ABSTRACT

Surface crop residues lower soil temperatures delaying emergence of corn (Zea mays L.) under no-till tillage systems in the northern Corn Belt. This study evaluates the use of planting depth as a management tool to overcome the disadvantages of cool temperature under residue covered soils. Growth chamber experiments evaluated the effects of planting depths, ranges of soil temperatures, and soil matric potentials on corn emergence. The seeding medium was aggregates of Webster clay loam (fine-loamy, mixed, mesic Typic Haplauolls). Deep planting (75 mm) delayed emergence from 2.8 to 18 d as the soil temperatures decreased from ranges of 15 to 25 °C and 5 to 15 °C. Seed zone growing degree days (GDD) needed to achieve 75% emergence increased with an increase in planting depth and a decrease in soil matric potential. Relationships of corn emergence vs. seed zone GDD needed to achieve 75% corn emergence at various planting depths were tested in the field for three planting depths, three tillage and three surface residue conditions during 1984 and 1985. Predicted time to 75% corn emergence was within 2 d of the field-measured values for three planting depths, and seven tillage and surface residue conditions, over two seasons. Simulation studies were conducted to predict the effects of tillage, planting depth, and planting date on the probability of obtaining 75% corn emergence within 14 d of planting. Input data for simulation studies included 10 to 20 yr of daily maximum and minimum air temperatures from Morris, MN and Lexington, KY. Tillage treatments included moldboard plow, no surface residue, and no-till surface residues. Reducing the planting depth from 50 to 25 mm advanced the planting date within 14 d of planting. Input data for simulation studies included field-measured values for three planting depths, and seven tillage and surface residue conditions during 1984 and 1985. Predicted time to 75% corn emergence was within 2 d of the field-measured values for three planting depths, and seven tillage and surface residue conditions, over two seasons. Simulation studies were conducted to predict the effects of tillage, planting depth, and planting date on the probability of obtaining 75% corn emergence within 14 d of planting. Input data for simulation studies included 10 to 20 yr of daily maximum and minimum air temperatures from Morris, MN and Lexington, KY. Tillage treatments included moldboard plow, no surface residue, and no-till surface residues. Reducing the planting depth from 50 to 25 mm advanced the planting date from 2 d to several weeks, depending on the weather, soil matric potential, and tillage-surface residue conditions. When soil water is nonlimiting, the effect of cooler temperatures on corn emergence under a no-till tillage system (with surface residues) can be compensated for by reducing the planting depth by 25 mm or less from that of average planting depth under conventional tillage systems.

CONSERVATION TILLAGE practices in the U.S. northern Corn Belt have often delayed corn emergence, slowed corn seedling growth, reduced final population, and sometimes reduced corn yield (Olson and Schoeberl, 1970; Griffeth et al., 1973; Olson and Horton, 1975). Poor crop performance has been attributed to depressed seed zone temperatures due to surface residue cover under conservation tillage systems. Philips (1984) showed that delayed planting frequently reduces corn yields in the Corn Belt. In Wisconsin, Imholte and Carter (1987) found that delayed planting decreased corn grain yields, and yields of both conventional and no-tillage planted corn were generally highest when planting was completed by early May.

In noncrusting soils, corn emergence from a loosened seedbed is a function of soil temperature and matric potential, which in turn determines the rate of germination and subsequent shoot growth. The effects of soil temperature and matric potential on corn emergence have been documented in an earlier paper (Schneider and Gupta, 1985). To determine the influence of planting depth on these relationships is a twofold problem. First, the effect of depth on corn emergence must be evaluated independently of other soil physical parameters. Second, the effect of the temperature and water environment to which the seed is exposed, and the subsequent effect on emergence must be evaluated.

Alessi and Power (1971) showed that delay in time to corn emergence at a constant temperature of 13.3 °C was about 1 d for each 10-mm increase in planting depth. However, at constant temperatures of 20 °C or higher, no emergence response to planting depth was reported. To achieve 80% emergence, approximately 68 growing degree days (GDD) were required when water was not limiting and temperatures were above 13.3 °C, regardless of planting depth. However, at the shallowest field planting depth (25 mm), both number of days and GDD required for 80% emergence were greatly increased when soil water was limiting.

