015 for PD3. Each replication had the three seeding depths (shallow, standard, and deep) represented. Each replication had two sampling zones representative of relatively dry and wet areas where data were taken from emergence to physiological maturity.

Fig. 3.4. Volumetric soil moisture contents at depths of 25, 50, and 75 mm were monitored in fields IL-11 and IL-12, while soil temperatures at depths of 25, 50, and 75 mm were monitored only in IL-12. Moisture (a) and temperature (b) sensors were inserted horizontally at each depth. Sensors were attached to data loggers and set to record every 15 minutes.

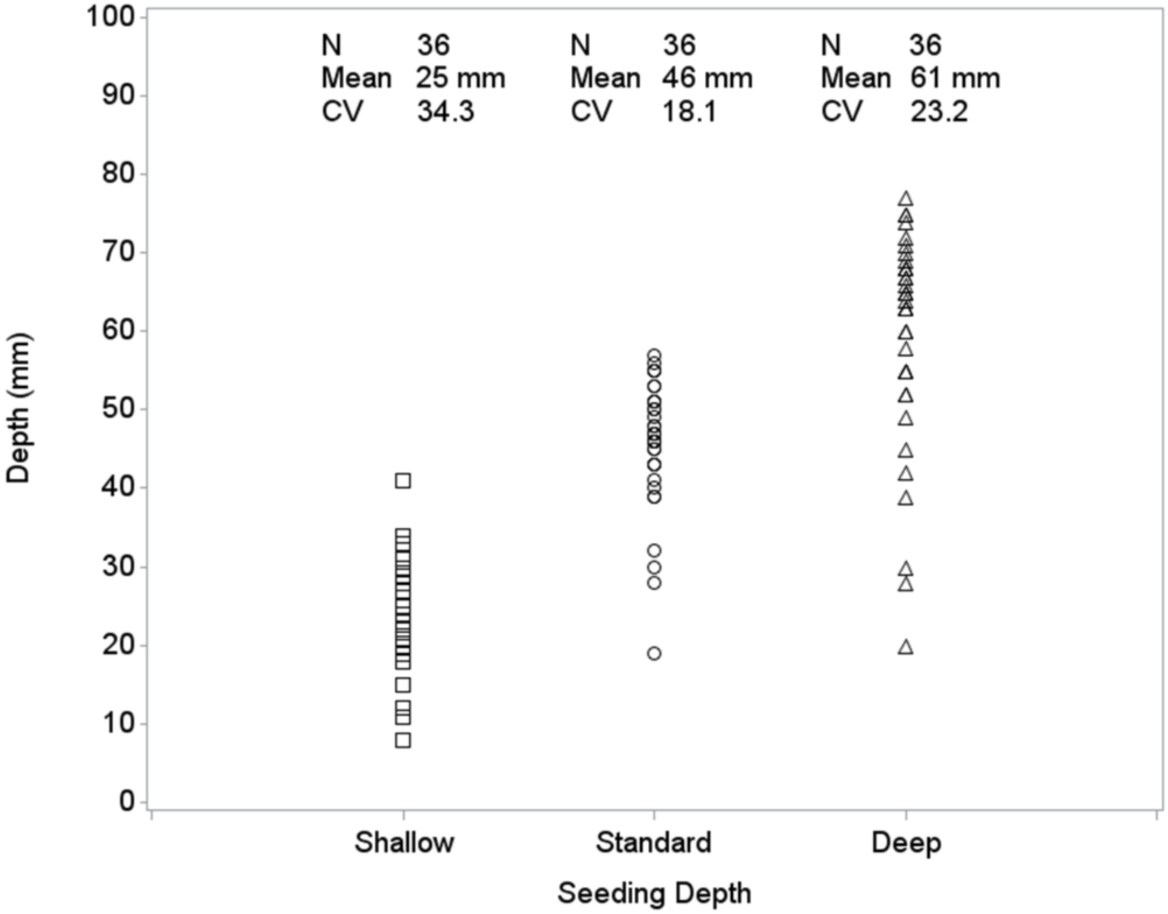


Fig. 3.5. Thirty-six plants at growth stages V1 to V2 from field IL-11 were sampled to verify the seeding depth placement for the shallow, standard, and deep seeding depth treatments. Depth was measured from the bottom of the seed to the soil surface.

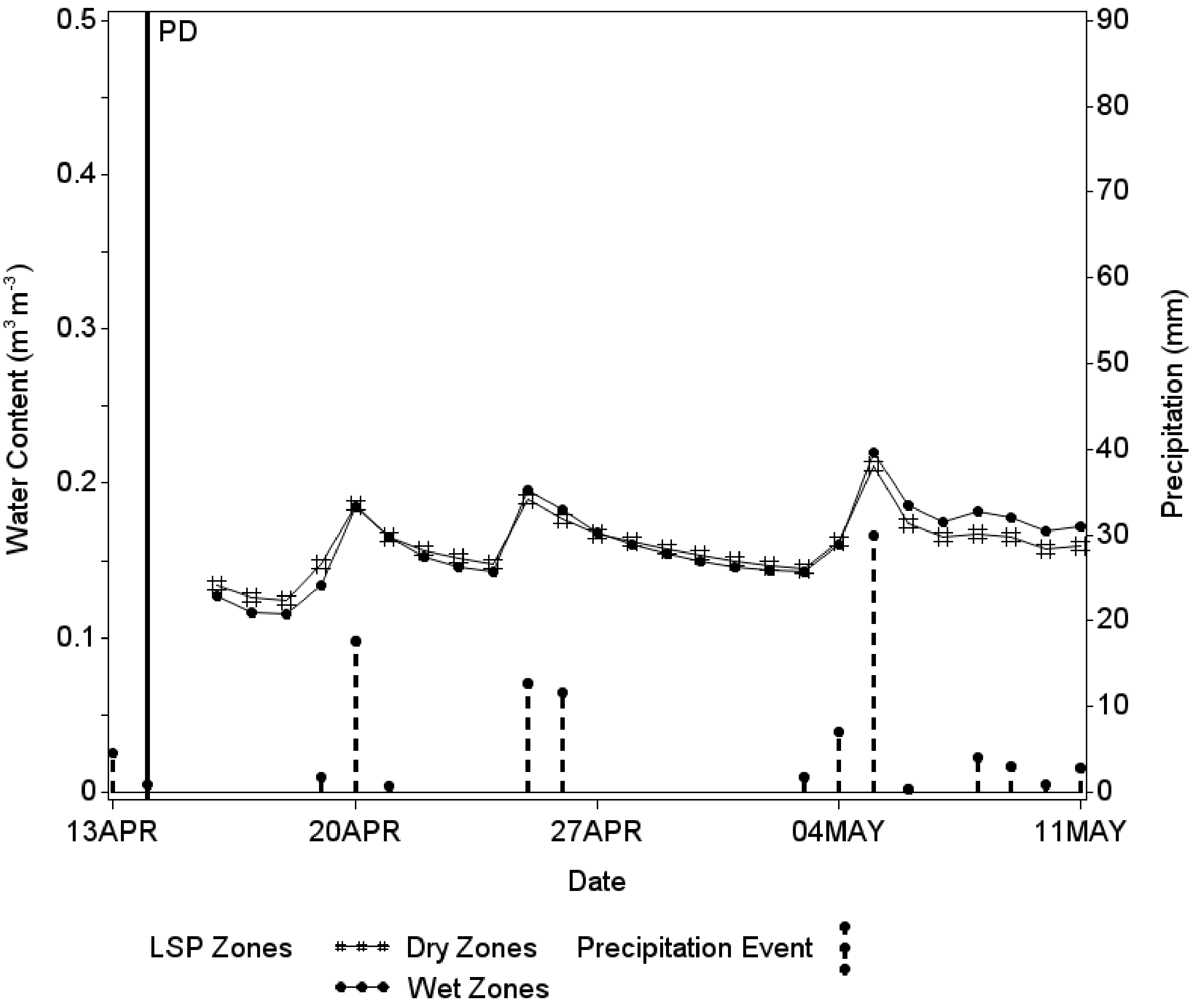


Fig. 3.6. Mean daily volumetric soil moisture content for the four weeks following the planting operation in IL-11 for the dry and wet landscape (LSP) zones at a depth of 25 mm, as measured by soil moisture sensors attached to data loggers, along with precipitation events. The planting date (PD) was on 14 Apr. 2015.

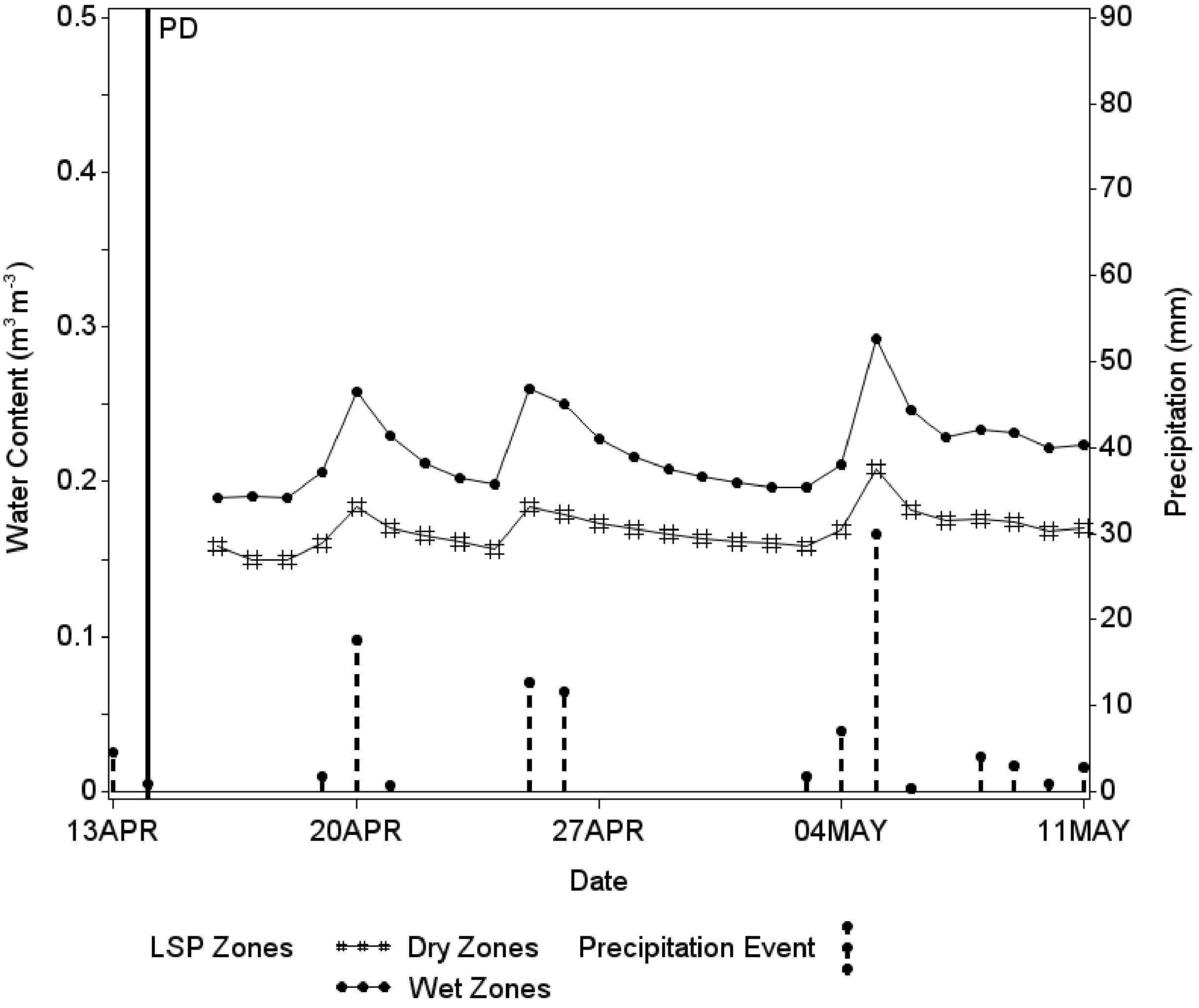


Fig. 3.7. Mean daily volumetric soil moisture content for the four weeks following the planting operation in IL-11 for the dry and wet landscape (LSP) zones at a depth of 50 mm, as measured by soil moisture sensors attached to data loggers, along with precipitation events. The planting date (PD) was on 14 Apr. 2015.

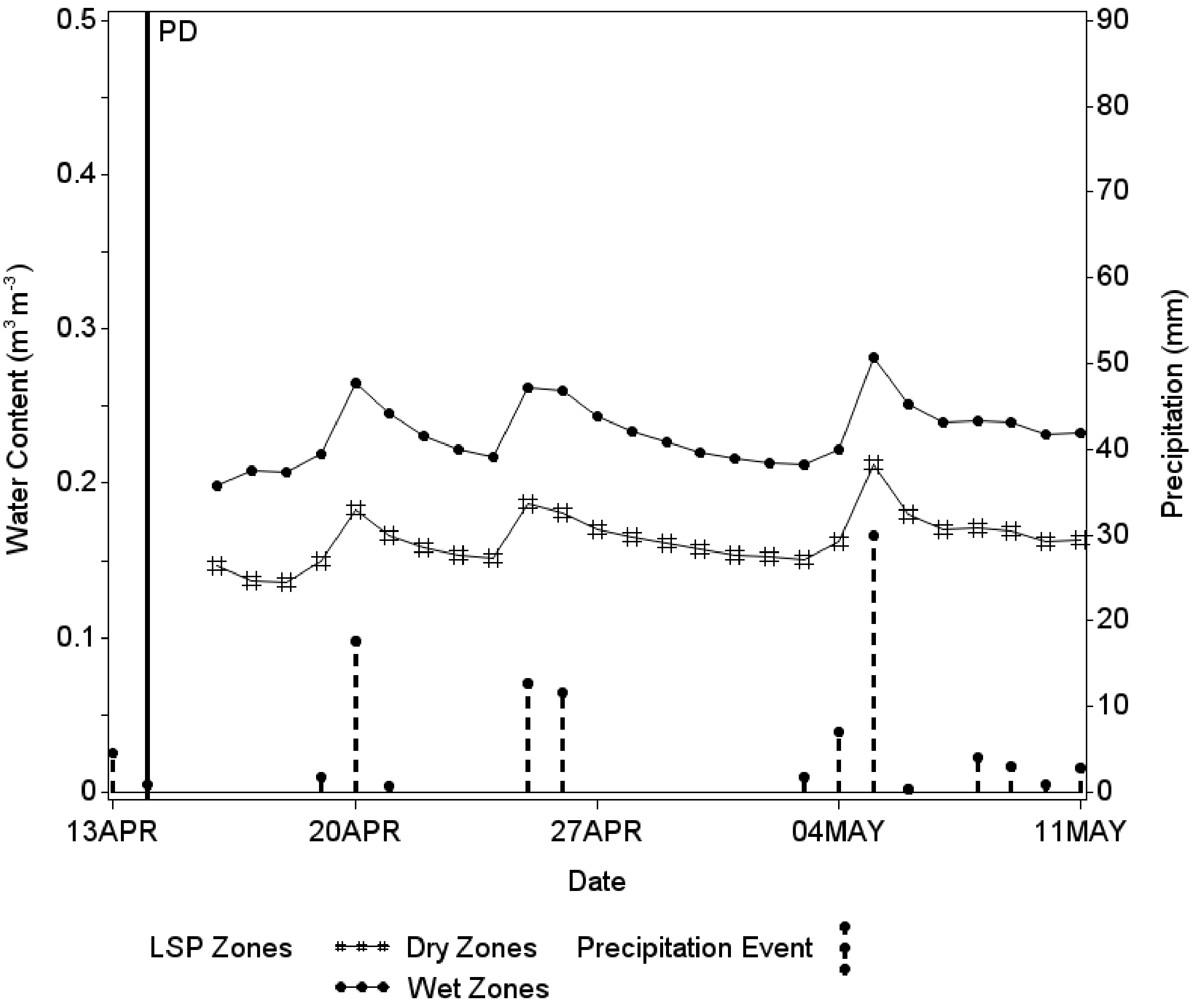


Fig. 3.8. Mean daily volumetric soil moisture content for the four weeks following the planting operation in IL-11 for the dry and wet landscape (LSP) zones at a depth of 75 mm, as measured by soil moisture sensors attached to data loggers, along with precipitation events. The planting date (PD) was on 14 Apr. 2015.

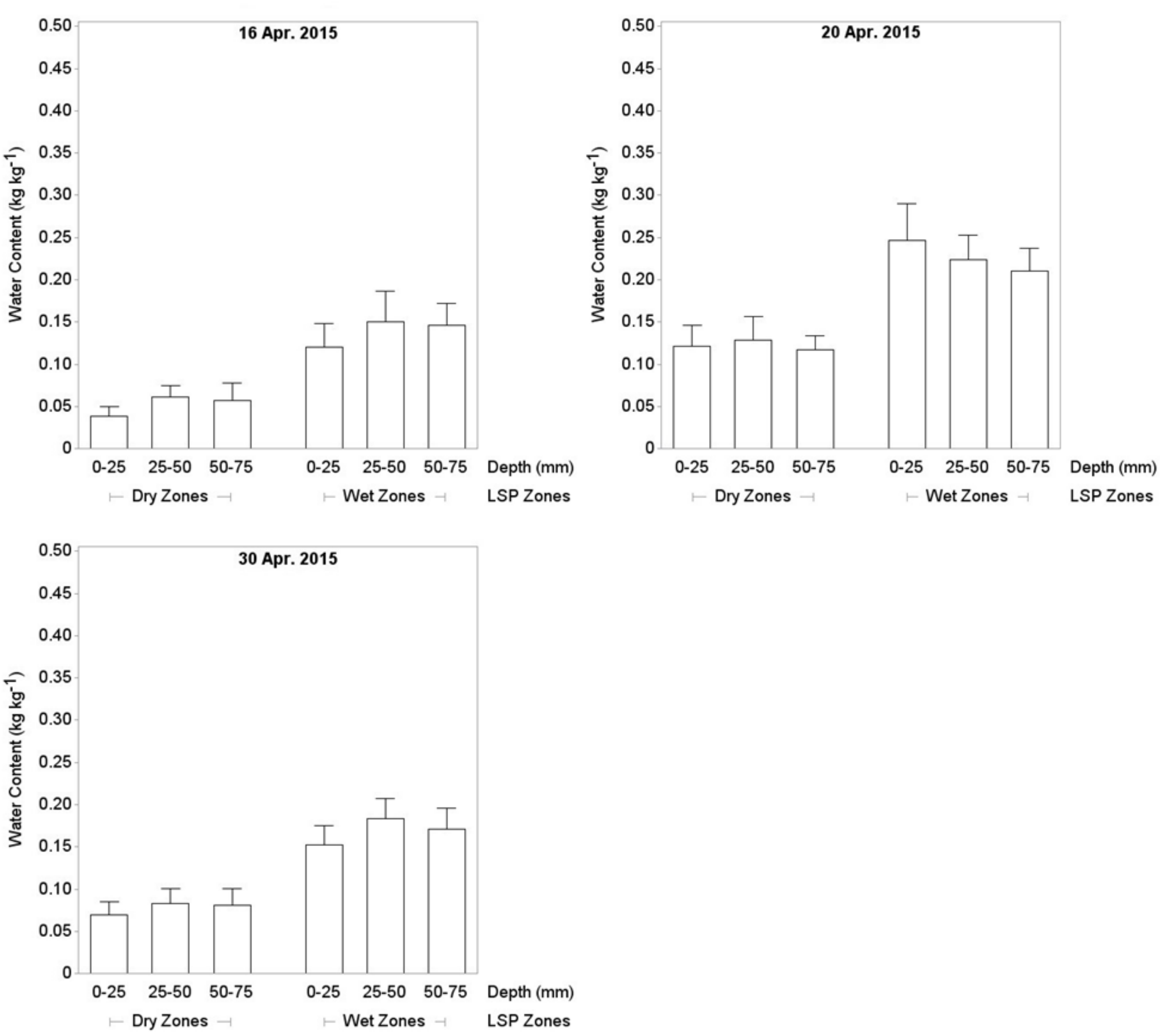


Fig. 3.9. Gravimetric soil moisture content for depths from 0 to 25, 25 to 50, and 50 to 75 mm in dry and wet landscape (LSP) zones in field IL-11 for three sampling events (16 Apr., 20 Apr., and 30 Apr. 2015). Five soil cores (40-mm wide and 100-mm long) near the volumetric soil moisture sensors were extracted within a 1-m^2 area and composited by depth. The soil cores were cut on site to the specified depths and the composited soil samples for each depth were kept in airtight aluminum cans. The soil cores were taken immediately to a shop to be weighed, dried for 48 h at 60°C, and weighed again after drying. Data shown are the means of three replicates and the vertical bars represent the standard error.

