INTRODUCTION

The 2015 growing season was one of adjusting to a new normal for many in agriculture. Crop production and economic trends established in 2014 largely continued in 2015. Corn yields remained high with the projected 169.3 bu/acre U.S. average yield second only to the all-time high of 171 set in 2014. The 2015 soybean crop was the largest ever, slightly above 2014’s record crop. Commodity prices were relatively stable in 2015 following the sharp drop off of recent highs that occurred over the previous two seasons. Although long-term prospects remain positive given demand growth associated with an expanding global population and growing middle class, tighter margins on the horizon for the near term have brought a renewed focus on efficient management that is driving changes on the farm and throughout the industry.

Successful crop management under current conditions requires smart and efficient use of resources driven by sound agronomic knowledge. Access to trusted advisors and research-based insights to provide a basis for sound decisions is more important than ever given the economic headwinds and continually evolving production challenges that growers face. At DuPont Pioneer, our commitment to improved crop management is the foundation of our GrowingPoint™ agronomy research structure – an industry-leading network of agronomists and researchers across North America. The mission of this team is to help maximize grower productivity by delivering useful insights built on rigorous, innovative research.

This Agronomy Sciences Research Summary provides insights on numerous crop production topics relevant to growers in Iowa; however, it represents just a small portion of the vast array of resources available in the Pioneer agronomy library. This wealth of information is more accessible than ever with the introduction of the Pioneer® GrowingPoint™ agronomy app in 2015. This free mobile app allows growers to quickly and easily view the hundreds of agronomy publications in the Pioneer agronomy library on a tablet or smartphone. We hope that resources available in this book and online will help you drive yield and profitability in 2016.

Mark Jeschke, Editor

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PLANTING OUTCOME EFFECTS ON CORN YIELD

FOUR PLANTING OUTCOMES FOR SUCCESS

Planning and execution associated with corn planting are critical if growers are to maximize the genetic potential of today’s elite corn hybrids. The simple secret for success is to “do everything right.” Many of these key management decisions are made well before the planting season, including choice of hybrid, crop rotation, tillage system, nutrient placement, target planting rate, and row spacing.

This article will focus on the four planting outcomes that are achieved during planting itself. The relative impact these four factors have on grain yield were recently summarized by Dr. Jeff Coulter from the University of Minnesota (2013) and are presented below.

These goals and their estimated typical impact on yield include:

1. Achieve uniform emergence (5-9%)  
2. Plant within the optimum window (2-5%)  
3. Achieve the correct population (1-2%)  
4. Achieve uniform plant spacing (1-2%)

The latest research related to achieving each of these four planting outcomes will be discussed and in several cases, suggest the need to rethink conventional wisdom regarding their importance in affecting grain yield.

1. ACHIEVE UNIFORM PLANT EMERGENCE

A primary goal of corn growers is to achieve stands containing uniformly large-sized plants that consistently produce one full-sized ear each. Small, delayed, or “runt,” plants rarely, if ever, produce full-sized ears. Traditionally, growers have assumed that the primary cause of these smaller, undesirable plants was a delay in the time of emergence. And often the cause for delayed emergence was assumed to be inconsistent seeding depth. Logically, late-emerging plants are less able to compete for limited light, nutrient, and moisture resources with earlier-emerging, and larger neighbors. Several studies have indeed documented significant yield loss when the development of plants within the stand was delayed (Nafziger et al., 1991; Ford and Hicks, 1992; Liu et al., 2004a, 2004c). These studies typically used multiple planting dates 7 to 28 days apart to achieve varying degrees of delayed plant growth. These studies are valuable in demonstrating certain aspects of plant-to-plant competition and give some guidance for making replant decisions. However, they are of little value in understanding the effects of emergence timing on individual plant yield in stands planted all on the same day, as is typical in commercial corn production. They also do not indicate the relative importance of time of emergence versus other factors occurring after stand establishment or how final plant yield is impacted by each.

Multiple Factors Shown to Affect Plant Yield

There is widespread agreement that large plants exhibiting well-synchronized silk emergence and pollen shed produce the largest and most consistent-sized ears (Pagano et al., 2007; Kovács and Vyn, 2014). However, these studies have also shown that time of emergence has relatively little effect on plant biomass and final grain yield. In a 2-year study in Indiana, Murua (2002) documented that time of emergence in conventionally-planted corn stands only explained about 4% of the variation in individual plant yield. A similar study by Kovács and Vyn (2014) found that value to be only about 1%.

Other studies from Argentina found that even when corn canopies emerge uniformly, they can develop well-established plant hierarchies as early as the V4 growth stage (Pagano et al., 2007; Maddonni and Otegui, 2004). These differences in plant size within the stand are probably explained by “other” factors such as moisture availability, compaction, soil textural differences, nutrient acquisition, or insect damage and clearly not time of emergence. The notion that a plant is a “weed” if it emerges more than 48 hours after its neighbors is clearly not supported by these studies. In fact, Kovács and Vyn (2014) further warn, “the importance of ultra-uniform seedling emergence times for adjacent plants within the row can easily be overstated.”

How Much Does Uniform Emergence Affect Plant Yield?