Planting depth has been incorporated into emergence models developed for several crops (Lindstrom et al., 1976; Sepaskhah and Ardekani, 1978). In the winter wheat (Triticum aestivum L.) emergence model presented by Lindstrom et al. (1976), the emergence rate progressively decreased with lowering of water potential, lowering of temperature from 25 °C, or with increase in planting depth. Barley (Hordeum vulgare L.) emergence in soil at several soil matric potentials was delayed about 1 d for each 20-mm increase in planting depth (Sepaskhah and Ardekani, 1978). At both the driest soil matric potential (—3000 kPa) and the deepest planting depth (120 mm), final plant populations were reduced.

The emergence of corn from deep planting depths is dependent on the mechanical ease with which the epicotyl can grow through the soil towards the surface, and the plant length achieved prior to splitting of the coleoptile sheath. Grant and Buckle (1974) reported that the length of the plumule (the combined length of the mesocotyl and coleoptile) prior to splitting of the coleoptile sheath can reach 150 mm with optimum seedbed conditions, but may reach only 50 mm under adverse conditions.

The objectives of this study were to: (i) determine the effects of planting depth on rate of corn emergence in a controlled environment over a range of soil temperatures and matric potentials, (ii) determine the effects of planting depth on rate of corn emergence in the field for several tillage systems and residue treatments, and (iii) evaluate planting depth as a management tool to overcome the negative effect (cooler temperatures) of conservation tillage on rate of corn emergence.

S.C. Gupta and J.B. Swan, Dep. of Soil Science, 1991 Upper Buford Circle, Univ. of Minnesota, St. Paul, MN 55108; E.C. Schneider, Minnesota Dep. of Health, 717 Delaware St. S.E., Minneapolis, MN 55440. Contribution from the Dep. of Soil Science and the Minnesota Agric. Exp. Stn., Univ. of Minnesota. Paper no. 15637, Science Journal Series. Laboratory and field research were completed when the senior author was with the Soil and Water Management Res. Unit, USDA-ARS, St. Paul, MN. Received 24 Sept. 1987. *Corresponding author.

METHODS AND MATERIALS

Growth Chamber Study

Methodology and calculations used in this study are similar to that of Schneider and Gupta (1985), but measurements are restricted to one aggregate size distribution, two temperature levels, two soil matric potentials, and three planting depths. For each temperature level, treatments of planting depths were replicated three times.

Soil used was collected from the plow layer of Webster clay loam, air-dried, then sieved into several size fractions, which were recombined to produce a geometric mean diameter (GMD) of 3.6 mm. This aggregate size distribution was shown by Schneider and Gupta (1985) to provide favorable conditions for germination and emergence of corn. Each soil core consisted of two aluminum cylinders 76 mm long by 76 mm i.d. Each cylinder was placed on a ceramic plate and the aggregate mixture was added through a funnel. One of the cylinders (bottom) for each treatment was completely filled with the aggregate mixture and the other cylinder (top) was filled with enough soil to provide planting depths of 25, 50, or 75 mm. Aggregates in each cylinder were saturated overnight from the bottom under a 10- to 30-mm head of water and then desorbed in pressure extractors to obtain \( \psi \) of -10 and -500 kPa.

On each bottom cylinder the base was wrapped in plastic and three corn seed (Pioneer 3780, Pioneer Hi-Bred International, Inc., Johnston, IA) were placed with plumules facing upward on the exposed soil surface. The top cylinder was inverted onto a spatula and carefully slid into place atop the bottom cylinder. Top and bottom cylinders were taped together and covered with a clear polyethylene bag to minimize water loss.