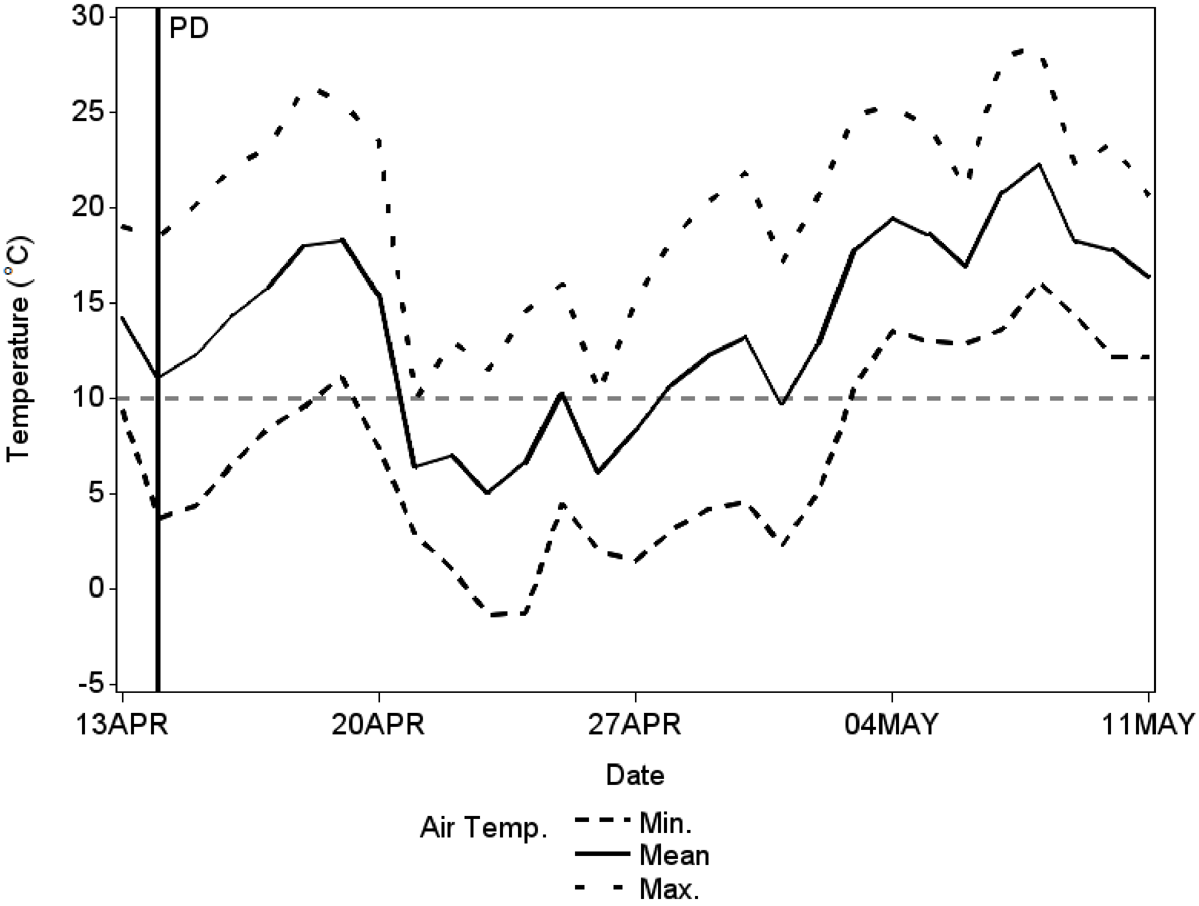


Fig. 3.10. Daily minimum (min.), mean, and maximum (max.) air temperatures (temp.) for the four weeks following the planting operation in IL-11. The planting date (PD) was on 14 Apr. 2015.

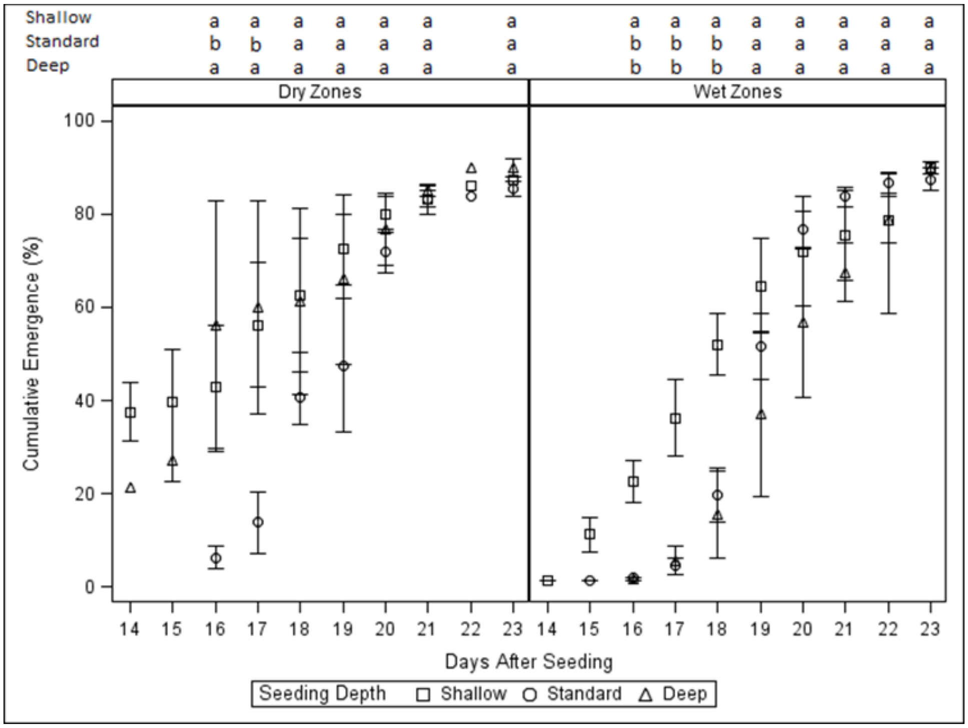


Fig. 3.11. Mean cumulative emergence day^{-1} in IL-11 for the three seeding depths (shallow, standard, and deep seeding depths) in the dry and wet landscape (LSP) zones. The planting date (PD) was on 14 Apr. 2015. Significant differences ($p < 0.1$) between mean cumulative emergence values at each sampling day after planting are shown by unique letters. Data shown are the means of three replicates and the vertical bars represent the standard error. The lack of standard error bars (and unique letters) indicates that only one replicate was observed to have new plants and no inferences can be made for that day.

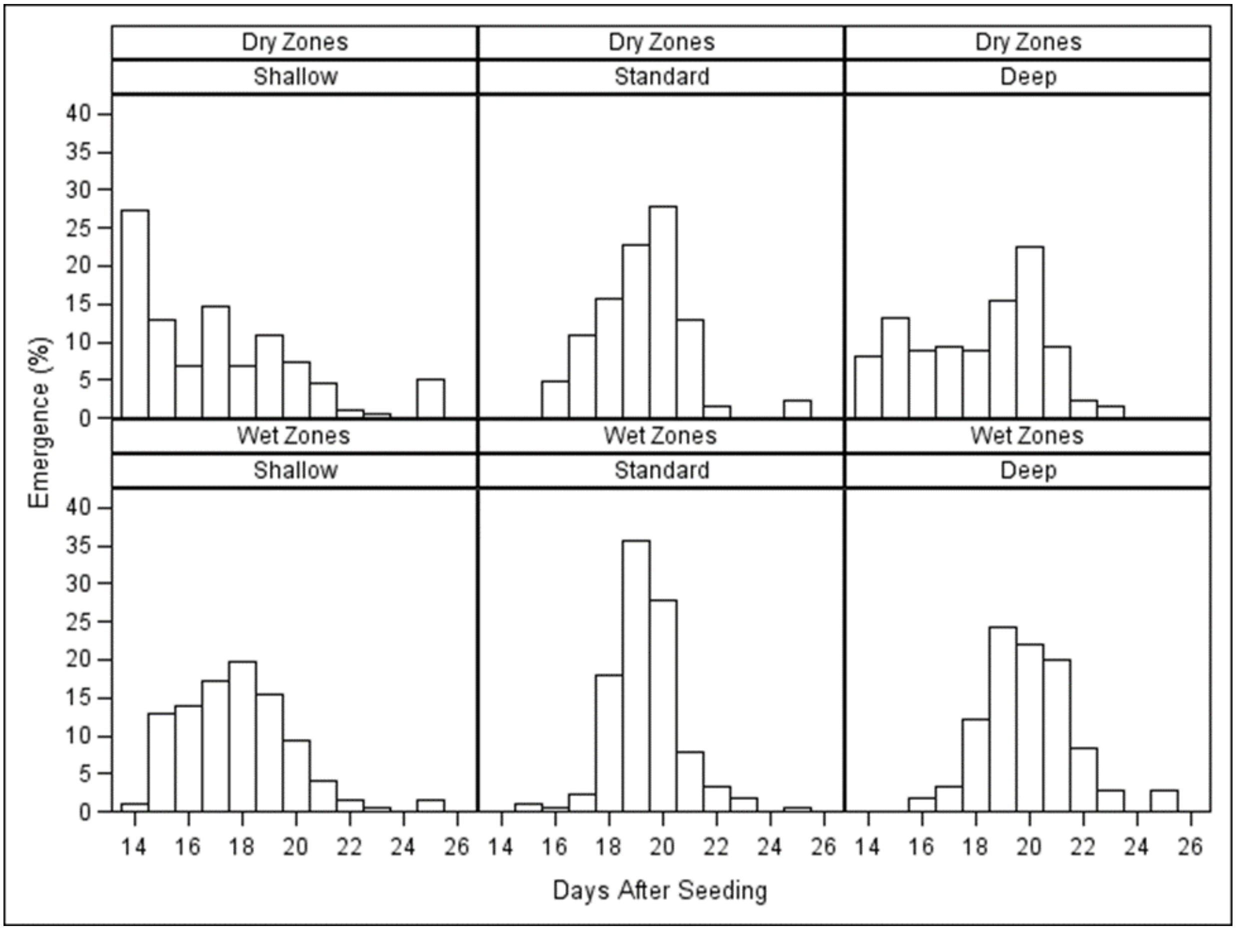


Fig. 3.12. Percent corn emergence day^{-1} after planting in field IL-11 during the 2015 growing season for the quantified plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

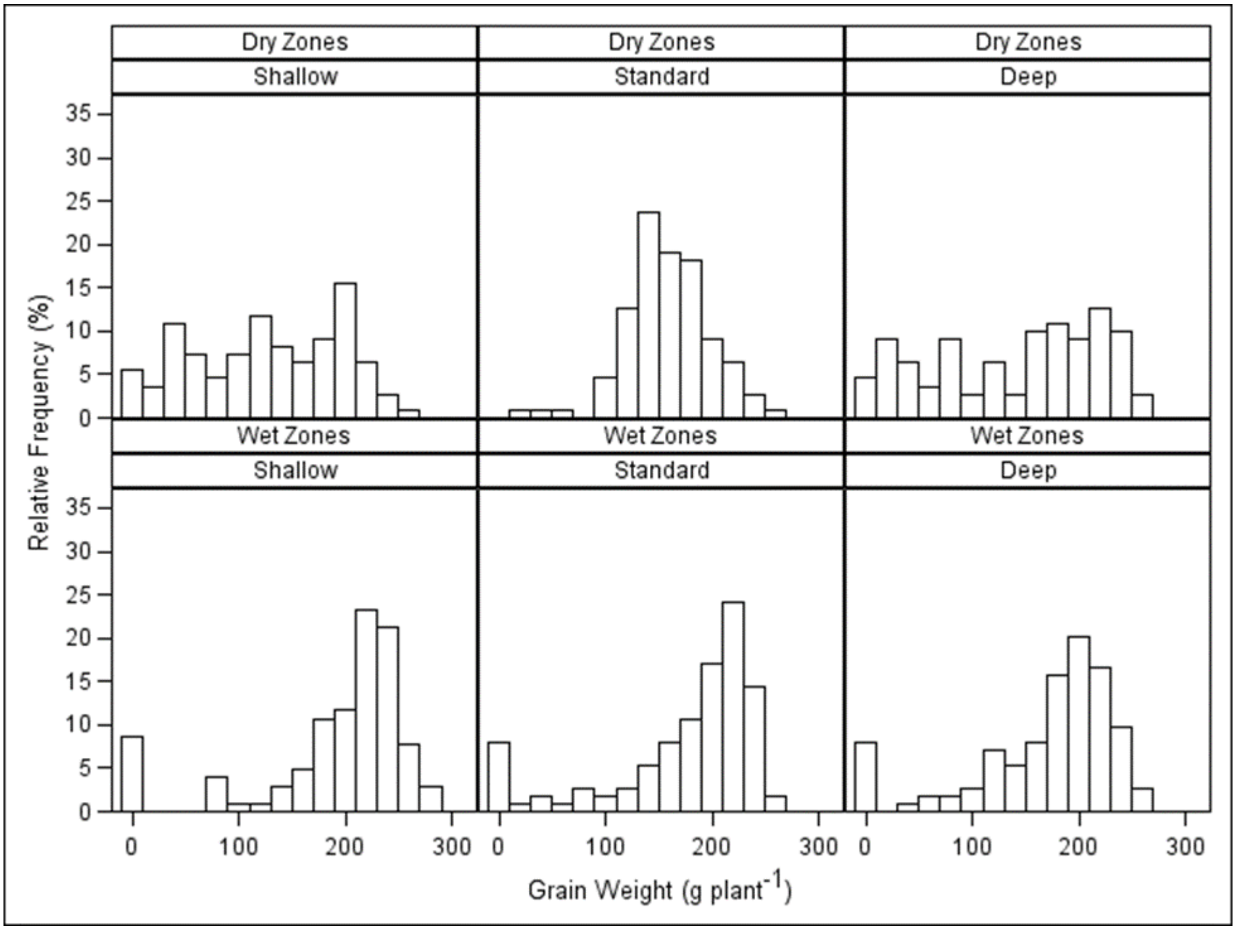


Fig. 3.13. Relative frequency distribution of grain weight plant^{-1} in field IL-11 during the 2015 growing season for the hand harvested plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

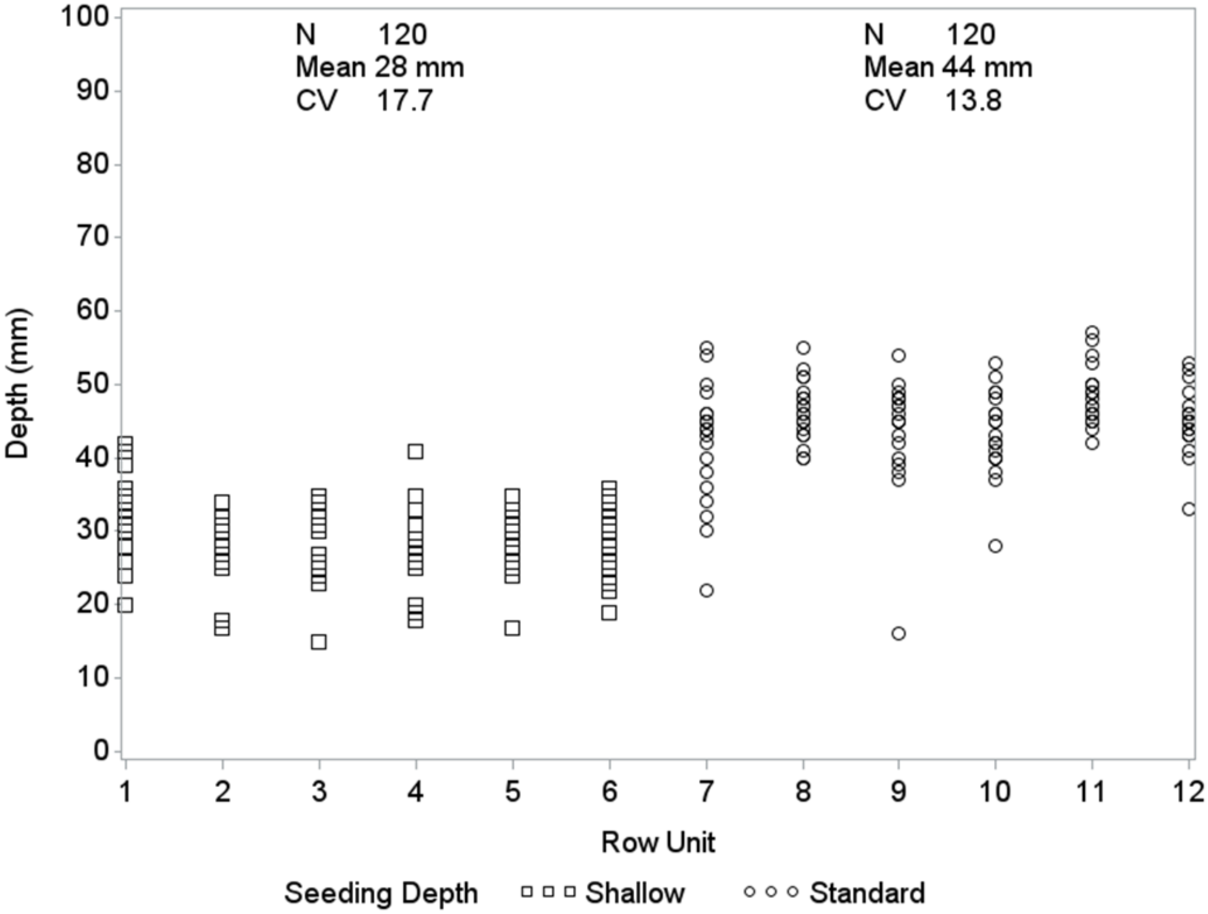


Fig. 3.14. One hundred and twenty plants (20 plants row unit^{-1}) at growth stages V1 to V2 from field IL-12 were sampled to verify the seeding depth placement for the shallow and standard seeding depth treatments for each row unit. Plants were only sampled for the first planting date (PD1), which was conducted on 23 Apr. 2015. Depth was measured from the bottom of the seed to the soil surface.

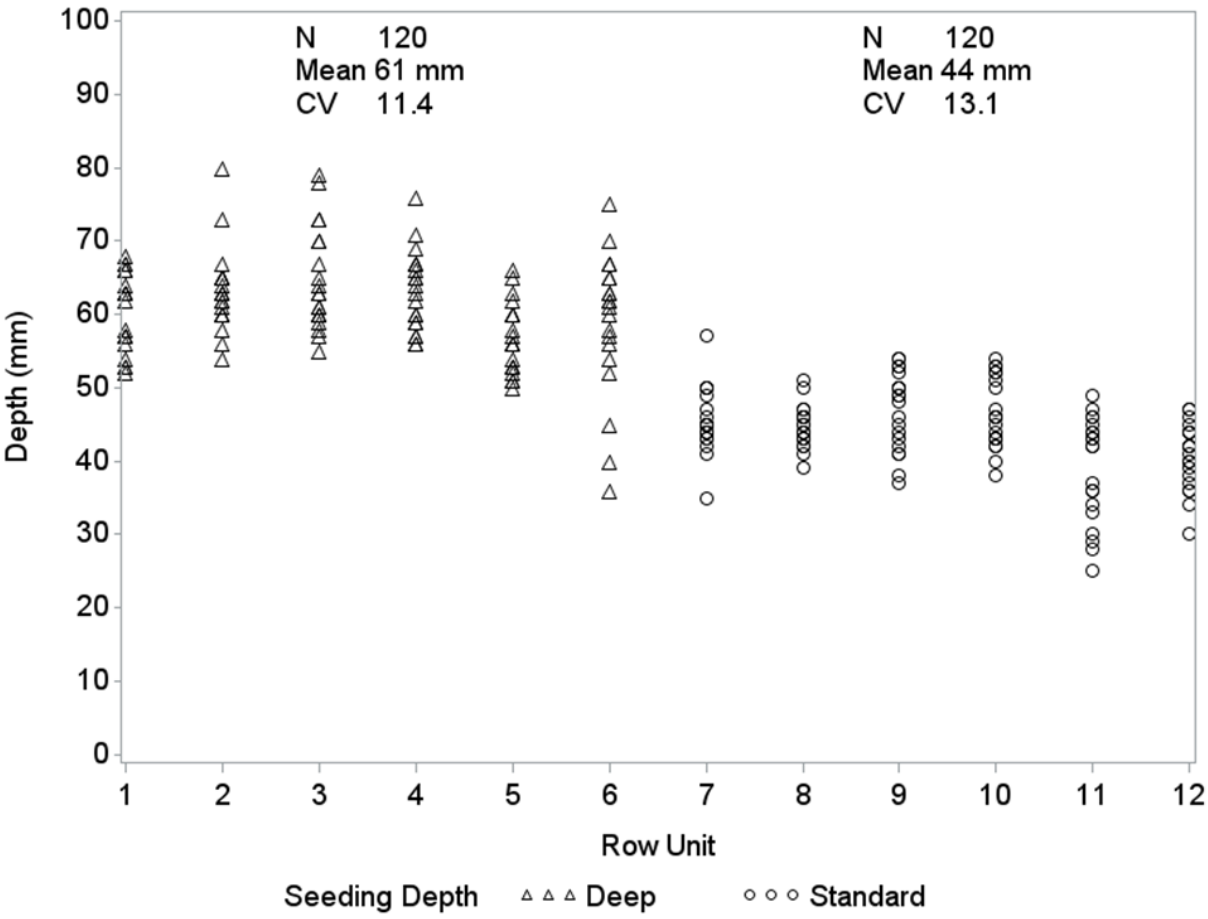


Fig. 3.15. One hundred and twenty plants (20 plants row unit^{-1}) at growth stages V1 to V2 from field IL-12 were sampled to verify the seeding depth placement for the deep and standard seeding depth treatments for each row unit. Plants were only sampled for the first planting date (PD1), which was conducted on 23 Apr. 2015. Depth was measured from the bottom of the seed to the soil surface.

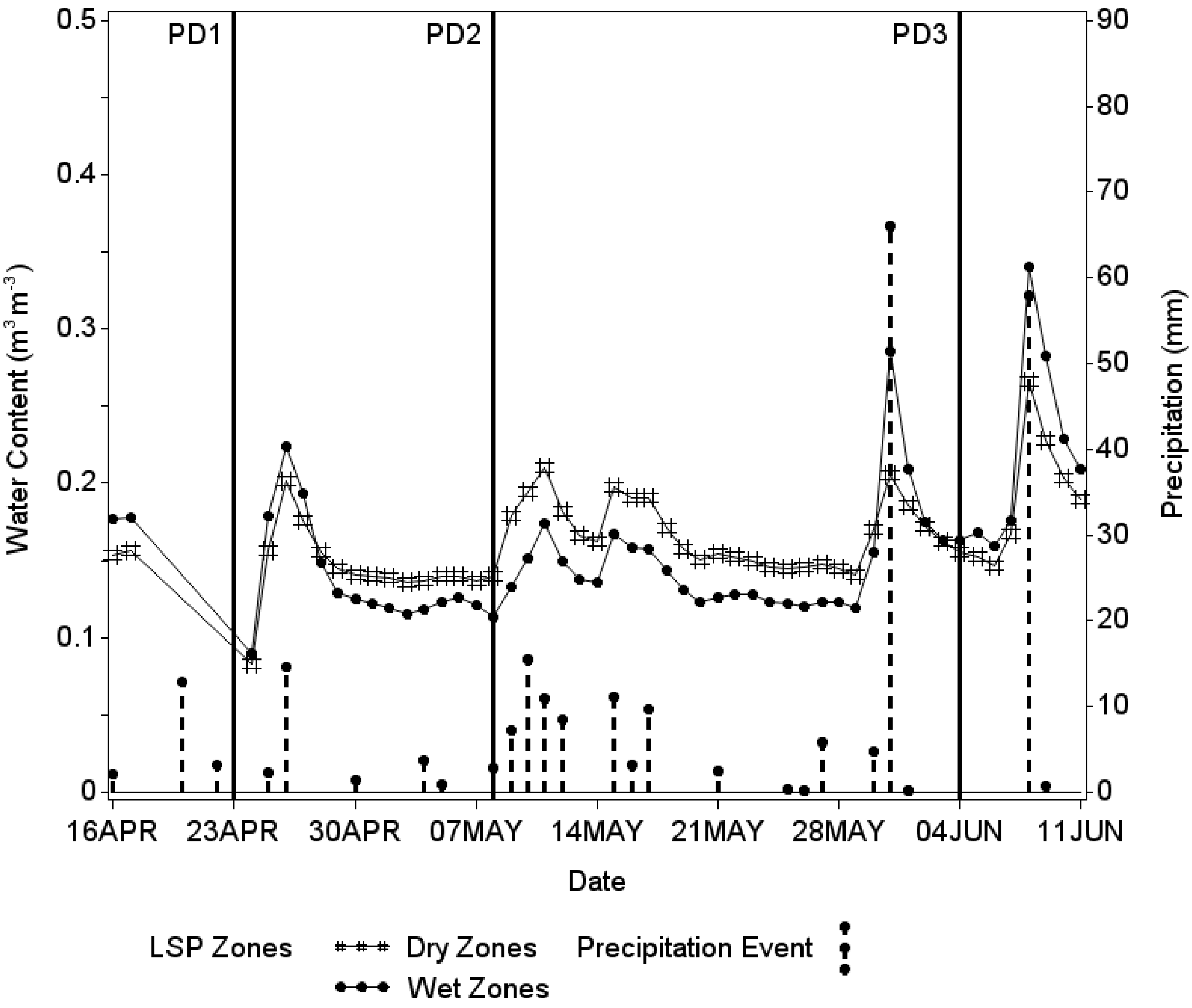


Fig. 3.16. Mean daily volumetric soil moisture content in IL-12 for the dry and wet landscape (LSP) zones in all three planting dates (PD1, PD2, and PD3) at a depth of 25 mm along with precipitation events, as measured by soil moisture sensors attached to data loggers. The planting dates were 23 Apr. 2015 for PD1, 8 May 2015 for PD2, and 4 June 2015 for PD3.

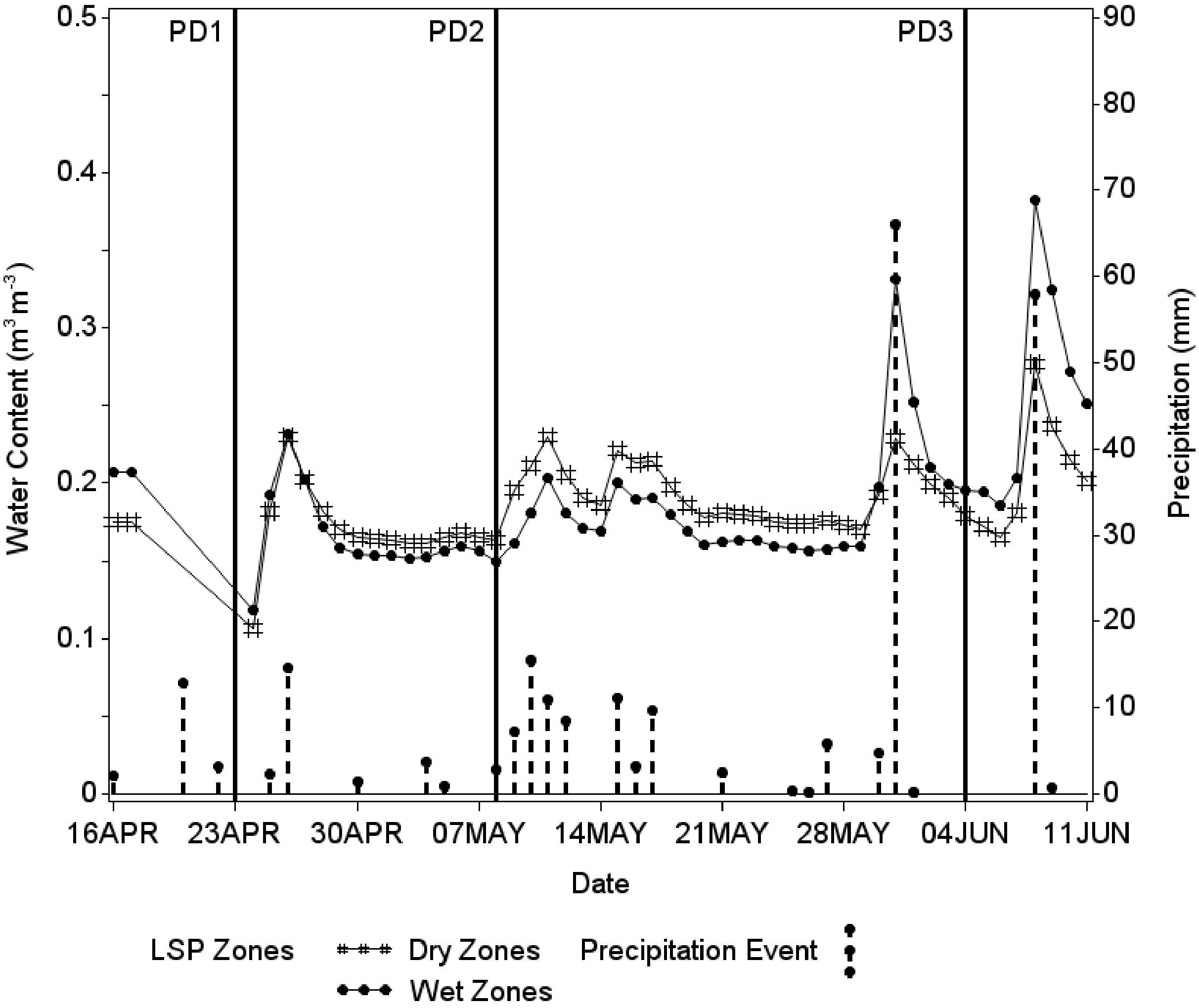


Fig. 3.17. Mean daily volumetric soil moisture content in IL-12 for the dry and wet landscape (LSP) zones in all three planting dates (PD1, PD2, and PD3) at a depth of 50 mm along with precipitation events, as measured by soil moisture sensors attached to data loggers. The planting dates were 23 Apr. 2015 for PD1, 8 May 2015 for PD2, and 4 June 2015 for PD3.

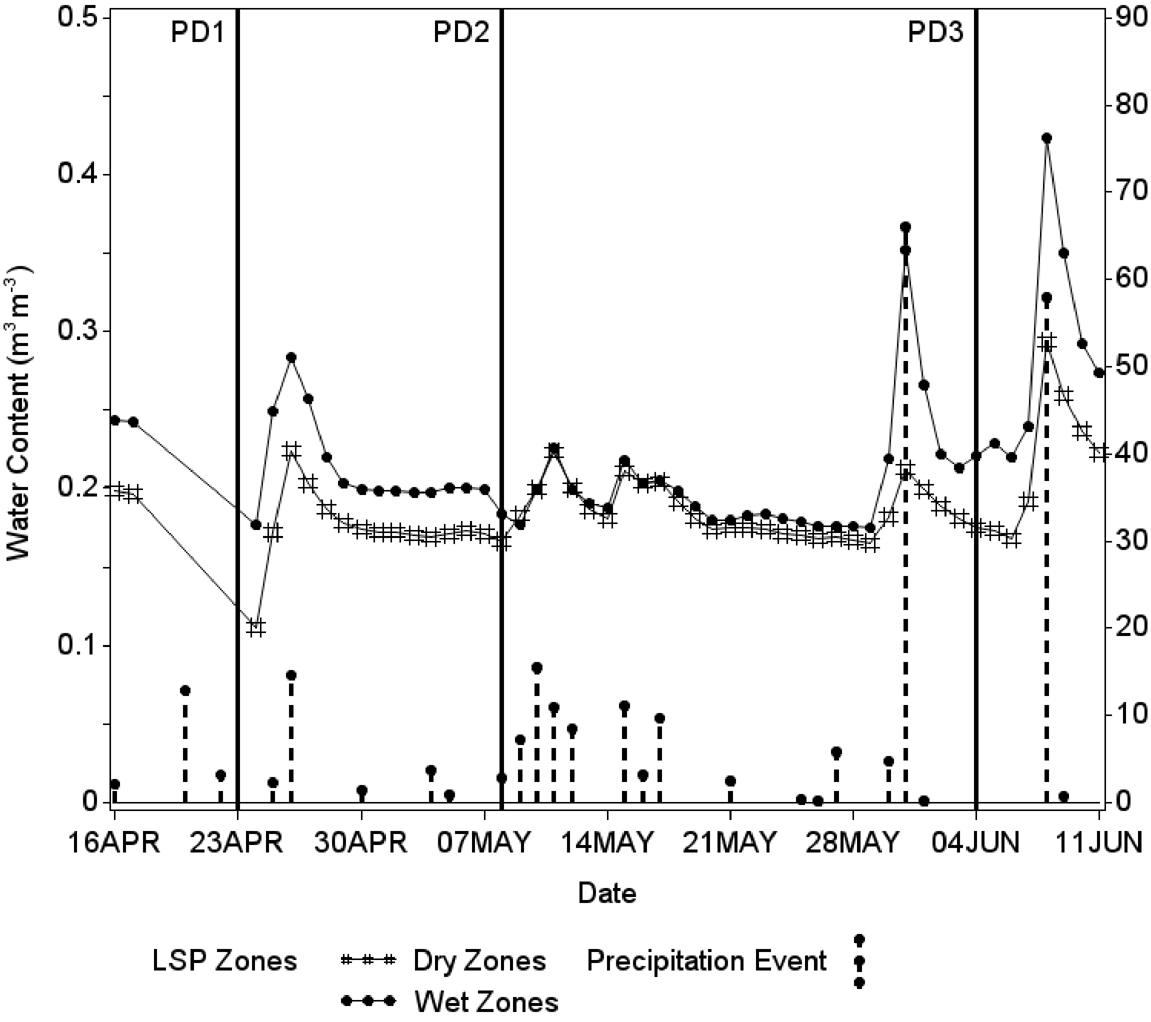


Fig. 3.18. Mean daily volumetric soil moisture content in IL-12 for the dry and wet landscape (LSP) zones in all three planting dates (PD1, PD2, and PD3) at a depth of 75 mm along with precipitation events, as measured by soil moisture sensors attached to data loggers. The planting dates were 23 Apr. 2015 for PD1, 8 May 2015 for PD2, and 4 June 2015 for PD3.

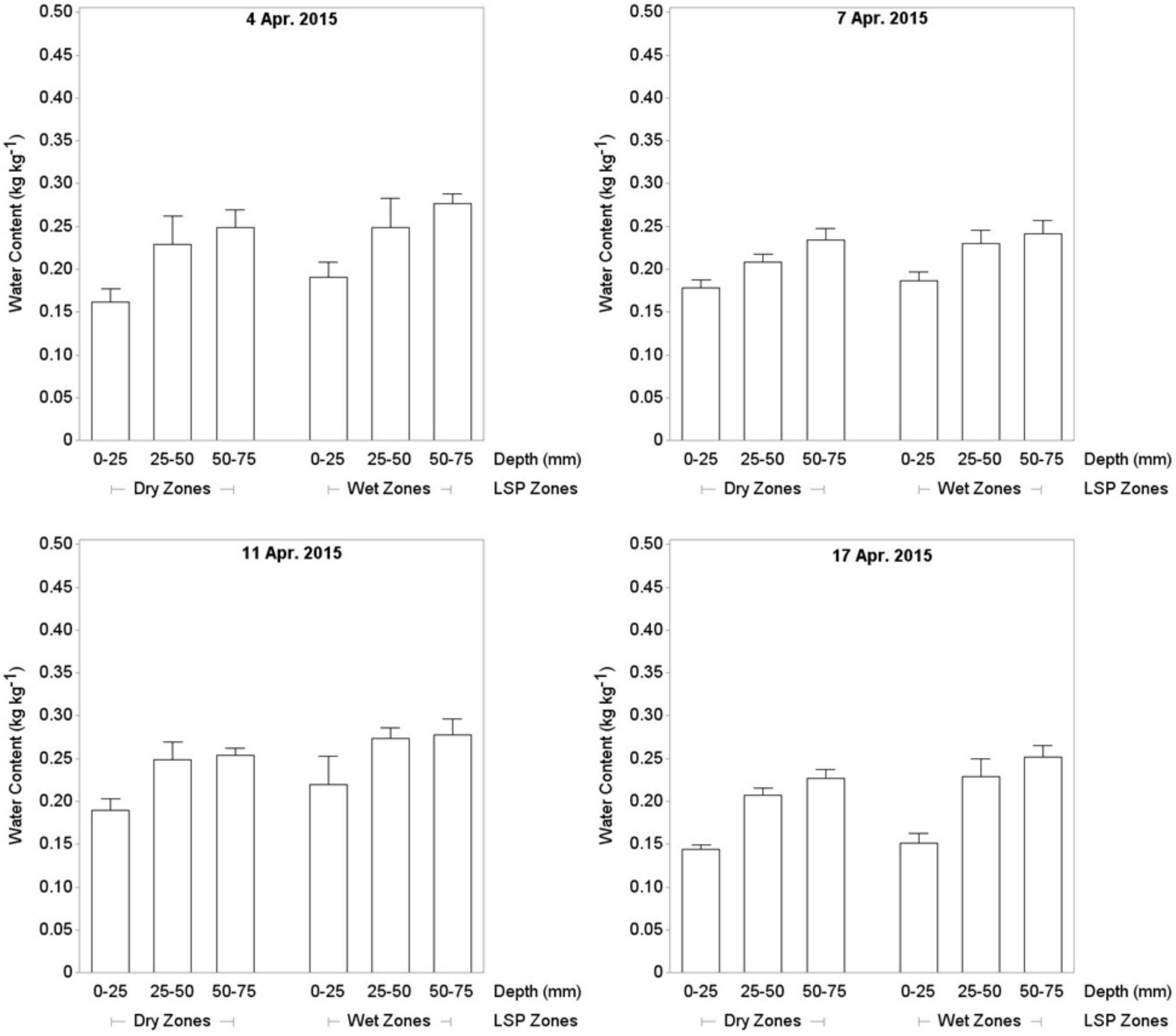


Fig. 3.19. Gravimetric soil moisture content for depths from 0 to 25, 25 to 50, and 50 to 75 mm in dry and wet landscape (LSP) zones in field IL-12 for four sampling events (4 Apr., 7 Apr., 11 Apr., and 17 Apr. 2015). Five soil cores (40-mm wide and 100-mm long) near the volumetric soil moisture sensors were extracted within a 1 m^2 area and composited by depth. The soil cores were cut on site to the specified depths and the composited soil samples for each depth were kept in airtight aluminum cans. Soil cores were taken immediately to a shop to be weighed, dried for 48 h at 60°C, and weighed again after drying. Data shown are the means of six replicates and the vertical bars represent the standard error.

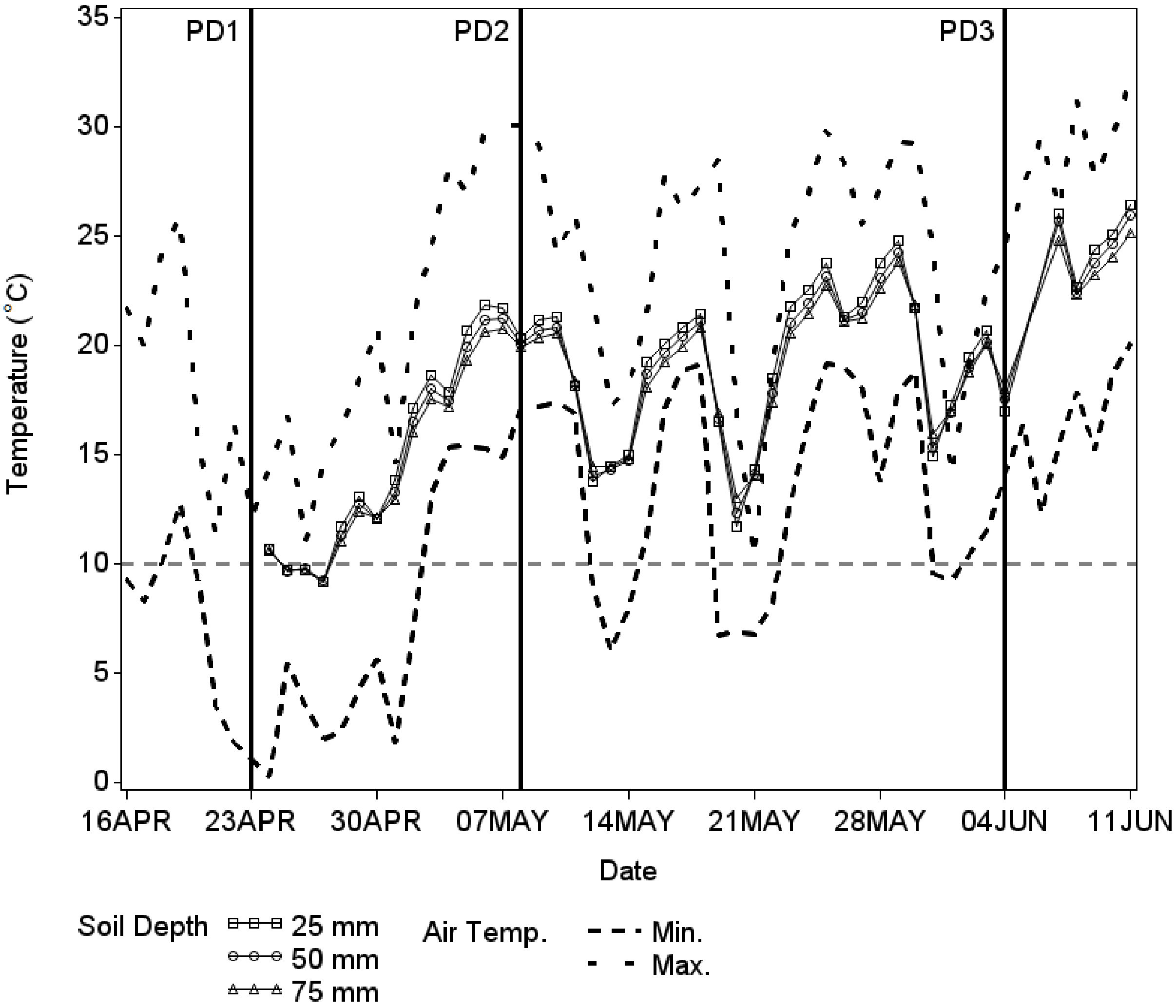


Fig. 3.20. Mean daily soil temperatures in IL-12 for all three planting dates (PD1, PD2, and PD3) at depths of 25, 50, and 75 mm, as measured by soil temperature sensors attached to data loggers, along with minimum (min.) and maximum (max.) daily air temperatures (temp.). The planting dates were 23 Apr. 2015 for PD1, 8 May 2015 for PD2, and 4 June 2015 for PD3.

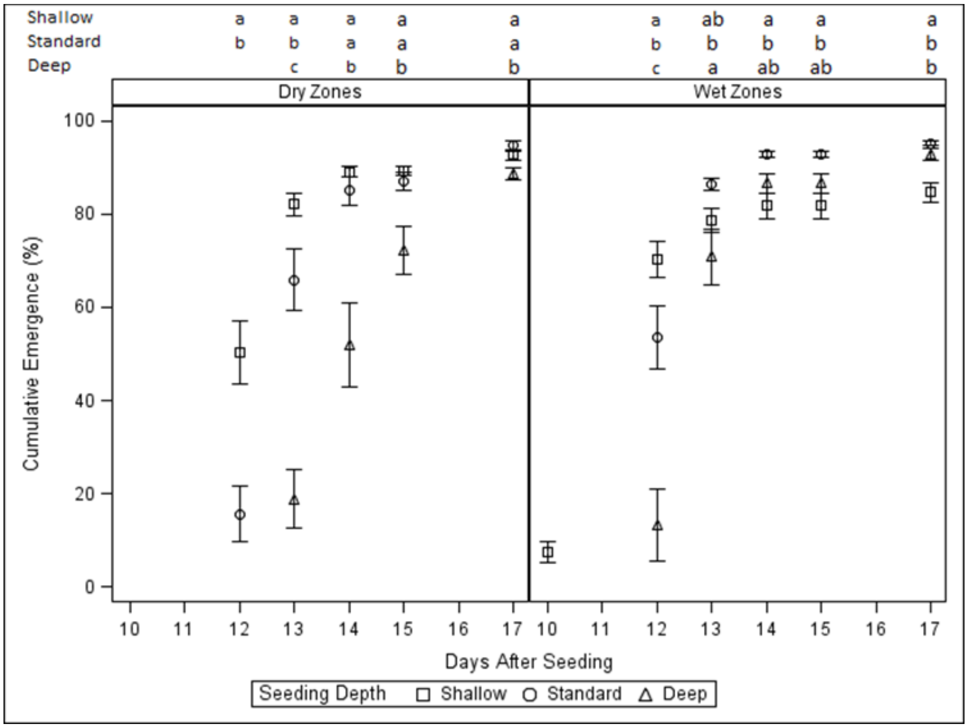


Fig. 3.21. Mean cumulative emergence day^{-1} in IL-12 for the three seeding depths (shallow, standard, and deep seeding depths) in the dry and wet landscape (LSP) zones in the first planting date (PD1) on 23 Apr. 2015. Measurements for day 11 and 16 after planting were omitted due to adverse weather conditions. Significant differences ($p < 0.1$) between mean cumulative emergence values at each sampling day after planting are shown by unique letters. Data shown are the means of four replicates and the vertical bars represent the standard error.