Core assemblies were placed in a growth chamber set to a 14-h photoperiod. Air temperature fluctuation in the growth chamber during a 24-h cycle resembled a trapezoidal curve, with maximum and minimum temperatures, each being maintained for an 8-h period, and "ramp up" and "ramp down" periods of 4 h each occurring between maximum and minimum temperatures (Schneider and Gupta, 1985). Treatments were selected to produce a daily mean temperature of 10 and 20 °C with ranges of 5 to 15 °C and 15 to 25 °C, respectively. Because initial measurements showed <1 °C difference between air and soil temperatures, soil temperatures were assumed to be equal to air temperature.

Corn emergence in each core was monitored twice daily. At observation times, each core was examined by removing the plastic covering long enough to measure heights of emerged plants. After all plants in a core attained a minimum height of 100 mm, the core was removed from the growth chamber for determination of bulk density and gravimetric water content. During the core disassembly, the distance from the seed to the soil surface was measured to determine actual planting depth.

Emergence time in days was estimated for each plant using a linear regression of plant height vs. days after planting. Soil GDD accumulated from planting time to emergence were calculated using a variation of the relationship presented by Aspliau and Shaw (1972):

\[
GDD = \sum_{j=1}^{n} \frac{T_j - 10}{24} - 10 \quad 10 \leq T_i \leq 30
\]

where \( T_i \) is soil temperature at the \( i \)-th hour of the day, and \( j \) is the number of days since planting.

Field Experiment

Planting depth effects on corn emergence were studied during 1984 and 1985 in an ongoing tillage-residue field experiment at the University of Minnesota Experiment Station at Rosemount, MN, on a Waukegan silt loam (fine-silty, mixed, mesic Typic Hapludolls). Details of the experimental design have been described earlier (Gupta et al., 1983). The tillage and surface residue treatments and percent corn residue cover are presented in Table 1. Percent residue was measured within 2 wk after planting. Air temperatures at the 2-m height were recorded hourly, beginning immediately

Table 1. Corn residue cover in the field experiment.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>1984</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPNR</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>CHNR</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>NTNR</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>MPRI</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>MPSR</td>
<td>53</td>
<td>50</td>
</tr>
<tr>
<td>CHSR</td>
<td>73</td>
<td>46</td>
</tr>
<tr>
<td>NTSR</td>
<td>84</td>
<td>76</td>
</tr>
</tbody>
</table>

† MPNR = moldboard plow no residue, CHNR = chisel plow no residue, NTNR = no-till no residue, MPRI = moldboard plow residue incorporated, MPSR = moldboard plow surface residue, CHSR = chisel plow surface residue, NTSR = no-till surface residue.

Table 2. Comparison of average time to emergence between the Schneider and Gupta (1985) data and the present study at 50-mm planting depth.

<table>
<thead>
<tr>
<th>Soil matric potential</th>
<th>5 to 15°C</th>
<th>16 to 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S &amp; G</td>
<td>Present</td>
</tr>
<tr>
<td>kPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>22.0 ± 3.2</td>
<td>25.3 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>(8)</td>
</tr>
<tr>
<td>-500</td>
<td>37.4 ± 4.9</td>
<td>28.0 ± 4.2</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>(9)</td>
</tr>
</tbody>
</table>

† Average ± SD.
‡ S & G refers to Schneider and Gupta (1985) data.
§ No. in parentheses refers to the no. of observations.

Fig. 1. Time to corn emergence as influenced by planting depth at two soil matric potentials, and two ranges of soil temperatures.
after planting, using a Campbell CR5 data acquisition system and a copper-constantan thermocouple (Campbell Scientific, Inc., Logan, UT). Corn was planted on 9 May 1984 and on 7 May 1985 using a John Deere (Waterloo, IA) Max-Emerge planter. The four-row planter was set to provide planting depths of approximately 25, 50, and 75 mm. For each tillage-residue-depth treatment, four 3.05-m lengths of row were identified for daily counting of emerged plants.

1 Trade and company names are included for the benefit of the reader and do not imply endorsement by the Univ. of Minnesota or USDA.