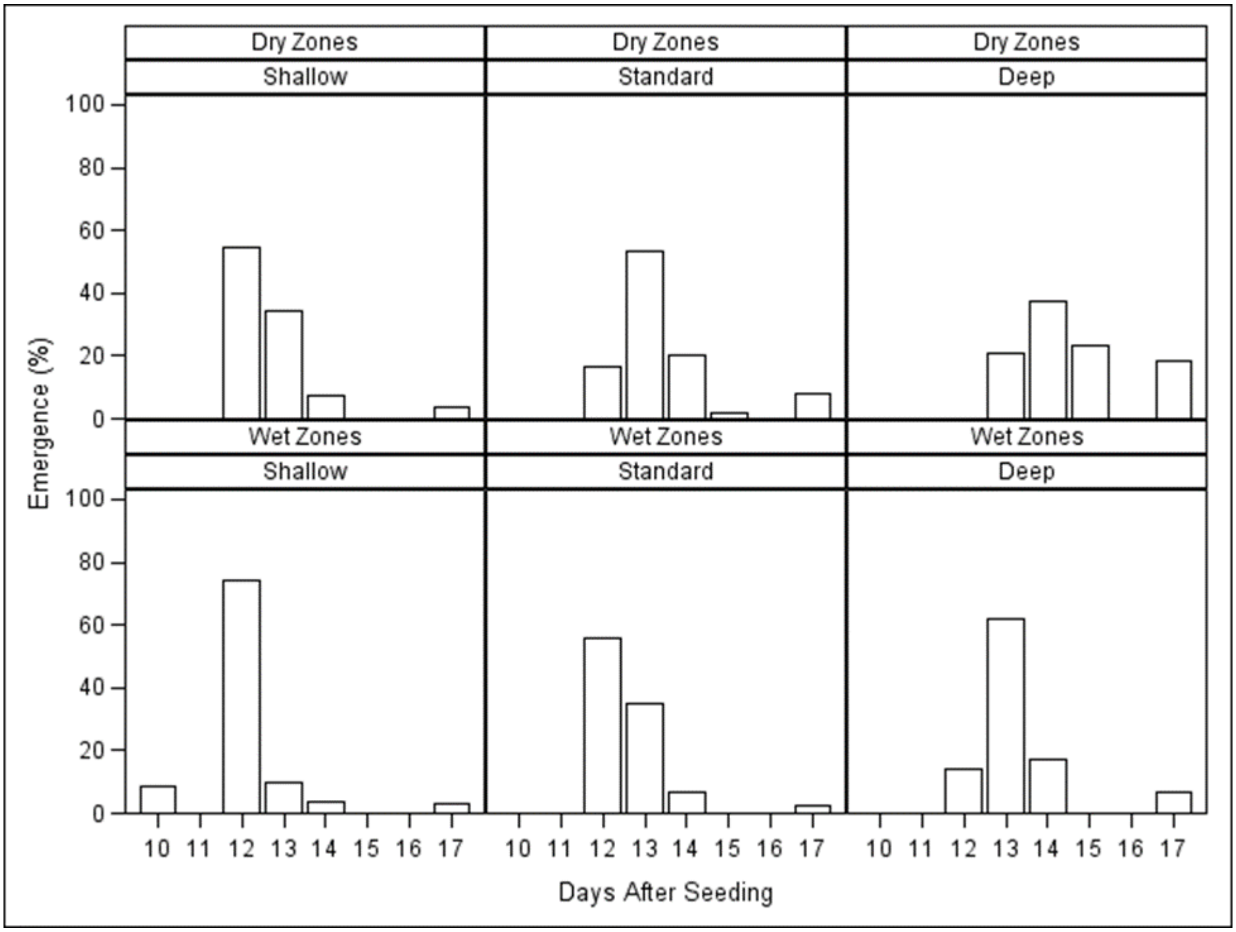


Fig. 3.22. Percent corn emergence day^{-1} after planting for the first planting date (PD1) in field IL-12 during the 2015 growing season for the quantified plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

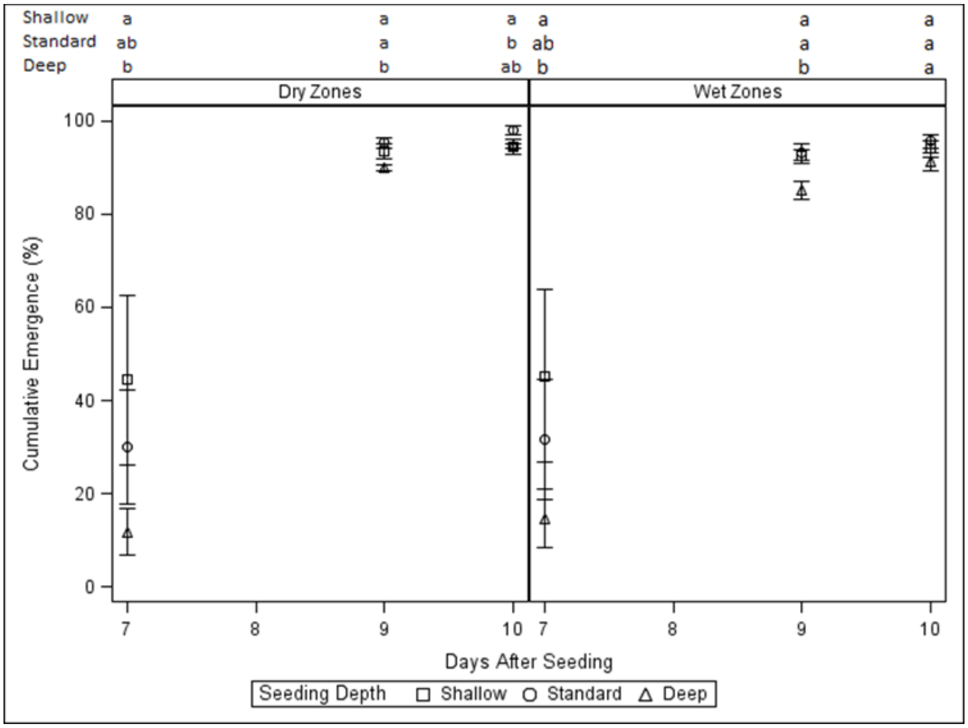


Fig. 3.23. Mean cumulative emergence day^{-1} in IL-12 for the three seeding depths (shallow, standard, and deep seeding depths) in the dry and wet landscape (LSP) zones in the second planting date (PD2) on 8 May 2015. Measurements for day 8 after planting were omitted due to adverse weather conditions. Significant differences ($p < 0.1$) between mean cumulative emergence values at each sampling day after planting are shown by unique letters. Data shown are the means of four replicates and the vertical bars represent the standard error.

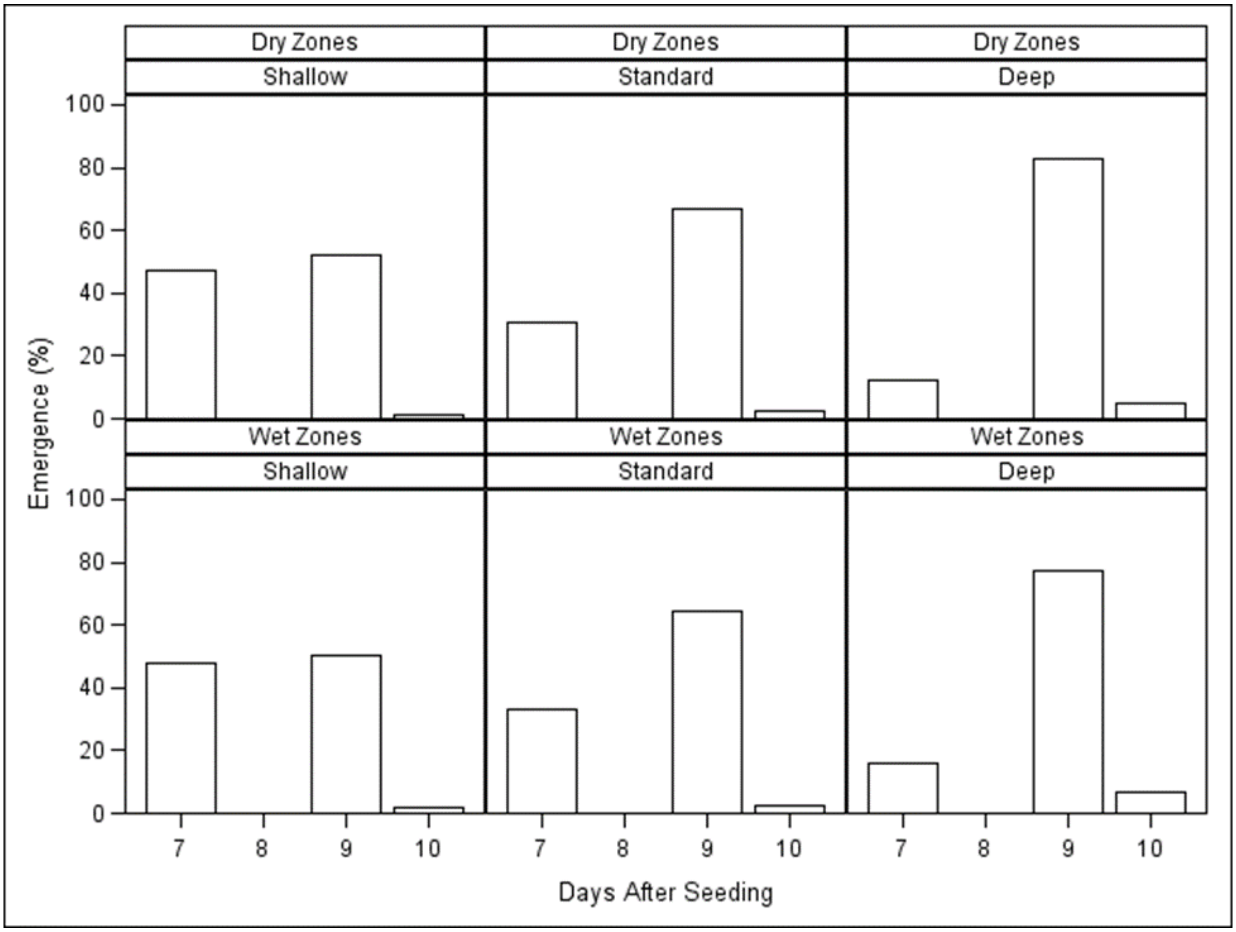


Fig. 3.24. Percent corn emergence day^{-1} after planting for the second planting date (PD2) in field IL-12 during the 2015 growing season for the quantified plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

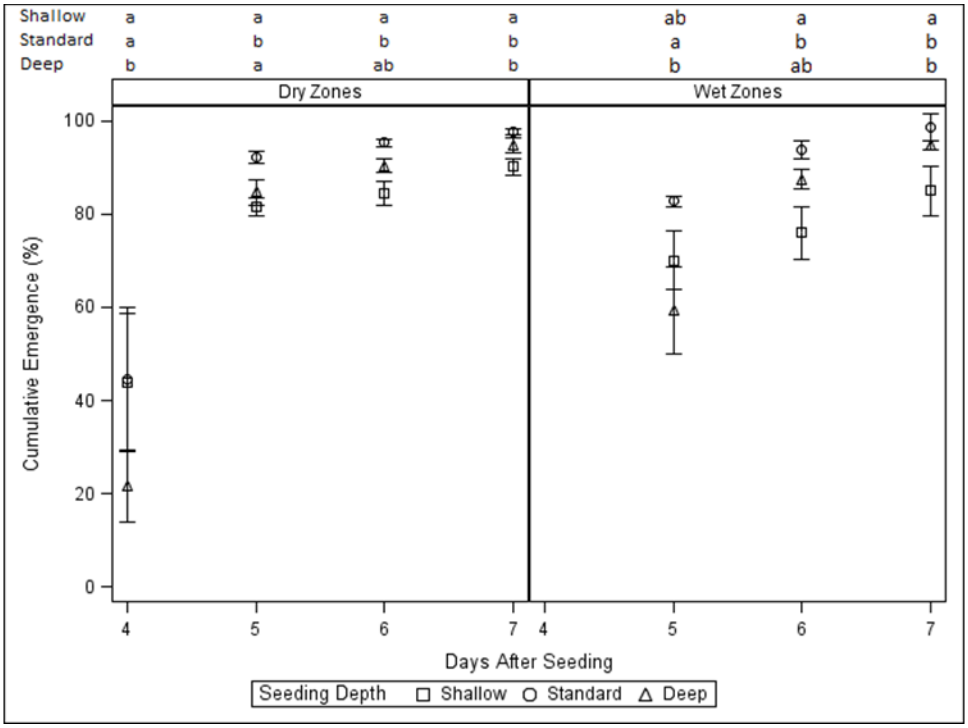


Fig. 3.25. Mean cumulative emergence day^{-1} in IL-12 for the three seeding depths (shallow, standard, and deep seeding depths) in the dry and wet landscape (LSP) zones in the third planting date (PD3) on 4 June 2015. Significant differences ($p < 0.1$) between mean cumulative emergence values at each sampling day after planting are shown by unique letters. Data shown are the means of four replicates and the vertical bars represent the standard error.

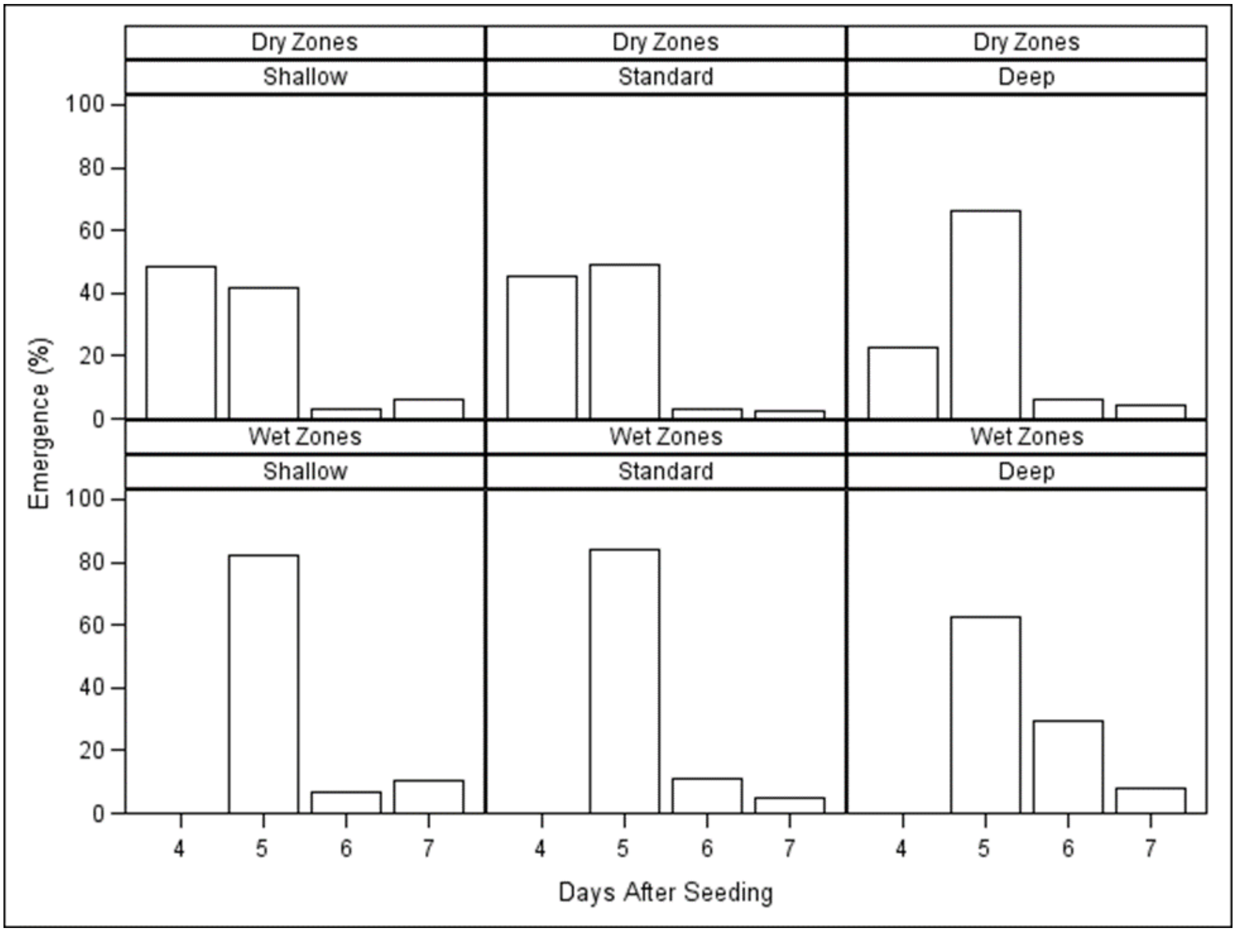


Fig. 3.26. Percent corn emergence day^{-1} after planting for the third planting date (PD3) in field IL-12 during the 2015 growing season for the quantified plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

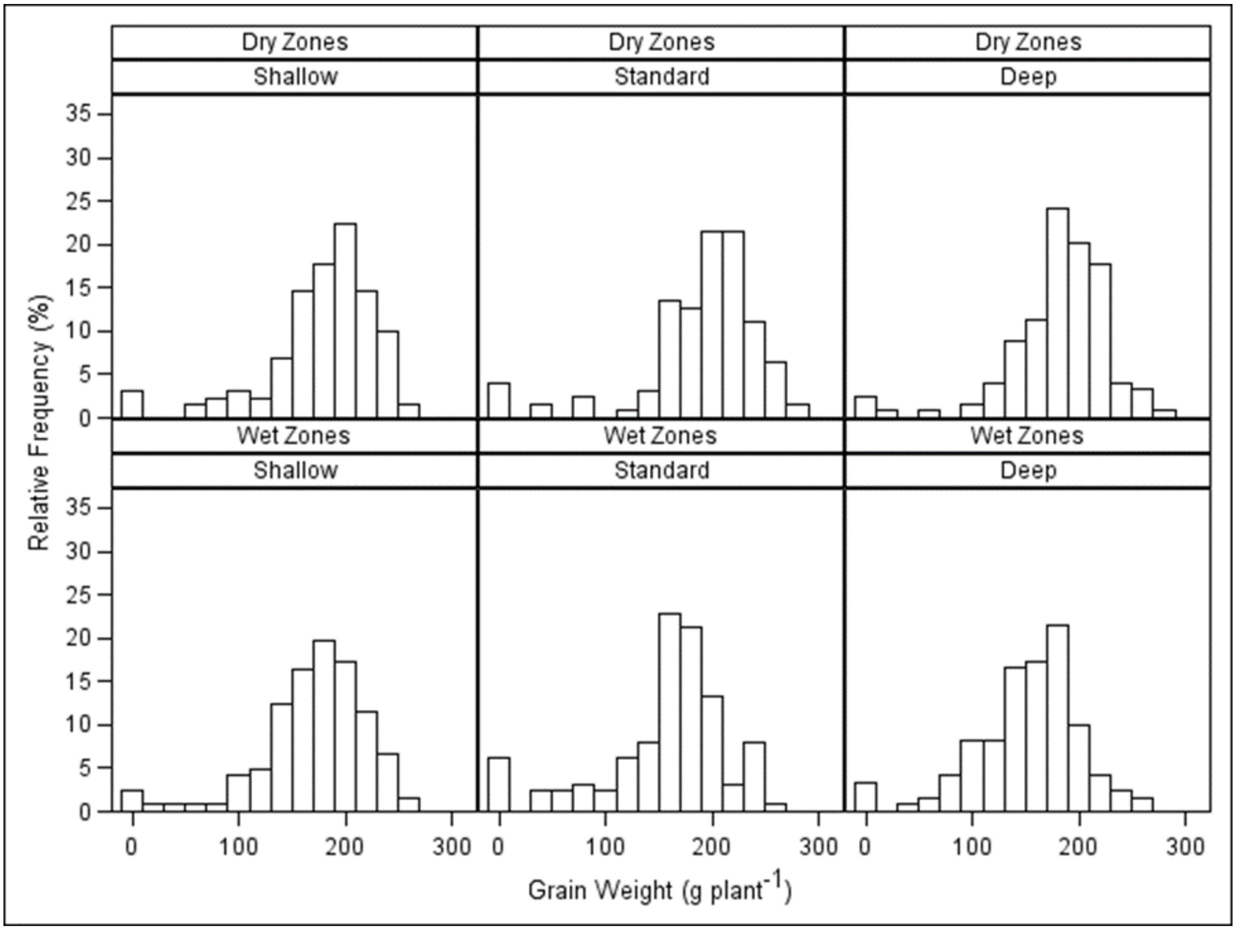


Fig. 3.27. Relative frequency distribution of grain weight plant^{-1} for the first planting date (PD1) on 23 Apr. 2015 in field IL-12 for the hand harvested plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

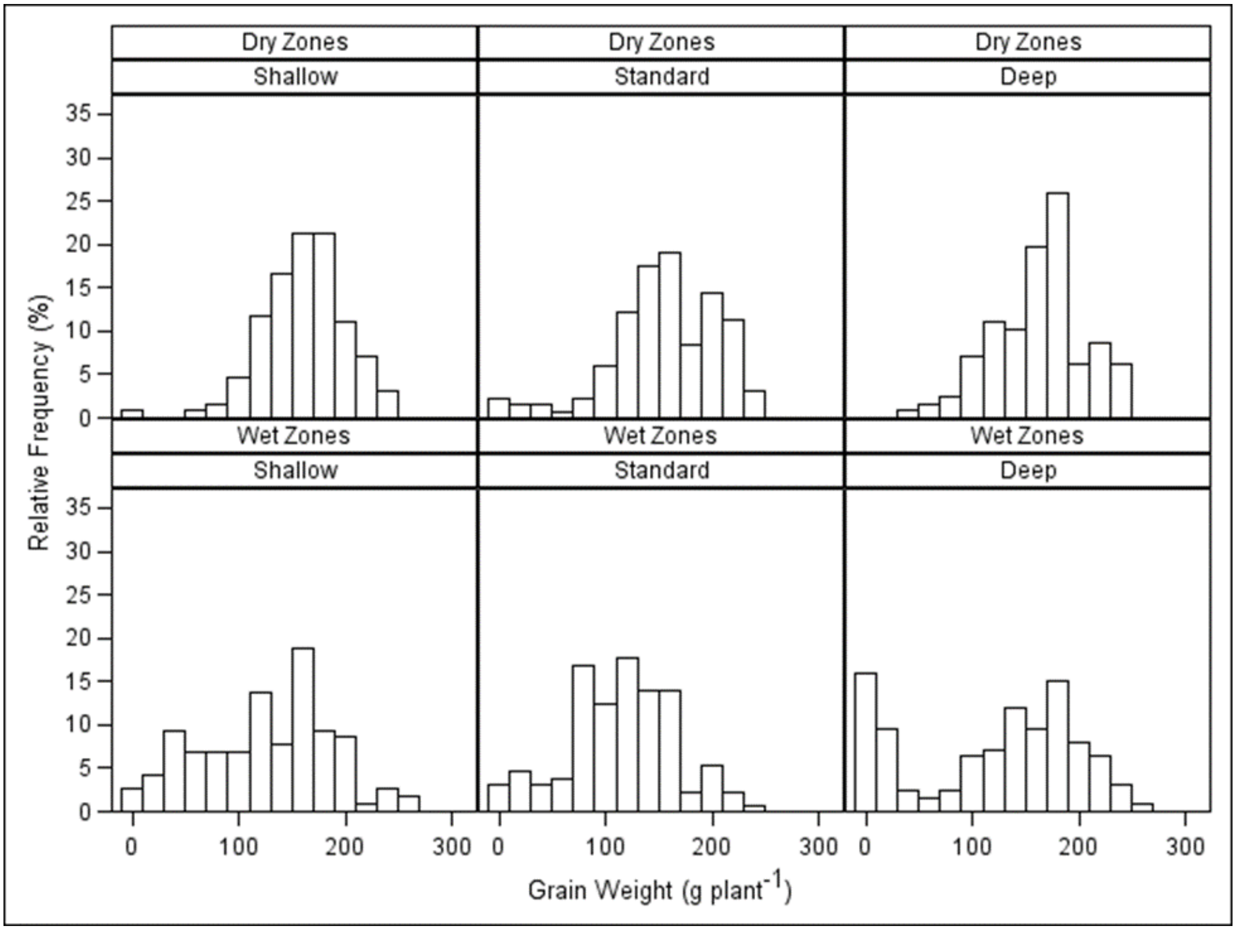


Fig. 3.28. Relative frequency distribution of grain weight plant^{-1} for the second planting date (PD2) on 8 May 2015 in field IL-12 for the hand harvested plants in the dry and wet landscape (LSP) zones (referred to as "Dry Zones" and "Wet Zones" in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as "Shallow", "Standard", and "Deep" in the cell headers).

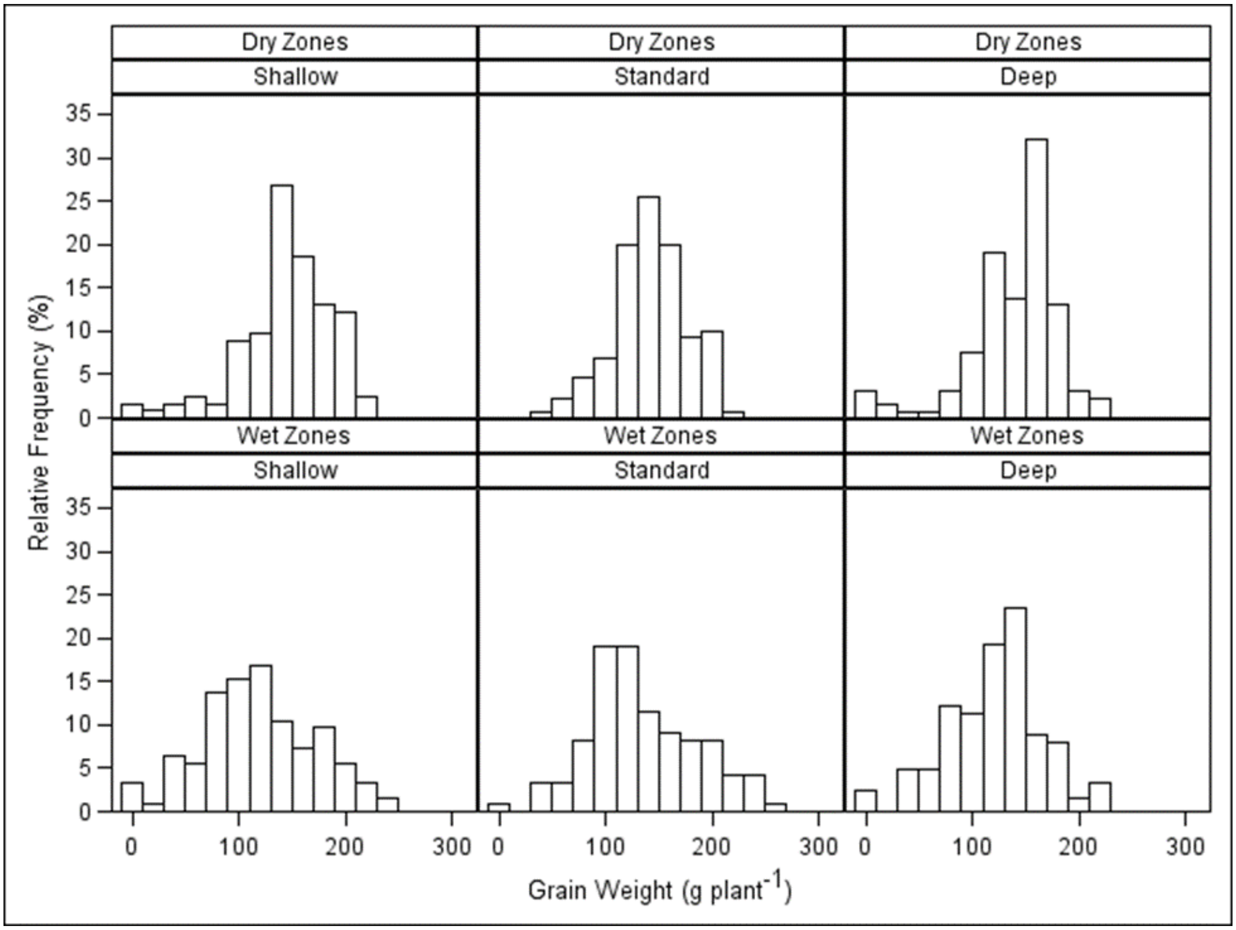


Fig. 3.29. Relative frequency distribution of grain weight plant^{-1} for the third planting date (PD3) on 4 June 2015 in field IL-12 for the hand harvested plants in the dry and wet landscape (LSP) zones (referred to as “Dry Zones” and “Wet Zones” in the cell headers) for the shallow, standard, and deep seeding depths of corn (referred to as “Shallow”, “Standard”, and “Deep” in the cell headers).

REFERENCES

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State University Extension, Ames, Iowa.

Adamchuk, V.I., J.W. Hummel, M.T. Morgan, and S.K. Upadhyaya. 2004. On-the-go soil sensors for precision agriculture. Comput. Electron. Agric. 44:71-91.

Akaike, H. 1974. A new look at the statistical model identification. IEEE Trans. on Automatic Control 19:716-723.

Alessi, J., and J.F. Power. 1971. Corn emergence in relation to soil temperature and seeding depth. Agron. J. 63:717-719.

Atherton, B.C., M. Morgan, S.A. Shearer, T.S. Stombaugh, and A.D. Ward. 1999. Site-specific farming: A perspective on information needs, benefits and limitations. J. Soil Water Cons. 54:455-461.

Barger, G.L. 1969. Total growing degree days. In Weekly Weather and Crop Bulletin; US Department of Commerce and USDA: Washington, DC, USA.

Benech-Arnold, R. L., and R.A. Sanchez. 2004. Handbook of seed physiology: applications to agriculture. Food Products Press.

Boomsma, C.R., and T.J. Vyn. 2009. Per-plant eco-physiological responses of maize to varied nitrogen availability at low and high plant densities. Proceedings of the International Plant Nutrition Colloquium XVI, Sacramento, CA. August 2009. Dep. of Plant Sci., Univ. of California, Davis. http://repositories.cdlib.org/ipnc/xvi/1233 (accessed 7 Aug. 2016).

Bradley, C.A. 2009. Managing diseases. Illinois Agronomy Handbook: 24th Edition. University of Illinois at Urbana-Champaign. Cooperative Extension Service. p. 197-207.

Brady, N.C., and R.R. Weil. 2008. Elements of the nature and properties of soils. Pearson Prentice Hall.

Burrough, P.A. 1983. Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels of soil variation. J. Soil Sci. 34:577-597.

Campbell, G.S., and J.M. Norman. 1998. An introduction to environmental biophysics. Springer-Verlag. New York.

Carter, L.M., and J.H. Chesson. 1993. A soil moisture seeking planter control. ASAE paper 93-1553.

Carter, L.M., and J.H. Chesson. 1996. Below the surface. Seed World 134:14-15.

Choi, M., J.M. Jacobs, and M.H. Cosh. 2007. Scaled spatial variability of soil moisture fields. Geophys. Res. Lett. 34 L01401.

Cobos, D. 2015. Measurement volume of Decagon volumetric water content sensors. http://manuals.decagon.com/Application%20Notes/14955_VWC%20Sensor%20Measurement%20Volumes_Web.pdf (accessed 5 July 2016).

Coulter, J. 2016. Corn planting decisions to establish a foundation of success. University of Minnesota Extension. http://www.extension.umn.edu/agriculture/corn/planting/corn-planting-decisions/ (accessed 1 July 2016).

Doerge, T.A., and D.L. Gardner. 1999. On-farm testing using the adjacent strip comparison method. In: P.C. Robert, R.H. Rust, W.E. Larson, editors, Precision Agriculture, ASA, CSSA, SSSA, Madison, WI. p. 603-609.

Duffy, M. 2015. The 2011 costs of crop production. Ag Decision Maker 15(2) art. 2. http://lib.dr.iastate.edu/agdm/vol15/iss2/2 (accessed 27 June 2016).

Dyck, F.B., W.K. Wu, R. Lesko. 1985. Automatic depth control for cultivators and air seeders developed under the AERD program. In: Proceedings of the Agri-Mation I. Conference and exhibition. 25–28 Feb 1985. St. Joseph. p. 265–277.

Elmore, R., M. Al-Kaisi, and M. Hanna. 2014. Corn seeding depth: back to the basics. Integrated Crop Management News. Iowa State University Extension.https://extension.umd.edu/sites/default/files/_docs/Agronomy%20News%20May%201%202014.pdf (accessed 20 July 2014).

Espinoza, L., and J. Ross. 2004. Corn production handbook. MP437-2M-2-03N. Little Rock: University of Arkansas Division of Agriculture Cooperative Extension Service.

Green-Tracewicz, E., E.R. Page, and C.J. Swanton. 2011. Shade avoidance in soybean reduces branching and increases plant-to-plant variability in biomass and yield per plant. Weed Sci. 59:43–49.

Gupta, S.C., E.C. Schneider, and J.B. Swan. 1988. Planting depth and tillage interactions on corn emergence. Soil Sci. Soc. Am. J. 52:1122-1127.

Hanna, A.Y., P.W. Harlan, and D.T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. Agron J. 74:999–1004.

Hawley, M.E., T.J. Jackson, and R.H. McCuen. 1983. Surface soil moisture variation on small agricultural watersheds. J. Hydrol. 62:179-200.

Heege, H.J. 2013. Site-specific sowing. Precision in Crop Farming: Site Specific Concepts and Sensing Methods: Applications and Results. p. 171.

Helms, T.C., E.L. Deckard, and P.A. Gregoire. 1997. Corn, sunflower, and soybean emergence influenced by soil temperature and soil water content. Agron. J. 89:59-63.

Hillel, D. 1990. Role of irrigation in agricultural systems. In B.A. Stewart and D.R. Nielsen, editors, Irrigation of Agricultural Crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI. p. 5-30.

Hoeft, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. Modern corn and soybean production. Champaign, IL, MCSP Publications. p. 88.

Howell, T. 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation. In B.A. Stewart and D.R. Nielsen, editors, Irrigation of Agricultural Crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI. p. 391-434.

Hunter, R.B., and L.W. Kannenberg. 1972. Effects of seed size on emergence, grain yield, and plant in corn. Can. J. Plant Sci. 52: 252-256.

Hupet, F., and M. Vanclooster. 2002. Intraseasonal dynamics of soil moisture variability within a small agricultural maize cropped field. J. Hydrol. 261:86-101.

Jiang, P., and K.D. Thelen. 2004. Effect of soil and topographic properties on crop yield in a north-central corn–soybean cropping system. Agron. J. 96:252-258.

Knappenberger, T., and K. Köller. 2012. Spatial assessment of the correlation of seeding depth with emergence and yield of corn. Precis. Agric. 13:163-180.

Kovács, P., and T.J. Vyn. 2014. Full-season retrospectives on causes of plant-to-plant variability in maize grain yield response to nitrogen and tillage. Agron. J. 106:1746-1757.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Lawles, K., W. Raun, K. Desta, and K. Freeman. 2012. Effect of delayed emergence on corn grain yields. J. Plant Nutr. 35:480-496.

Madsen, M.D., K.W. Davies, C.J. Williams, and T.J. Svejcar. 2012. Agglomerating seeds to enhance native seedling emergence and growth. J. Appl. Ecol. 49:431-438.

Mastorakos, M., V. Adamchuk, F. Réne-Laforest, and C. Hemplemen. 2014. Development of a capacitance-based sensor for on-the-go soil moisture measurements. In I.C. Paltineanu, editor, Transactions of the Fourth International Symposium on Soil Water Measurement Using Capacitance, Impedance and TDT, Montreal, Quebec, Canada, 16-18 July 2014, Laurel, MD. Paltin International, Inc. p. 97-106.

Mayer, L.I., M.A. Rossini, and G.A. Maddonni. 2012. Inter-plant variation of grain yield components and kernel composition of maize crops grown under contrasting nitrogen supply. Field Crops Res. 125:98–108.

Miedema, P. 1982. The effects of low temperature on *Zea mays*. Adv. Agron. 35:93–128.

Nafziger, E.D. 2009. Corn. Illinois Agronomy Handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign, pg. 91-112.

Nielsen, R.L. 2010. Requirements for uniform germination and emergence of corn. Corny News Network, Purdue University.http://www.agry.purdue.edu/ext/corn/news/timeless /germemergreq.html (accessed 20 Feb. 2014).

Parera, C.A., and D.J. Cantliffe. 1994. Presowing seed priming. Hortic. Rev. 16:109-141.

Pierce, F.J., and P. Nowak. 1999. Aspects of precision agriculture. Adv. Agron. 67:1-85.

Pinheiro, J.C., and D.M. Bates. 2000. Mixed effects models in S and S-Plus. Springer, New York.

Price, R.R., and L.D. Gaultney. 1993. Soil moisture sensor for predicting seed planting depth. Trans. ASAE 36:1703-1711.

Price, R.R., X. Huang, and L.D. Gaultney. 1990. Development of a soil moisture sensor. ASAE paper 90-3555. St. Joseph, MI.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

René-Laforest, F.F. 2015. Real-time variable control technologies for precision agriculture. Master's thesis. McGill University, Montreal, Quebec, Canada.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1996. How a corn plant develops. Special Rpt. No. 48. Iowa State Univ. of Sci. and Tech., Coop. Ext. Ser., Ames, IA.

Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty. 2010. Crop planting dates: an analysis of global patterns. Glob. Ecol. Biogeogr. 19:607-620.

SAS Institute. 2013. SAS Software v. 9.4. SAS Inst., Cary, NC.

Schneider, E.C., and S.C. Gupta. 1985. Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. Soil Sci. Soc. Am. J. 49:415-422.

Schnitkey, G. 2015. Corn seed costs from 1995 to 2014. Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. farmdoc daily 5:214.

Scott, R.W., E.C. Krug, S.L. Burch, C.R. Mitsdarfer, and P. Nelson. 2010. Investigation of soil moisture variability under sod in east-central Illinois. Illinois State Water Survey.

Shearer, S.A., and S.K. Pitla. 2014. Precision planting and crop thinning. In Automation: The Future of Weed Control in Cropping Systems. Springer Netherlands. p. 99-124.

Swan, J.B., E.C. Schnieder, J.F. Moncrieg, W.H. Paulson, and A.E. Peterson. 1987. Estimating corn growth, yield, and grain moisture from air growing degree days and residue cover. Agron. J. 79:53-60.

Timlin, D.J., Y. Pachepsky, V.A. Snyder, and R.B. Bryant. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Sci. Soc. Am. J. 62:764-773.

Vega, C.R.C., and V.O. Sadras. 2003. Size-dependent growth and the development of inequality in maize, sunflower and soybean. Ann. Bot. 91:795–805.

Verdú, M., and A. Traveset. 2005. Early emergence enhances plant fitness: A phylogenetically controlled meta-analysis. Ecology 86:1385-1394.

Weatherly, E.T., and C.G. Bowers Jr. 1997. Automatic depth control of a seed planter based on soil drying front sensing. Trans. ASAE 40:295-305.

CHAPTER 4: CONCLUDING REMARKS

The second and third chapters of this dissertation studied the potential application of variable seeding depth as a way to improve corn yield in the U.S. Corn Belt. The second chapter evaluated variable seeding depth using corn yield as recorded by the yield monitors of harvesters, while the third chapter evaluated variable seeding depth using grain weights of hand harvested plants. The third chapter also provided insights about the differential corn emergence patterns observed by the corn seeds planted at three seeding depths (shallow, standard, and deep) in relatively dry and wet landscape zones. The first chapter is tangentially connected to the second and third chapters in regards to the issue of corn residue buildup experienced by some no-till corn producers applying a continuous-corn cropping system. Under this no-till cropping system, cool and moist conditions can result in poor crop establishment and reduced yield. One researcher suggested that shallower corn seeding depth could compensate for cooler soil temperatures in no-till cropping systems when soil moisture is sufficient at the seeding depth (Gupta et al., 1988).

The data in the appendix shows the plant-to-plant variability from adjacent corn plants sampled within-row as found in the field. This is particularly interesting and meritorious of further research as corn seeds are assumed to be nearly identical clones (Kovács and Vyn, 2014), and except for spacing differences, the growing environment of corn plants across short distances as used in this study could be assumed to be homogeneous. At least in the two fields sampled during the 2015 growing season, the application of variable seeding depth did not succeed in reducing plant-to-plant variability. Many efforts have been undertaken by previous researchers to understand and reduce corn plant-to-plant yield variability (Martin et al., 2005; Hodgen, 2007; Boomsma et al., 2009; Kovács and Vyn, 2014, among others).

The measurements of soil moisture during the 2015 growing season within the potential range of seeding depths used by corn producers in the U.S. Corn Belt showed that given the conditions after planting in IL-11 and IL-12, planting corn seeds at depths near 50 mm was likely sufficient to reach near optimal moisture conditions. Emergence delays, seed diseases, and failure to emerge can result from planting corn seeds deeper into the soil when soil moisture is high. However, when soil temperatures were well above 10°C the influence of seeding depth was greatly reduced. Only for the third planting date in IL-12 was observed that emergence was delayed for one extra day in the wet landscape zones regardless of seeding depth. It is unlikely that an emergence delay of just one day could result in significantly lower yield (Nafziger et al., 1991).

The measurement of soil temperature was conducted in a single location in field IL-12. Nevertheless, important insights were gained from the soil temperature data. It was observed that soil temperatures at the 25-mm depth, usually considered by agronomists as the minimum depth at which corn seeds should be placed, nearly matched the air temperatures in these silty clay loam soils under conventional tillage conditions (raw data not shown). Thus, air temperatures could be used as a proxy to estimate the soil temperature at the 25-mm depth in similar soils and tillage systems. At deeper soil depths, it was found that the mean daily soil temperatures at the 50-mm depth were 0.6 to 1.9°C cooler than at the 25-mm depth, while the soil at the 75-mm depth was 1.3 to 3°C cooler than at the 25-mm depth. These soil temperature differences at the 25- to 75-mm depths are not an impediment to fast corn emergence when corn is planted late (i.e. May corn seeding in Illinois) and temperatures are higher, as seen for the second and third planting dates in IL-12. However, corn producers aim to start corn planting operations in mid- to late April, when temperatures are historically lower, and it is possible that soil temperature differences within the range of potential seeding depths chosen by corn producers could have a considerable impact on corn emergence and plant establishment, particularly if corn seeds are placed deeper into the soil in the wet landscape zones. Although this experiment lacked soil temperature monitoring between contrasting soil types or landscape zones, previous research has shown soil temperature differences of 2 to 4.5°C among different soil types within the same field (Barr et al., 2000).

The corn emergence data from the first planting date in IL-12, which is representative of early corn planting in Illinois, suggested that deep seeding in zones predicted to be relatively dry when soil moisture was adequate resulted in emergence delays. The soil moisture content at which deep seeding is warranted was likely not observed during the generally wet conditions experienced during the 2014 and 2015 growing seasons. In IL-11, the dry landscape zones consisted mostly of fine sand soils. Deep seeding in these relatively dry landscape zones did not result in evident improvements in terms of emergence patterns and grain yield. These fine sand soils are an example of soils that tend to be much drier than typical soils in the U.S. Corn Belt and little can be done to ameliorate the effects on plant growth due to their characteristically low soil moisture capacity and soil fertility.

In Illinois, corn producers aim to start planting operations as early as mid-April (Nafziger, 2009; Sacks et al., 2010). Early planting is usually seen as advantageous since longer-season corn varieties, which tend to yield more than shorter-season varieties, can be planted (Nafziger, 2009). However, constraints to early planting often seen in the U.S. Corn Belt include excessive soil moisture and lower temperatures in April (Sacks et al., 2010). More often than not, corn producers wait for soils to dry and temperatures to increase in order to start planting operations. In the last two decades in Illinois, corn producers have planted as early as the 13th week of the year (which includes part of the first week of April) only during the 2012 growing season (Fig. 4.1). However, this was due to a historical weather anomaly that brought warm temperatures and low precipitation early in the season (Mallya et al., 2013). Corn planting progress of over 10% in Illinois has been observed by the 15th week of the year (11 to 18 April) in 5 out of the last 20 growing seasons (Fig. 4.1). By the 17th week of the year (28 April to 1 May), corn planting progress of over 25% was observed in 15 out of the last 20 growing seasons (Fig. 4.1). In addition, over 20% of fields in Illinois have been rated with low topsoil moisture in 6 out of the past 20 years after the 16th week of the year (18 to 25 April) (Fig. 4.2). Considering these corn planting trends of the past 20 years, and acknowledging that soil moisture during planting operations has been commonly adequate for most fields in Illinois, it is likely that corn producers could benefit from varying seeding depths between shallow and standard seeding depths during moist years, and from varying seeding depths between deep and standard seeding depths during dry years such as 1997, 2000, 2001, 2005, 2007, or 2012 (Fig. 4.2). It is also likely that fields with greater elevation ranges and more prominent topographic features could benefit from the application of shallow, standard, and deep seeding depths during all growing seasons due to more evident soil water distribution patterns. However, until soil moisture at the seeding depth can be measured at a high spatial resolution within fields using the planting equipment, the application of variable seeding depth depends on *a priori* management zones that predict how water distributes within a field based on elevation, or on previous knowledge and intuition about the fields by corn producers.