WEBSTER CLAY LOAM
PLANTING DEPTH = 25 mm

Two to 3 wk after planting, planting depths were measured for two plants in each of the emergence rows. Plants were excised at the soil surface and the underground shoot and attached seed were exhumed to determine actual planting depth.

In both years, gravimetric water samples were taken weekly beginning on planting day. In 1984, samples were taken in 76-mm increments from the soil surface to a depth of 304 mm. In 1985, gravimetric water content was sampled in 25-mm increments from the soil surface to a depth of 100 mm. Bulk density in the row was determined in 1985 for 0- to 50-mm and 50- to 100-mm increments using 50 mm long by 50 mm i.d. brass cores. Precipitation was recorded at a weather station immediately adjacent to the plots.

RESULTS AND DISCUSSION

Growth Chamber Study

The effects of planting depth on time to corn emergence at two soil matric potentials, two temperatures, and one aggregate size distribution (GMD = 3.6 mm) are shown in Fig. 1. Time to corn emergence increases as the depth of planting increases from 25 to 75 mm. Delay in corn emergence, due to an increase in planting depth, was much greater at lower (5 to 15 °C) than at higher (15 to 25 °C) temperatures. For a given temperature and planting depth, matric potential had little influence on time to corn emergence.

Corn Emergence Model

Average times to corn emergence at the 50-mm depth between the present and Schneider and Gupta

Fig. 2. Percent corn emergence as a function of seed zone growing degree days for three planting depths, two soil matric potentials, and two ranges of soil temperatures. Solid lines in Fig. 2c and d correspond to an average relationship previously reported by Schneider and Gupta (1985).

Fig. 3. Average relationship of percent corn emergence vs. seed zone growing degree days at three planting depths and two soil matric potentials.
(1985) studies are shown in Table 2. Average times to corn emergence at the 50-mm planting depth were similar in both studies. The differences at low matric potential ($\psi_m = -500$ kPa) and low soil temperatures (5 to 15 °C) are due to a small number of observations in the Schneider and Gupta (1985) study.

Using the procedure of Schneider and Gupta (1985), corn emergence data from the growth chamber study was converted into percent emergence vs. seed zone GDD (Fig. 2). The solid line in Fig. 2c and d is taken from the Schneider and Gupta (1985) study and corresponds to an average for three soils, five aggregate size distributions, and four ranges of soil temperatures. The percent emergence vs. seed zone GDD relationship of Webster aggregates (GMD = 3.6 mm) matches well with the average relationship of Schneider and Gupta (1985) at a soil matric potential of $-10$ kPa (Fig. 2c). At $\psi_m = -500$ kPa, the relationship of percent emergence vs. seed zone GDD (Fig. 2d) is slightly different than the average line from Schneider and Gupta (1985). However, the data from the present study (GMD = 3.6 mm) is within the range of scatter encountered in the study of Schneider and Gupta (1985) for three soils, four temperatures, four soil matric potentials, and five aggregate size distributions. Because of the slight differences in the percent emergence vs. seed zone GDD between the present and the Schneider and Gupta (1985) studies at the 50-mm planting depth, data on percent emergence vs. seed zone GDD for three planting depths at two soil matric potentials resulting from lower soil temperatures associated with specific conservation tillage systems.

Field Experiments

Tillage Effect on Planting Depth

The measured and the targeted planting depths for seven tillage and surface residue treatments in the field experiment are summarized in Table 3. Measured planting depths were deeper at targeted planting depth of 25 mm and shallower at targeted planting depths of 50 and 75 mm. The variability (standard deviation) was higher at targeted planting depths of 50 and 75 mm. Additionally, the data show that the correspondence between the measured and targeted planting depth depended more on the tillage tool than on the surface residue condition of the soil. In general, at the 50 and 75 mm targeted depths, the measured planting depth increased in the following order: moldboard > chisel

![Fig. 4. Predicted vs. measured time to 75% corn emergence at three planting depths for seven different tillage and surface residue treatments. Mean and standard deviation of the difference between predicted and measured values are: (a) $-3.9 \pm 2.9$, (b) $-1.3 \pm 0.9$, (c) $-0.1 \pm 1.7$, (d) $-1.6 \pm 2.4$, (e) $1.3 \pm 1.8$, and (f) $2.3 \pm 2.4$.](image)

Table 3. Comparison of measured and targeted planting depths for seven tillage and surface residue conditions.