This study chose to conduct the experiments on commercial corn fields in collaboration with corn producers for several reasons. Most prominently, the testing of fields distributed across larger geographical areas where university resources are limited or would not have been feasible to transport university equipment, the testing of variability faced by corn producers in their own fields and using their own machinery, and the testing of seeding depths over larger field areas instead of using the more common small test plots. Although agricultural research has traditionally been conducted on research stations, the expectation that results from small-scale plots translate to large-scale agricultural producers has not always been met with success (Mutsaers et al., 1997).

The application of variable seeding depth takes into account the same decision process currently used by corn producers. Corn producers balance the objective to start the planting operations as early as possible in the season at a seeding depth where the soil moisture is adequate but shallow enough to the soil surface to benefit from warmer temperatures. Antecedent precipitation, precipitation amounts, and air temperatures are useful guides to decide when to start corn planting operations. Most of the fields tested in this experiment had precipitation in the 7-d period before planting, and shortly after planting operations. When corn producers face a dry forecast, having the possibility to apply variable seeding depth would give them the option to plant corn seeds deeper in areas in which soils dry faster, such as on field ridges or soils with higher sand content or erodibility potential. If planting equipment in the near future integrates soil moisture sensors, corn producers may also be able to make more informed decisions about their chosen seeding depths.

FIGURES

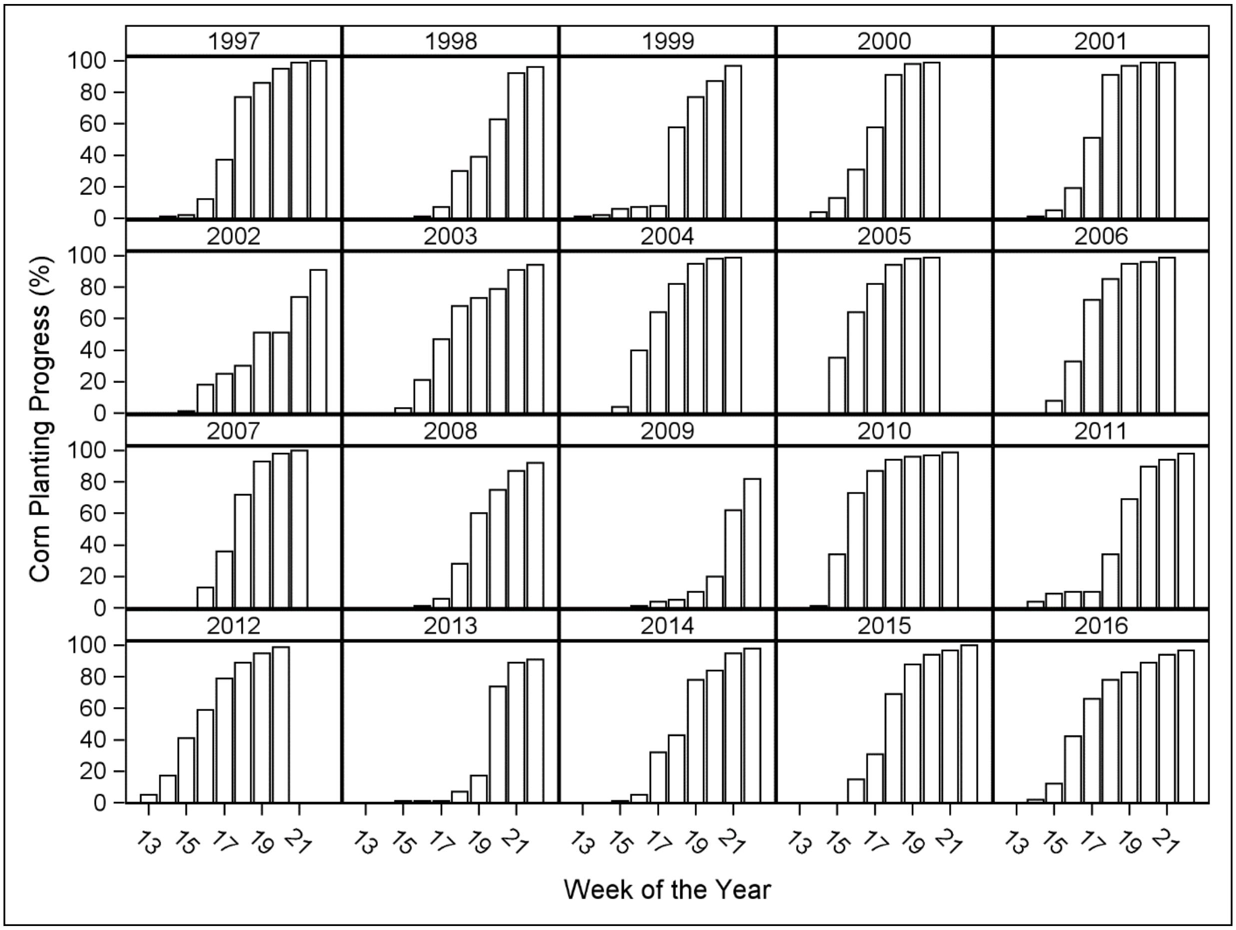


Fig. 4.1. Corn planting progress from 1997 to 2016 in Illinois. Week of the year starts at week no. 13 (30 March to 3 April) and ends in week no. 22 (1 June to 6 June). Data reported by the USDA National Agricultural Statistics Service.

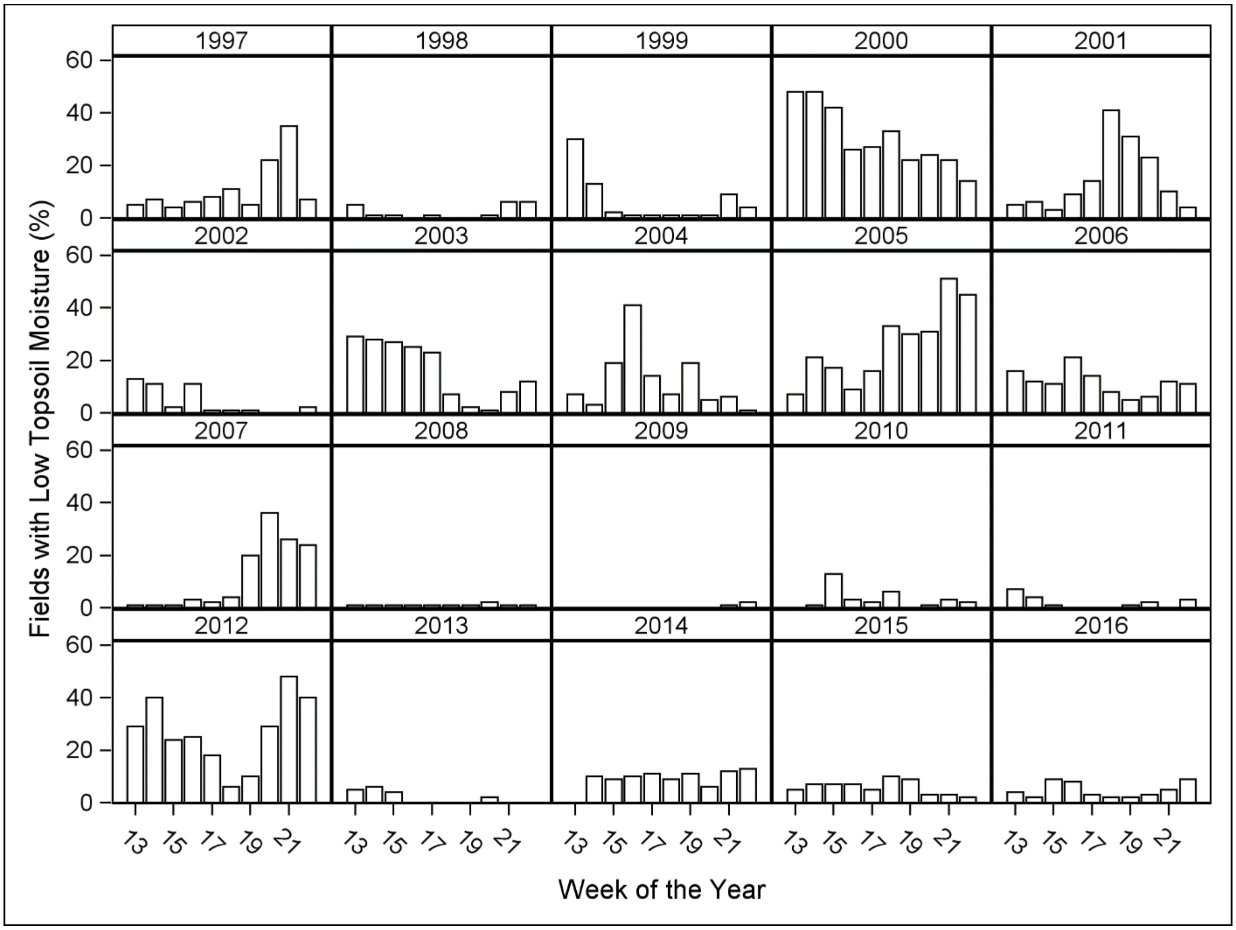


Fig. 4.2. Low topsoil moisture rating from 1997 to 2016 in Illinois. Week of the year starts at week no. 13 (30 March to 3 April) and ends in week no. 22 (1 June to 6 June). Data reported by the USDA National Agricultural Statistics Service.

REFERENCES

Barr, A., M. Bennett, and J. Cardina. 2000. Geographic information systems show impact of field placement on sh2 sweet corn stand establishment. HortTechnology 10:341-350.

Boomsma, C.R., J.B. Santini, M. Tollenaar, T.J. Vyn. 2009. Maize morphophysiological responses to intense crowding and low nitrogen availability: An analysis and review. Agron. J. 101:1426-1452.

Gupta, S.C., E.C. Schneider, and J.B. Swan. 1988. Planting depth and tillage interactions on corn emergence. Soil Sci. Soc. Am. J. 52:1122-1127.

Hodgen, P.J. 2007. Individual corn plant nitrogen management. Ph.D. dissertation, University of Nebraska, Lincoln, NE.

Kovács, P., and T.J. Vyn. 2014. Full-season retrospectives on causes of plant-to-plant variability in maize grain yield response to nitrogen and tillage. Agron. J. 106:1746-1757.

Mallya, G., L. Zhao, X.C. Song, D. Niyogi, and R.S. Govindaraju. 2013. 2012 Midwest drought in the United States. J. Hydrol. Eng. 18:737-745.

Martin, K.L., P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal, R.W. Mullen, K. Desta, S.B. Phillips, J.B. Solie, M.L. Stone, O. Caviglia, F. Solari, A. Bianchini, D.D. Francis, J.S. Schepers, J.L. Hatfield, and W.R. Raun. 2005. Plant-to-plant variability in corn production. Agron. J. 97:1603-1611.

Mutsaers, H.J.Z., G.K. Weber, P. Walker, and N.M. Fischer. 1997. A field guide for on-farm experimentation. IITA/CTA/ISNAR.

Nafziger, E.D., P.R. Carter, and E.E. Graham. 1991. Response of corn to uneven emergence. Crop Sci. 31:811-815.

Nafziger, E.D. 2009. Corn. Illinois Agronomy Handbook. Univ. Illinois Coop. Ext. Serv., Urbana-Champaign, pg. 91-112.

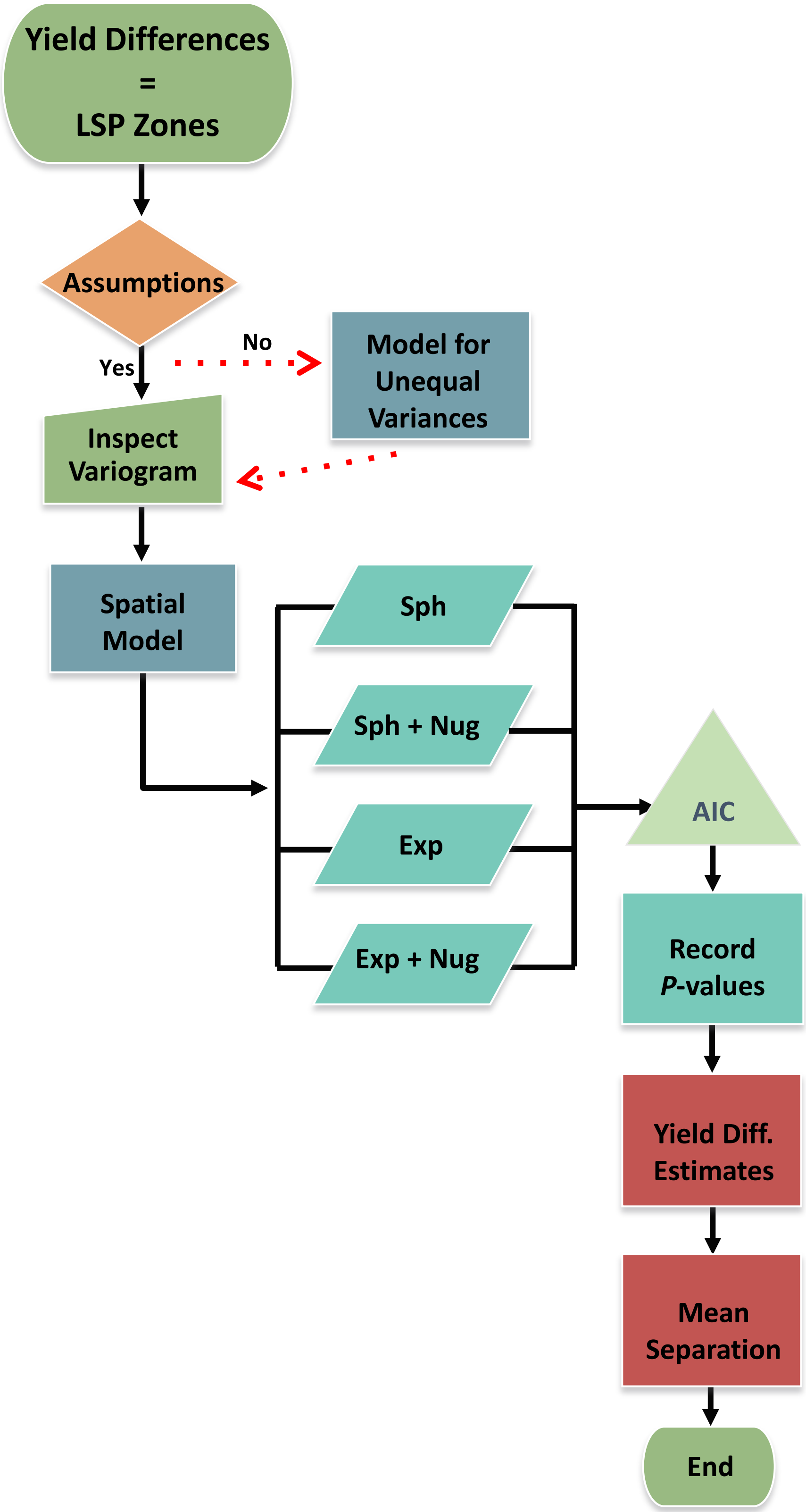
Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty. 2010. Crop planting dates: an analysis of global patterns. Glob. Ecol. Biogeogr. 19:607-620.

APPENDIX A: SAS CODE FOR AUGMENTED FACTORIAL

```
* Adding 'control' and 'trt' columns to dataset;
data yield;
     set yield;
          if treatment = 8 then contr_vs_trt = 'control';
          else contr_vs_trt = 'trt';
run;

* Augmented factorial with mean separation;
* Mean separation provided by mult macro;
* Mult macro available at https://www.uni-
hohenheim.de/bioinformatik/ beratung/toolsmacros/sasmacros/mult.sas;
proc mixed data = yield;
where season = 1; * Each season was analyzed individually;
     class block contr_vs_trt source timing;
          model yield_metric =
                              contr_vs_trt
                              contr_vs_trt*source
                              contr_vs_trt*timing
                              contr_vs_trt*source*timing;
          random block;
          lsmeans  contr_vs_trt        / pdiff;
          *lsmeans  contr_vs_trt*source / pdiff;
          *lsmeans  contr_vs_trt*timing / pdiff;
          *lsmeans  contr_vs_trt*source*timing / pdiff;
          %mult(trt=contr_vs_trt, alpha=0.10);
run;
```

APPENDIX B: DATA ANALYSIS WORKFLOW FOR CHAPTER 2



APPENDIX C: WITHIN-ROW PLANT-TO-PLANT VARIABILITY OF CORN

Many research efforts have been dedicated to study the plant-to-plant variability found in corn fields (Martin et al., 2005; Hodgen, 2007; Boomsma et al., 2009; Kovács and Vyn, 2014). It has been hypothesized by others that the plant-to-plant variability could be a result of uneven emergence, lack of seeding depth uniformity, soil crusting, soil clods or residue interfering with seed placement, and non-uniform soil moisture, among other factors (Martin et al., 2005).

This study attempted to find out whether plant-to-plant variability could be reduced if seeding depth of corn was changed based on landscape zones that present relatively drier or wetter soil conditions. Among other data, Chapter 3 reported the mean days to emergence, stalk diameter, and grain weight plant^{-1} in field IL-11, and stalk diameter and grain weight plant^{-1} in field IL-12.

This appendix presents the raw data behind the means for each of the rows that were measured for emergence, stalk diameter, and grain weight plant^{-1} in fields IL-11 and IL-12 during the 2015 growing season. The materials and methods for the emergence, stalk diameter, and hand harvest procedures are described in Chapter 3. For simplicity, only three out of the four replications in IL-12 are shown.

Corn emergence in IL-11 started 14 days after planting operations and was mostly completed 23 days after planting operations (Fig. C.1). Ideally, corn plants should emerge at about the same time, particularly along short distances like the distance sampled in IL-11. However, an emergence period of 5 to 11 days was observed in the majority of the sampling areas, with the seeds from the shallow depth presenting the most sporadic emergence patterns (Fig. C.1). Uneven corn emergence can result in yield losses (Nafziger et al., 1991).

The within-row stalk diameters measured in IL-11 presented more variability in the dry zones for all seeding depths, as shown by the disperse data points (Fig. C.2). In addition, deep seeding in wet landscape zones also resulted in more disperse plant-to-plant stalk diameters for the second and third replications (Fig. C.2).

In general, the grain weight plant^{-1} data showed a large proportion of low-yielding plants in IL-11 (Fig. C.3), as was also described in Chapter 3. No particular combination of seeding depth and landscape zone was successful in reducing grain weight plant-to-plant variability, as shown by the dispersion of the data points (Fig. C.3).

The stalk diameters for each of the planting dates in field IL-12 are shown in Fig. C.4 to C.6. No major differences in corn stalk diameters are observed among the seeding depths in the wet and dry landscape zones for the first planting date (Fig. C.4). For the second and third planting date, the plants in the dry zones exhibited higher stalk diameters regardless of seeding depth (Fig. C.5 and C.6).

The majority of sampling zones for the first planting date in IL-12 presented some incidence of low-yielding plants, and in some cases a large dispersion of data points for the grain weight plant^{-1} data (Fig. C.7). The grain weight plant^{-1} for the second planting date in IL-12 showed that plants growing in wet zones had lower grain weights, particularly the plants from the deep seeding depth in the second replication (Fig. C.8). The grain weight plant^{-1} for the third planting date in IL-12 was lower for the plants in wet landscape zones, and dispersion of data points was also higher for the plants in wet landscape zones (Fig. C.9).

Corn producers strive to reduce plant-to-plant variability to achieve more uniform yield within their fields. Future research is needed to identify more precisely why the yield of plants adjacent to each other differs as much as they have been observed in this study and others.

FIGURES

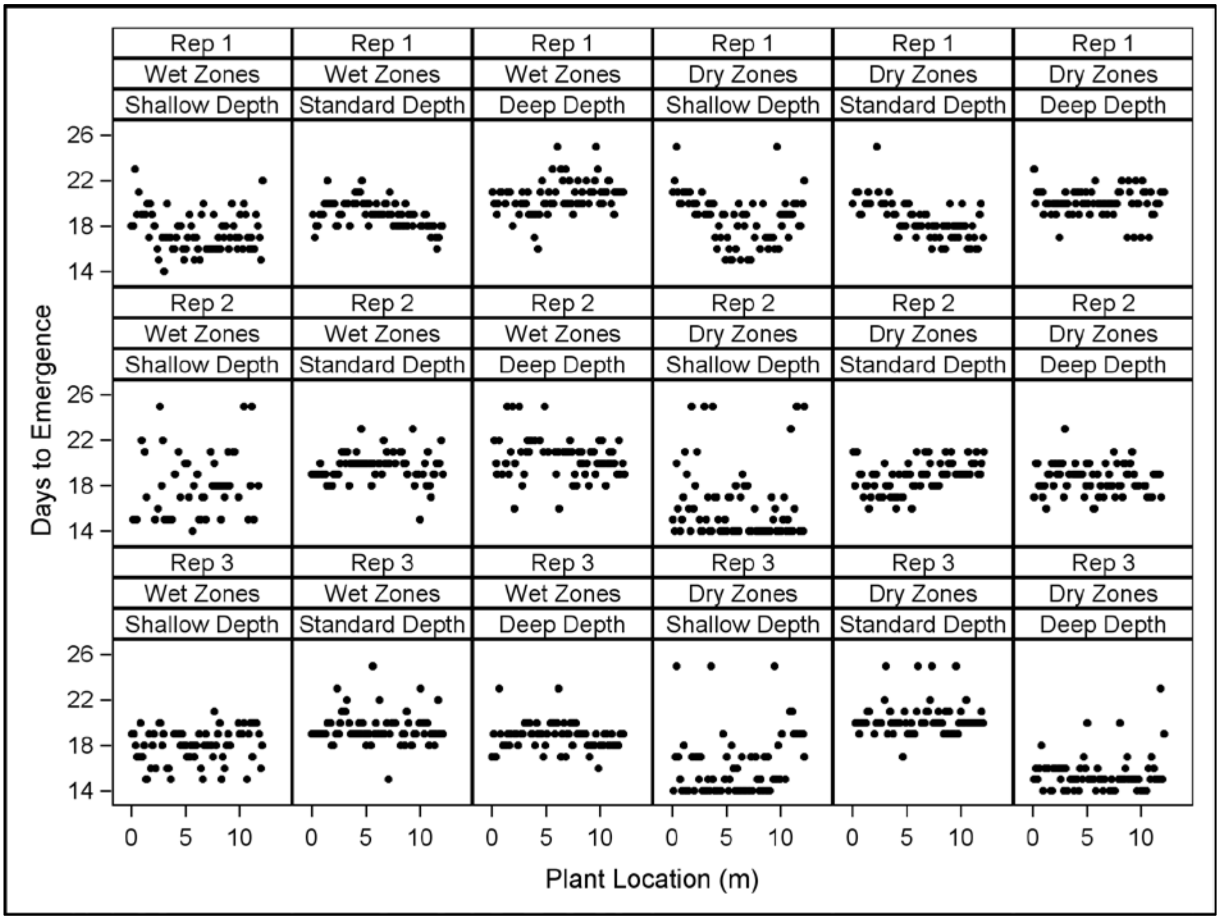


Fig. C.1. Individual plant emergence within a 12-m row in field IL-11 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The field was scouted daily until no more emerging seedlings were found.

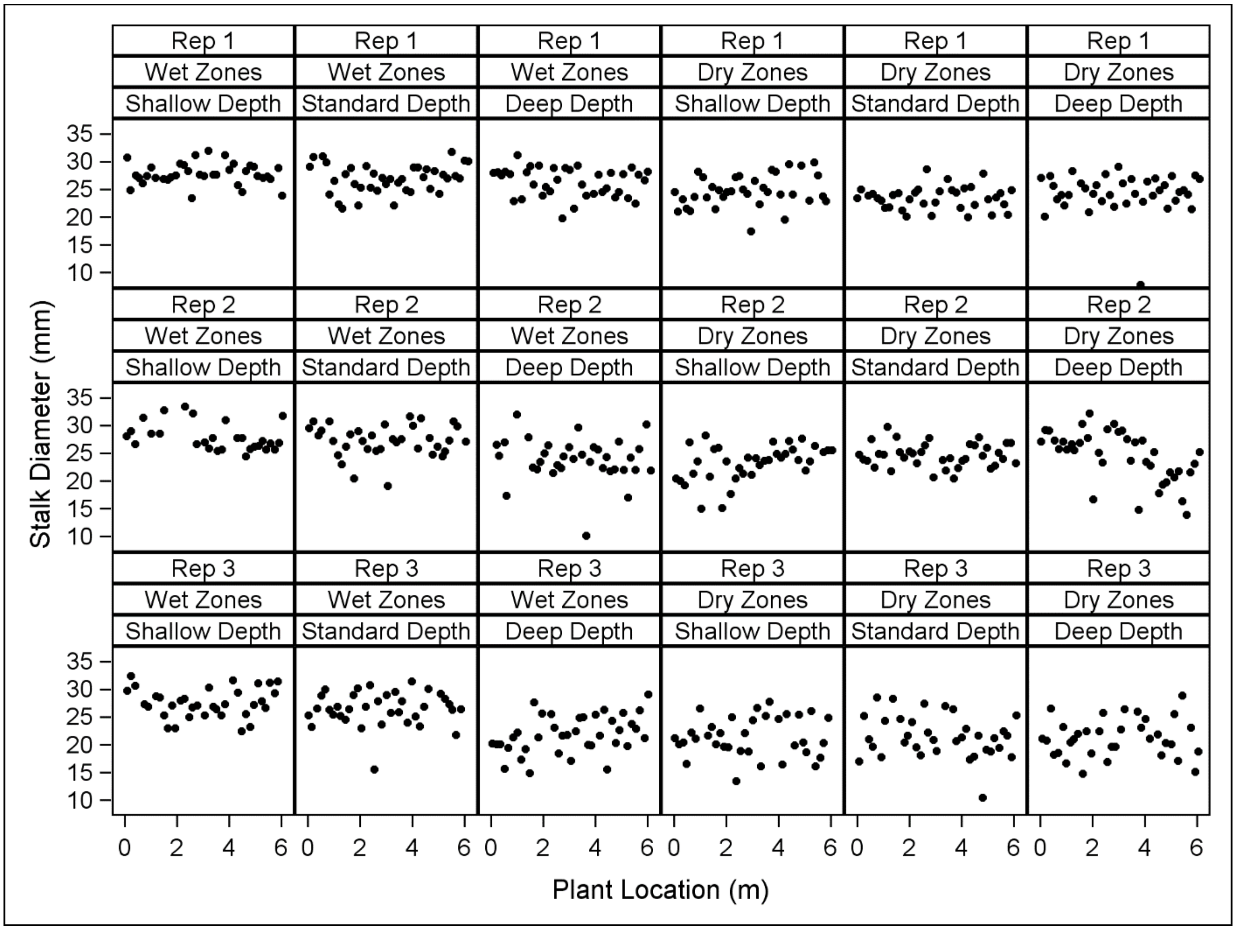


Fig. C.2. Individual stalk diameters within a 6-m row in field IL-11 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The stalk diameters were taken at growth stages R1-R2.

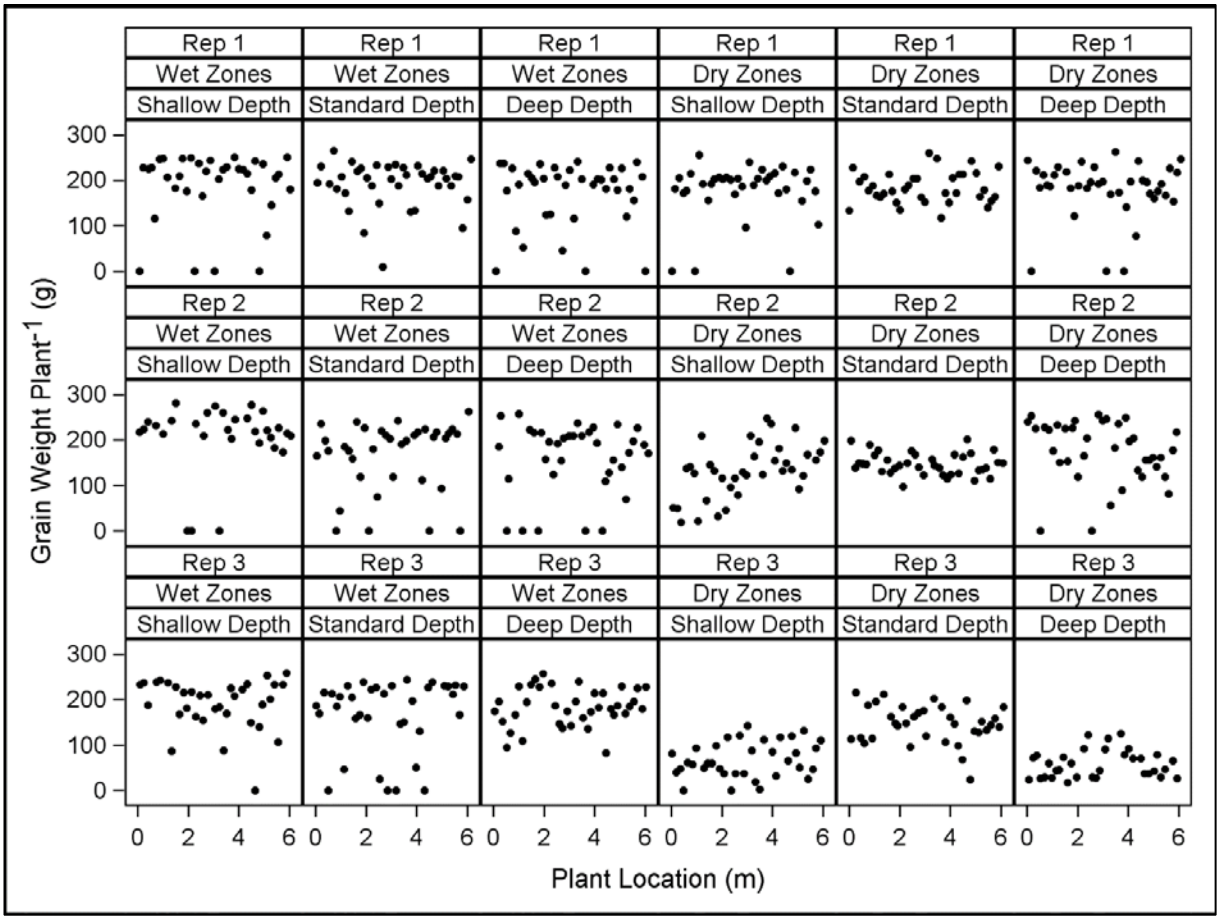


Fig. C.3. Grain weight plant^{-1} within a 6-m row in field IL-11 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The corn ears were hand harvested shortly after physiological maturity.

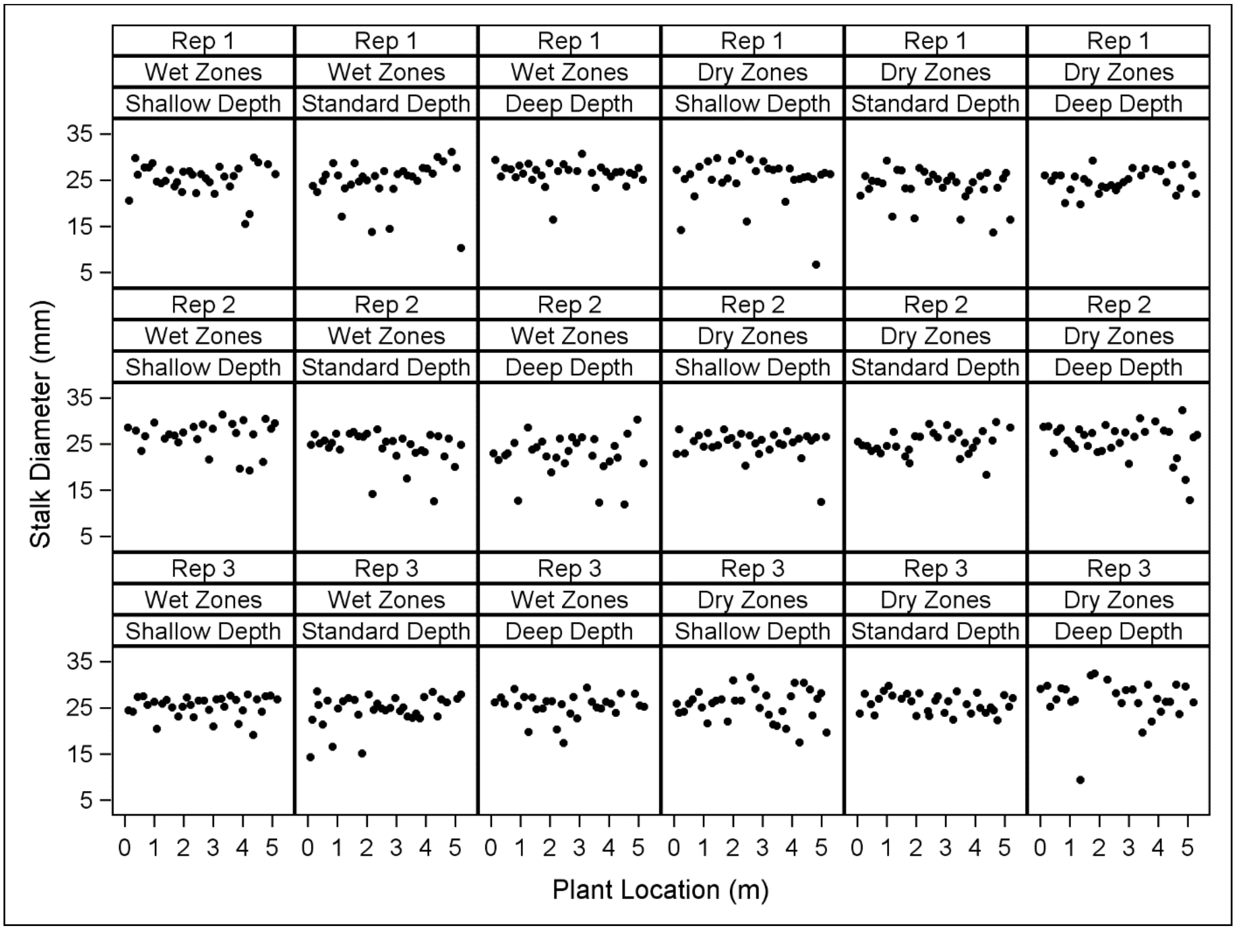


Fig. C.4. Individual stalk diameters within a 5-m row for the first planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The stalk diameters were taken at growth stages R1-R2.

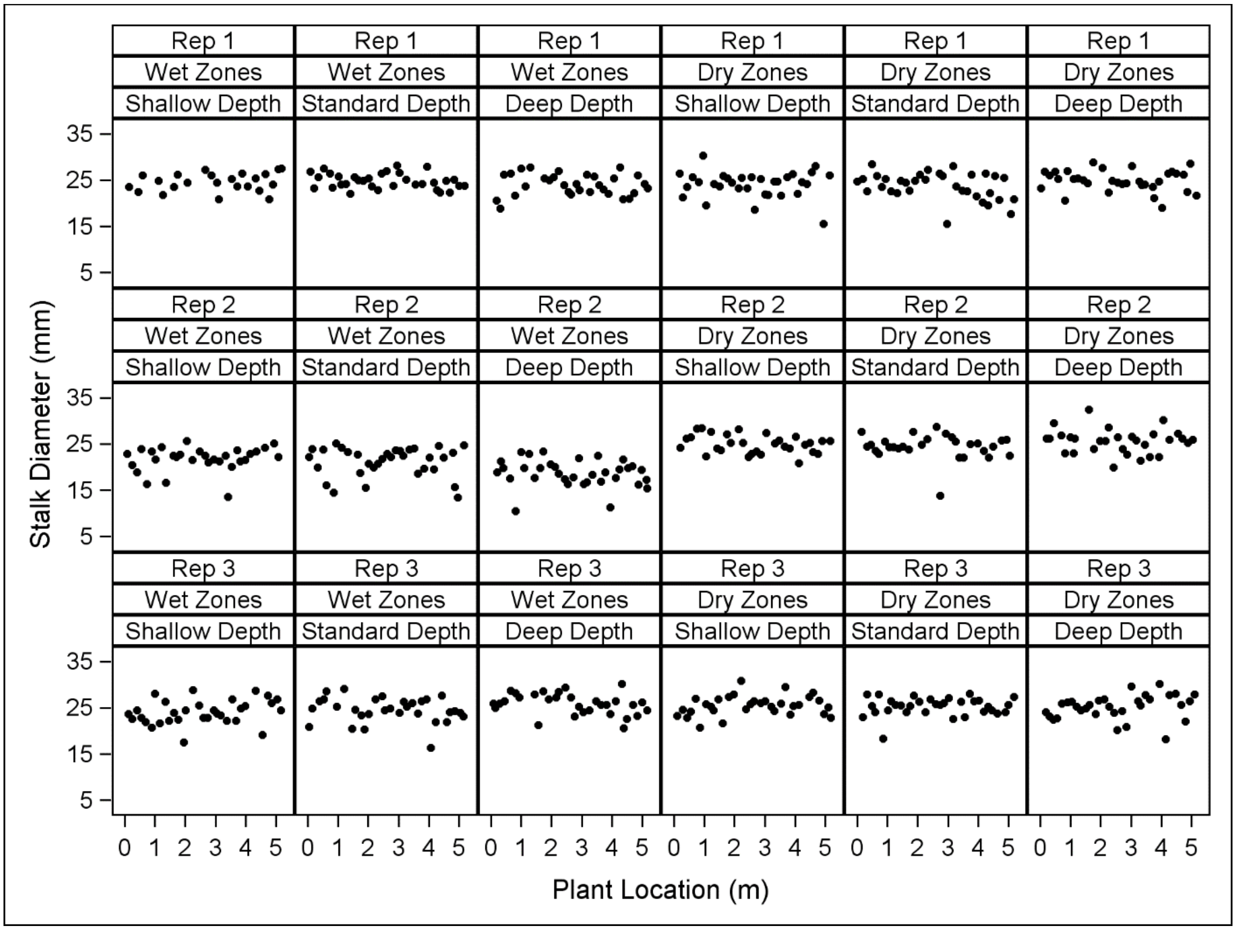


Fig. C.5. Individual stalk diameters within a 5-m row for the second planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The stalk diameters were taken at growth stages R1-R2.

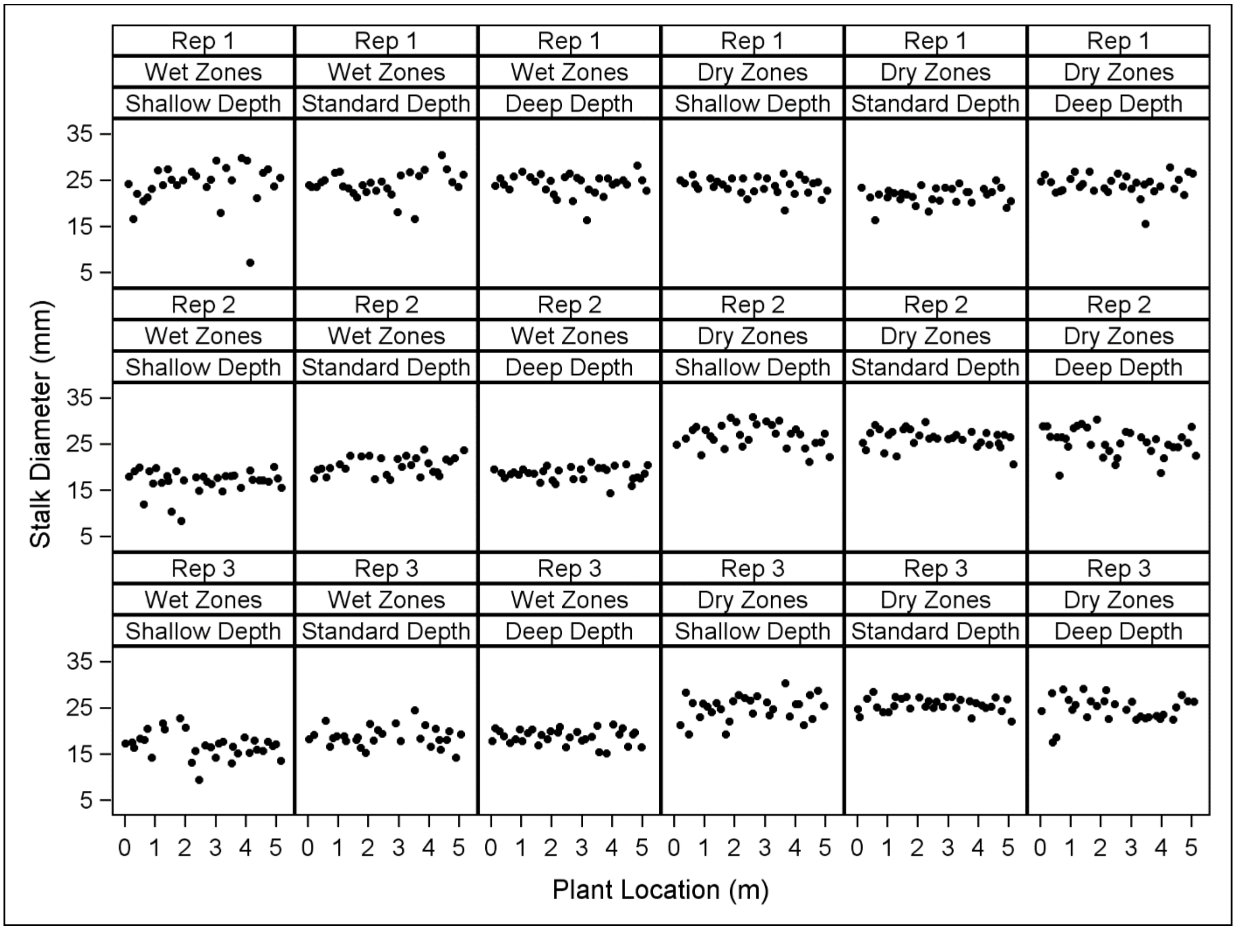


Fig. C.6. Individual stalk diameters within a 5-m row for the third planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The stalk diameters were taken at growth stages R1-R2.

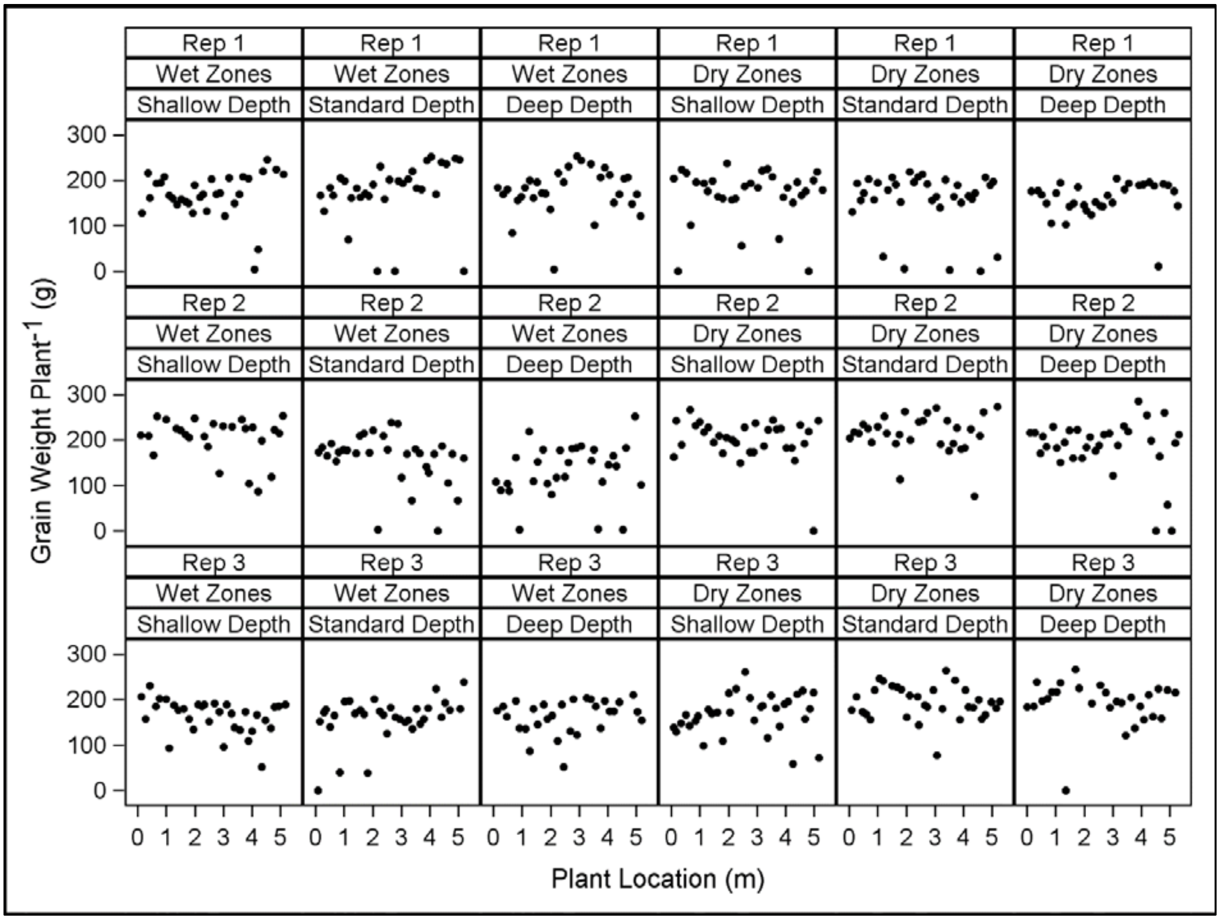


Fig. C.7. Grain weight plant^{-1} within a 5-m row for the first planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The corn ears were hand harvested shortly after physiological maturity.