<table>
<thead>
<tr>
<th>Treatments†</th>
<th>Planting depths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Targeted</td>
</tr>
<tr>
<td>MPNR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>CHNR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>NTSR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>MPRI</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>MPSR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>CHSR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>NTSR</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
</tbody>
</table>

† MPNR = moldboard plow no residue, CHNR = chisel plow no residue, NTSR = no-till surface residue, CHSR = chisel plow surface residue, NTNR = moldboard plow no residue, MPRI = moldboard plow residue incorporated, MPSR = moldboard plow surface residue, CHSR = chisel plow surface residue.

‡ Predictions of time to corn emergence over several years can be useful in evaluating planting depth as a management tool to overcome the negative effects resulting from lower soil temperatures associated with specific conservation tillage systems.
Early corn planting dates for 75% emergence in 14 d

Spring weather? | MPNR | NTSR |
--- | --- | ---
Cool | 1 May 13 May 18 May 25 May | 20 May 22 May |
Warm | 1 May 6 May 9 May 10 May 20 May | 22 May 25 May |
Average | 1 May 13 May 16 May 15 May 18 May 25 May | 25 May 31 May |

\[ v = -10 \text{ kPa} \]

\[ \psi_m = -10 \text{ kPa} \]

\[ \psi_m = -500 \text{ kPa} \]

Table 4. Earliest corn planting dates for 75% emergence in 14 d for three spring weather conditions, three planting depths, and two soil matric potentials at Morris, MN.

Table 5. Depth of planting for no-till surface residue (NTSR) system that has a similar cumulative probability vs. planting date curves as that of moldboard plow no residue (MPNR) at the 50-mm planting depth.

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3. Although measured average planting depths were slightly different than the targeted planting, we ignored the variability (standard deviation) in planting depth measurements and assumed the measured time to corn emergence corresponded to the targeted planting depths. This assumption simplified the simulation process.

The corn emergence model for the three planting depths was tested on the 1984 and 1985 field emergence data. Figure 4 shows the comparison between predicted and measured time to 75% corn emergence for three planting depths at soil matric potentials of —10 (Fig. 4a, b, and c) and —500 kPa (Fig. 4d, e, and f). Predicted time to 75% corn emergence is close to the measured values when soil water potential is assumed to be —500 kPa at the 25-mm planting depth and —10 kPa for 50- and 75-mm depths. Agreement between the predicted and measured times to emergence was tested by calculating the mean and standard deviation of the difference between predicted and measured values (Gupta et al., 1984). The mean of the difference between predicted and measured values over 2 yr corresponded to —1.6 d for 25-mm planting depth at \( \psi_m \) of —500 kPa, and —1.3 and —0.1 d for 50- and 75-mm planting depths, respectively, at \( \psi_m \) of —10 kPa. Since field soil water content measurements were taken at weekly intervals, or when the field was relatively dry, soil water content could not be used to test this assumption. However, the assumption is reasonable because the soil near the surface is drier than the soil at deeper depths during most rainfree days. During the period from planting to 75% emergence, there were 10 rainfree d in 1984 and 11 in 1985.

The close correspondence between the predicted and measured time to corn emergence in Fig. 4 indicates that the relationships of percent emergence vs. seed zone GDD at various planting depths (Fig. 3) are valid

Table 5. Depth of planting for no-till surface residue (NTSR) system that has a similar cumulative probability vs. planting date curves as that of moldboard plow no residue (MPNR) at the 50-mm planting depth.

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Table 5. Depth of planting for no-till surface residue (NTSR) system that has a similar cumulative probability vs. planting date curves as that of moldboard plow no residue (MPNR) at the 50-mm planting depth.