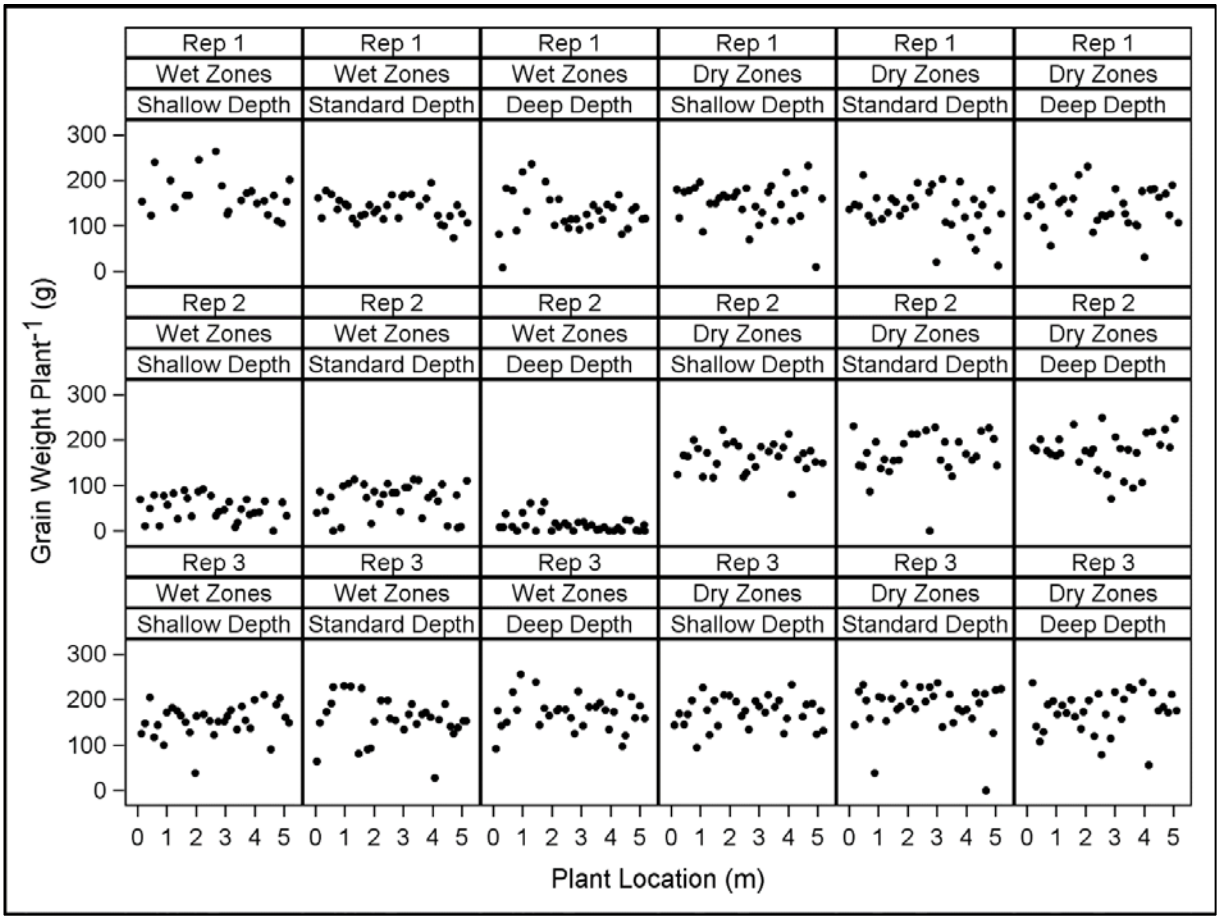


Fig. C.8. Grain weight plant^{-1} within a 5-m row for the second planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The corn ears were hand harvested shortly after physiological maturity.

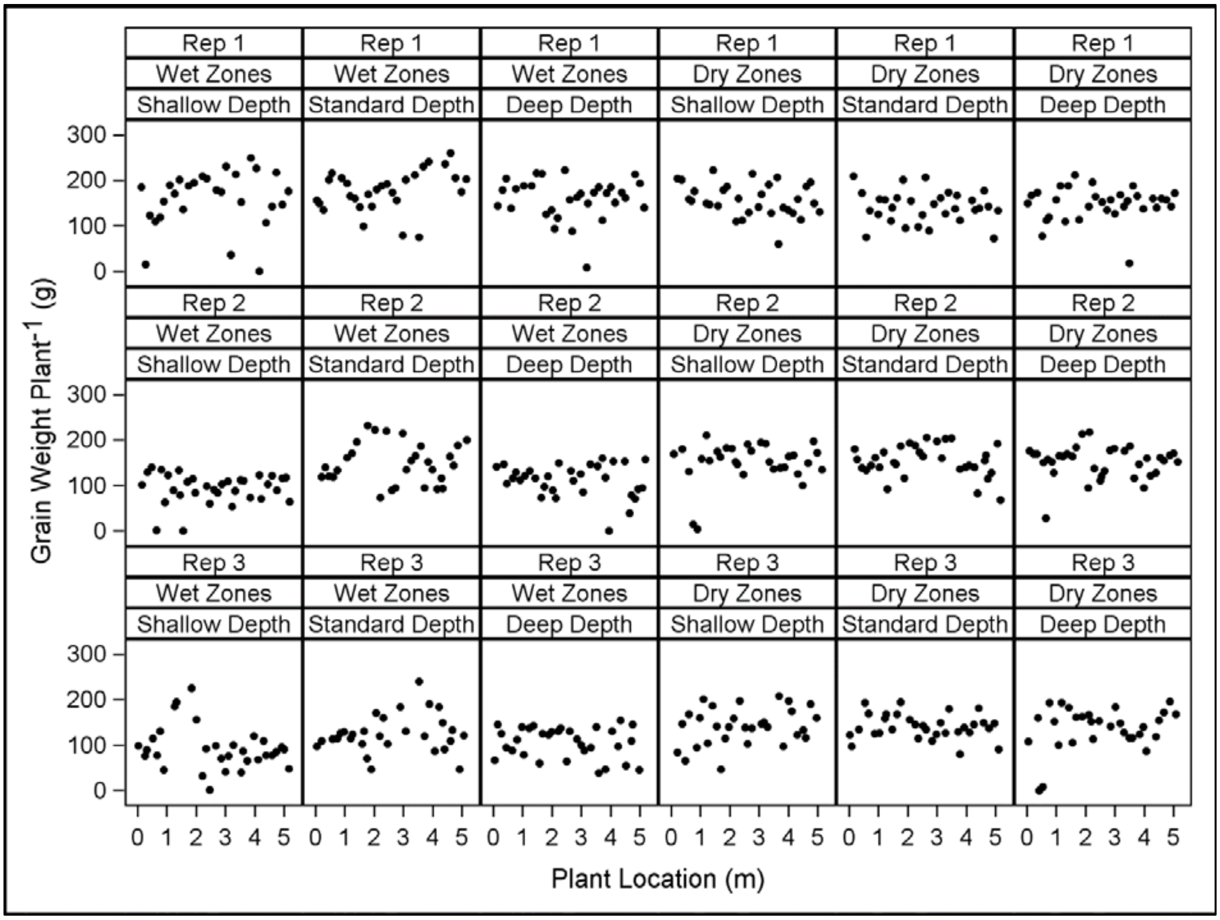


Fig. C.9. Grain weight plant^{-1} within a 5-m row for the third planting date in field IL-12 during the 2015 growing season as influenced by shallow, standard, and deep seeding depths in wet and dry landscape zones. The corn ears were hand harvested shortly after physiological maturity.

REFERENCES

Boomsma, C.R., J.B. Santini, M. Tollenaar, T.J. Vyn. 2009. Maize morphophysiological responses to intense crowding and low nitrogen availability: An analysis and review. Agron. J. 101:1426-1452.

Hodgen, P.J. 2007. Individual corn plant nitrogen management. Ph.D. dissertation, University of Nebraska, Lincoln, NE.

Kovács, P., and T.J. Vyn. 2014. Full-season retrospectives on causes of plant-to-plant variability in maize grain yield response to nitrogen and tillage. Agron. J. 106:1746-1757.

Martin, K.L., P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal, R.W. Mullen, K. Desta, S.B. Phillips, J.B. Solie, M.L. Stone, O. Caviglia, F. Solari, A. Bianchini, D.D. Francis, J.S. Schepers, J.L. Hatfield, and W.R. Raun. 2005. Plant-to-plant variability in corn production. Agron. J. 97:1603-1611.

Nafziger, E.D., P.R. Carter, and E.E. Graham. 1991. Response of corn to uneven emergence. Crop Sci. 31:811-815.

APPENDIX D: R CODE

DEVELOPMENT OF LANDSCAPE ZONES

Objective

- Group `TPI values` into four equally represented classes.
- Group `TPI values` into clusters using non-hierarchical clustering algorithm (k-means).

Packages

```
library(maptools)
library(lattice)
library(rgdal)
library(cluster)
library(parallel)
```

Data

```
utm15n <- "+init=epsg:32615"
LSP_values <- readGDAL("LSP_values_aoi.tif", p4s = utm15n)
```

Four landscape zones equally represented

```
# Cut range into 4 equal count classes
quantClassifier <- function(X) {
  cuts <- quantile(X, na.rm = T)
  classes <- findInterval(X, cuts, rightmost.closed = T)
  factor(classes)
}

# Assign classification
LSP_values@data <- within(LSP_values@data, {
  equal_count_classes <- quantClassifier(band1)
})

spplot(LSP_values, zcol = 2)
```

Equal interval cuts

```
LSP_values@data <- within(LSP_values@data, {
  equal_size_classes <- cut(band1, breaks = 4, labels = 1:4)
})

spplot(LSP_values, zcol = 2:3)
```

Clustering (k-means)

Exploring non-hierarchical classification with `k-means` algorithms. Evaluating 2 to 6 clusters.

```
max_cl <- 6

# Exclude NAs
sel <- !is.na(LSP_values$band1)

# bands names
```

```
band <- paste("cl", 2:max_cl, sep = "")

# Random seed
set.seed(1)

# Clustering
km_LSP <- mclapply(2:max_cl, function(i) {
  kmeans(LSP_values$band1[sel], centers = i)
})

# Variance reduction
res <- data.frame(cl = 1:max_cl, RV = 1, dif = 0)
res <- within(res, {
  RV[-1] <- sapply(km_LSP, function(X) {
    X$tot.withinss/X$totss
  })
  dif <- c(NA, abs(diff(RV)))
})

xyplot(RV ~ cl, res, type = "b")
res

# Select number of clusters
nzones <- 3

# Assigning classification
LSP_values@data <- within(LSP_values@data, {
  km_classes <- equal_count_classes
  km_classes[sel] <- as.factor(km_LSP[[nzones - 1]]$cluster)

  # Reorder
  km_classes <- reorder(km_classes, band1)
  km_classes <- factor(km_classes, labels = 1:nzones)
})

spplot(LSP_values, zcol = 2:4)
```

Saving to raster

```
LSP_values@data <- as.data.frame(apply(LSP_values@data, MARGIN = 2, as.numeri
c))
writeGDAL(LSP_values, "LSP_aoi.tif")
```

YIELD DATA CLEANING

Objective

- To clean problematic yield data points

Packages

```
library(lattice)
library(maptools)
library(rgdal)
```

Data

```
utm15n <- "+init=epsg:32615"
yields <- readShapePoints("yields_aoi.shp", proj4string = CRS(utm15n))

# Drop unused columns
names(yields) <- c('Distance', 'DryYield', 'TRT', 'REP')
yields@data <- within(yields@data, {
    REP <- as.factor(REP)
    TRT <- factor(TRT, levels = c("1", "21", "23", "3"))
    # 1 kilogram/hectare (kg/ha) = .0159 bushels/acre
    DryYield <- (DryYield / 0.0159) /1000
    pass <- as.factor(paste("T", TRT, "R", REP, sep = ""))
})
```

Screening for outliers

```
# Function
get_outliers <- function(X, k) {
  boxplot.stats(X, coef = k)$out
}

# By distance
bwplot(~ Distance, yields@data, coef = 3, pch = "|")
rm_dist <- with(yields@data, Distance %in% get_outliers(Distance, 3))
bwplot(~ Distance, yields@data, coef = 3, subset = !rm_dist, pch = "|")

# By yield
bwplot(~ DryYield, yields@data, coef = 3, pch = "|", subset = !rm_dist)
rm_yld <- with(yields@data, DryYield %in% get_outliers(DryYield[!rm_dist], 3)
)
spplot(yields,  zcol = "DryYield", scales = list(draw = T, y = list(rot = 90)
), subset = rm_yld,
       key.space = "right")
bwplot(~ DryYield, yields@data, coef = 3, subset = !rm_yld, pch = "|")
```

Plotting by treatment

```
spplot(yields,  zcol = "DryYield", scales = list(draw = T, y = list(rot = 90)
), subset = !rm_dist & !rm_yld,
       key.space = "right")
```

Saving to shapefile

```
writeSpatialShape(yields[!rm_dist & !rm_yld, ], "yields_aoi_cleaned")
showWKT(utm15n, "yields_aoi_cleaned.prj")
```

COMPUTING PAIRED DIFFERENCES

For a field closely aligned in east-to-west direction

Objective

- Estimate paired differences between seeding depth treatments (shallow and deep seeding depths) and control (standard seeding depth)

Packages

```
library(maptools)
library(lattice)
library(tidyr)
library(rgdal)
```

Data

```
utm15n <- "+init=epsg:32615"
field <- readShapeSpatial("yields_aoi_cleaned.shp", proj4string = CRS(utm15n)
)
```

5-m grid approach

Each treatment pass is cut into 5-m bins along the longest side of the field. Then, it is computed the average of the data points included in each bin-pass combination. First, coordinates must be rotated to get aligned to the longest side of the field.

```
# Drop 3rd coordinate
if (ncol(field@coords) == 3 | nrow(field@bbox) == 3) {
  field@coords <- field@coords[, -3]
  field@bbox <- field@bbox[-3, ]
  field$coords_x3 <- NULL
}

# Calculate the pivoting coordinate
pivot <- colMeans(field@coords)

# Approximate the angle of rotation
rot <- data.frame(angle = seq(1, 3, by = 0.1), delta = 0)

for (i in rot$angle) {
  tmp <- elide(field, rotate = i, center = pivot)
  rot <- within(rot, delta[angle == i] <- diff(bbox(tmp)[2, ]))     # NS = 1,
EW = 2
}
xyplot(delta ~ angle, rot)
angle <- with(rot, angle[delta == min(delta)])

# Rotate the coordinates
field_rot <- elide(field, center = pivot, rotate = angle)
spplot(field_rot, zcol = "DryYield")
```

Once rotated the bins are computed.

```
# Defining bins and getting the X coordinate for each bin
bin_size <- 5
bb <- bbox(field_rot)
bin_lim <- seq(bb[1, 1] - bin_size/2, bb[1, 2] + bin_size/2, by = bin_size)
X_coords <- data.frame(bin = 1:length(bin_lim), X = bin_lim + bin_size/2)

# Find points in each bin
field_rot@data <- within(field_rot@data, {
  bin <- findInterval(field_rot@coords[, 1], bin_lim)
  Y <- field_rot@coords[, 2]
})

# Average DryYield and Y coordinate within each bin (add landscape zones or
other covariates)
field_rot_paired <- aggregate(cbind(Y, DryYield) ~ TRT + REP + bin,
                              field_rot@data, mean)

# Add X_coordinates
field_rot_paired <- merge(field_rot_paired, X_coords, by = "bin")
coordinates(field_rot_paired) <- ~ X + Y
proj4string(field_rot_paired) <- utm15n

# Back-rotation
field_paired <- elide(field_rot_paired, center = pivot, rotate = -angle)
field_paired@data <- within(field_paired@data, {
  X <- field_paired@coords[, 1]
  Y <- field_paired@coords[, 2]
})
proj4string(field_paired) <- utm15n

spplot(field_paired, zcol = 'DryYield')

# Save to shapefile
writeSpatialShape(field_paired, 'yields_aoi_paired.shp')
showWKT(utm15n, 'yields_aoi_paired.prj')
```

Once points are paired along the longest side, the differences between treatments are computed for each bin and rep combination.

```
# Define pairs
field_rot_paired@data <- within(field_rot_paired@data, {
  levels(TRT) <- c("T1", "T21", "T23", "T3")
})
# Compute differences between paired treatments
dif <- spread(field_rot_paired@data, TRT, DryYield)
dif <- within(dif, {
  T1_vs_T21 <- dif[, 3] - dif[, 4]
  T3_vs_T23 <- dif[, 6] - dif[, 5]
  T1_vs_T3 <- dif[, 3] - dif[, 6]
})
dif <- dif[, -c(3:6)]
```

```r
# Excluding outliers defined by boxplot
bwplot(~ T1_vs_T21, dif, coef = 3, pch = "|")
bwplot(~ T3_vs_T23, dif, coef = 3, pch = "|")
bwplot(~ T1_vs_T3, dif, coef = 3, pch = "|")
outs <- with(dif, {
  out <- apply(cbind(T1_vs_T21, T3_vs_T23, T1_vs_T3), 2, get_outliers, k = 3)
  !c(T1_vs_T21 %in% out$T1_vs_T21 | T3_vs_T23 %in% out$T3_vs_T23 | T1_vs_T3 %
in% out$T1_vs_T3)
})
dif <- dif[outs, ]
```

Finally, in order to relate the differences with spatial covariates (landscape zones), the response (difference between treatments) is assigned to the middle coordinate of the pairs.

```r
# Add coordinates to attribute table
field_rot_paired@data <- within(field_rot_paired@data, {
  X <- field_rot_paired@coords[, 1]
  Y <- field_rot_paired@coords[, 2]
})

# Attach differences
dif <- merge(field_rot_paired@data, dif, by = c("bin", "REP"))

# Average coordinates for pair T1 vs T21 (shallow vs. standard seeding depth)
sel_T1_vs_T21 <- with(dif, TRT == "T1" | TRT == "T21")
dif_T1_vs_T21 <- aggregate(cbind(X, Y, T1_vs_T21) ~ bin + REP, dif[sel_T1_vs_
T21,], mean)

# Average coordinates for pair T3 vs T23 (deep vs. standard seeding depth)
sel_T3_vs_T23 <- with(dif, TRT == "T3" | TRT == "T23")
dif_T3_vs_T23 <- aggregate(cbind(X, Y, T3_vs_T23) ~ bin + REP, dif[sel_T3_vs_
T23,], mean)

# Average coordinates for pair T1 vs T3 (shallow vs. deep seeding depth)
sel_T1_vs_T3 <- with(dif, TRT == "T1" | TRT == "T3")
dif_T1_vs_T3 <- aggregate(cbind(X, Y, T1_vs_T3) ~ bin + REP, dif[sel_T1_vs_T3
,], mean)

# Combine data frames
names(dif_T1_vs_T21)[5] <- "dif"
names(dif_T3_vs_T23)[5] <- "dif"
names(dif_T1_vs_T3)[5] <- "dif"

dif_all <- rbind(
  cbind(pair = "T1_vs_T21", dif_T1_vs_T21),
  cbind(pair = "T3_vs_T23", dif_T3_vs_T23),
  cbind(pair = "T1_vs_T3", dif_T1_vs_T3)
)
```

```
# Back-rotation
coordinates(dif_all) <- ~ X + Y
field_dif <- elide(dif_all, center = pivot, rotate = -angle)
proj4string(field_dif) <- utm15n
spplot(field_dif, zcol = 4)

# Save to shapefile
writeSpatialShape(field_dif, 'yields_aoi_diff.shp')
showWKT(utm15n, 'yields_aoi_diff.prj')
```

Visualizing results

```
# Paired Yields
spplot(field_paired, zcol = 'DryYield')

# Differences
spplot(field_dif, zcol = 'dif', main = "T1_vs_T21", subset = field_dif$pair =
= "T1_vs_T21")
spplot(field_dif, zcol = 'dif', main = "T3_vs_T23", subset = field_dif$pair =
= "T3_vs_T23")
spplot(field_dif, zcol = 'dif', main = "T1_vs_T3", subset = field_dif$pair ==
"T1_vs_T3")

# Plot passes
xyplot(DryYield ~ X | REP, groups = TRT, field_paired@data, type = "l",
       layout = c(1, 4), subset = TRT %in% c(1, 21), auto.key=T)

xyplot(DryYield ~ X | REP, groups = TRT, field_paired@data, type = "l",
       layout = c(1, 4), subset = TRT %in% c(3, 23), auto.key=T)

xyplot(DryYield ~ X | REP, groups = TRT, field_paired@data, type = "l",
       layout = c(1, 4), subset = TRT %in% c(1, 3), auto.key=T)
```