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Table 5. Depth of planting for no-till surface residue (NTSR) system that has a similar cumulative probability vs. planting date curves as that of moldboard plow no residue (MPNR) at the 50-mm planting depth.
for variable soil temperatures encountered in the field. Also, relationships in Fig. 3 are unique, and the differences in time to corn emergence between different tillage and surface residue conditions are related to soil temperatures at a given planting depth.

Influence of Planting Depths on Earliest Corn Planting Dates

Using the procedure of Gupta (1985), cumulative probabilities of 75% corn emergence in 2 wk were simulated for various planting dates (1 April through 30 June), three planting depths (25, 50, and 75 mm), two soil matric potentials (−10 and −500 kPa), two tillage systems [moldboard plow no residue (MPNR) and no-till surface residue (NTSR)], and two locations in the Corn Belt (Morris, MN and Lexington, KY). The criterion of 75% emergence in 2 wk (between 8 to 14 d) originally selected by Gupta (1985) was based on field emergence data of Schneider and Gupta (1984). The premise of 75% emergence in 14 d or less was that a longer time to corn emergence increases the probability of seed rotting. This criterion seems reasonable considering the measured time to corn emergence at Rosemount, MN (Fig. 4). Except for one observation, measured time to corn emergence was <14 d for both 1984 and 1985 at Rosemount, MN.

The simulated cumulative probabilities of 75% emergence in 14 d or less at three planting depths under MPNR with a soil matric potential corresponding to −10 kPa at Morris, MN are shown in Fig. 5. At a given planting date, the cumulative probability of corn emergence increases with a decrease in the planting depth. This is expected because of higher temperatures at shallow soil depths and the reduced distance over which the cotyledon has to grow before its emergence. Probability curves in Fig. 5 also define the earliest corn planting date when 75% emergence can be achieved in 14 d or less. Table 4 shows the effect of planting depth on earliest corn planting dates at Morris, MN for three spring weather conditions, two tillage systems, and two soil matric potentials. Warm, average, and cool spring conditions in Table 4 refer to a cumulative probability of 25, 50, and 75% in Fig. 5, respectively (Gupta, 1985). For a given spring weather condition, an increase in planting depth delays the earliest planting date at which 75% emergence can be achieved in 14 d or less (Table 4). Comparison of earliest planting date between two tillage systems (Table 4) shows that shallow (25 mm) planting under NTSR provides the same earliest corn planting dates as an average (50 mm) planting depth under MPNR treatment. This is also demonstrated in Fig. 6 where cumulative probability curve of MPNR at the 50-mm planting depth is similar to the probability curve of NTSR at 25-mm planting depth.

Gupta (1985) demonstrated that under some circumstances (early fall frost), delay in emergence under NTSR may necessitate planting of shorter season corn cultivars in the northern Corn Belt. The premise of the present study was to evaluate planting depth as a management tool to overcome delays in corn emergence under typically cool and wet soil conditions of the conservation tillage systems (NTSR). Figure 6 shows that matching the probability curves of NTSR at various planting depths against the probability curve of MPNR at average (50 mm) planting depths can define the planting depth under NTSR that will result in similar time to corn emergence as that of MPNR at average planting depths. Table 5 shows the planting depth for two extreme locations (Morris, MN and Lexington, KY) in the Corn Belt under two tillage systems and at two soil matric potentials when the cumulative probability vs. planting date curves for NTSR are similar to that of MPNR. Decreasing the planting depth by 25 mm in NTSR treatment results in the probabilities of corn emergence similar to that of MPNR for the two extreme locations in the Corn Belt. In other words, the effect of cooler temperatures on corn emergence under no-till tillage system with surface residues can be compensated for by reducing the planting depth by 25 mm or less as compared to that of average planting depth under conventional tillage systems.

However, this analysis assumes that soil water is not limiting ($\psi_m > -500$ kPa) for corn emergence. For conditions when $\psi_m$ is $<-500$ kPa, additional research will be needed to determine the relative importance of soil temperature and soil water or the depth of planting in NTSR that gives similar probability curves to that of MPNR.

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