Determining the exact effect of uniform emergence is difficult, in part because studies have used different ways to measure and express emergence uniformity. Some of the different measures used include calendar or growing degree days from planting to emergence, time to 50% emergence, number of leaf stage growth differences, and days of emergence delay after the mean emergence date of the plant stand. Ford and Hicks (1992) measured a 6% yield loss when every second plant had a 1-leaf stage delay and a 5% yield loss when every 6th plant had a 2-leaf delay. Liu et al. (2004a, 2004c) found that yield decreased 2% per day whenever the time to 50% emergence was delayed by more than 3 days. Nishikawa and Kudo (1973) report that per plant yield declines by 5% for every day in emergence delay after the mean emergence date of the plant stand. And finally, Murua (2002) measured an average of 2.3% yield loss for every additional day’s delay in emergence of individual plants.
These results suggest that delays in emergence can result in average yield losses in the 5 to 9% range proposed by Coulter (2012). Careful attention to managing planting depth, seed trench compaction, surface crusting, seed furrow closure, and surface residue will minimize these yield losses. But beyond that, attention to other factors, such as uniform moisture, nutrient availability, soil compaction, and disease and insect protection, may be even more important in achieving uniform stands at physiological maturity with low plant-to-plant variability in ear size and maximum grain yield.

2. PLANT WITHIN THE OPTIMUM WINDOW

Timely planting of full-season hybrids allows the corn crop to take full advantage of the available growing season. Numerous studies have shown that corn yield potential declines as planting is delayed beyond the optimum planting window for a given geography (Coulter, 2012; Farnham, 2001; Myers and Wiebold, 2013; Nafziger, 2008).

Yield Reduction with Delayed Planting

Results from DuPont Pioneer planting date studies conducted over 18 growing seasons show that yield was maximized when corn was planted within the 2-week period around the optimum planting date (Jeschke and Paszkiewicz, 2013). The optimum planting date was April 16 for the central Corn Belt and April 30 for the northern Corn Belt. Yield declined for planting dates following the optimum window, and the rate of yield decline increased with delay duration. The yield penalty associated with delayed planting was greater in the northern Corn Belt where the growing season is shorter. Yield of corn planted 4 weeks following the optimum date was reduced by 7% in the central Corn Belt, compared to over 15% in the northern Corn Belt (Figure 1).

It is commonly believed that larger planters and improved technology have increased the pace at which the U.S. corn crop can be planted, although examinations of USDA planting data have shown this is not actually the case (Irwin and Good, 2011; Kucharik, 2006). Although larger planters have enabled a single operator to cover more acres in a day than was possible in the past, the total number of planters in use has declined as farm operations have consolidated. Planting data show that, in general, the U.S. corn crop is planted much earlier now than it was 30 years ago; however, the pace at which it is planted has not accelerated, and weather is the primary factor that determines planting progress. Since yield losses only occur on acres planted after the optimum window, typical farm-wide yield losses due to planting delays likely average no more than 2 to 5%.

3. ACHIEVE THE CORRECT POPULATION

Unlike planting timing, which is often heavily influenced by weather conditions, plant population is a yield determining factor largely within the control of the grower. However, determining and achieving the ideal population to maximize yield is complicated, as the optimum population in a given situation can be influenced by a number of factors, such as yield level, hybrid, and weather conditions.

Figure 1. Planting date effect on corn yield for the central and northern Corn Belt, based on DuPont Pioneer planting date studies conducted at 17 locations over 18 years. (Central Corn Belt locations in NE, central IA, central IL, and central IN. Northern Corn Belt locations in northern IA, southern and central MN, southwest SD, central MI, and southern ON.)

Factors That Influence Planting Timing

The ability to get corn planted within the optimum planting window is largely driven by weather conditions during this time. The number of suitable days can vary greatly from year to year. For example, an analysis of USDA data by Irwin and Good (2014) showed that the number of days suitable for fieldwork in Illinois from 1970-2013 during the 3 weeks spanning April 30 to May 20 ranged from as many as 19 to as few as 4 days across these years (Figure 2). On average, slightly over half (11.5) of the days in the 3-week period were suitable for field work.
In general, optimum populations for corn have steadily increased over time. Higher populations accompanied by improved stress tolerance in hybrids have contributed to incremental yield gains. Average corn seeding rates used by growers in the U.S. and Canada have increased from about 23,000 seeds/acre in 1985 to over 30,000 seeds/acre today, or approximately 300 seeds/acre per year (Figure 3).

Factors That Can Influence Optimum Population

Yield Level: DuPont Pioneer and university studies have shown that corn hybrid response to plant population varies by yield level. The population required to maximize yield increases as yield level increases. When grouped by yield level, results from DuPont Pioneer plant population trials showed that the economic optimum seeding rate increased from approximately 27,000 seeds/acre at yield levels below 130 bu/acre to over 38,000 seeds/acre at yield levels above 250 bu/acre (Figure 4). An Iowa State University study comparing corn yield response to plant population across soils with different corn suitability ratings found similar results. The most productive soils tended to have a higher optimum population for maximum yield (Woli et al., 2014).

Hybrid Maturity: Research has shown that early maturity hybrids (<100 CRM) may require higher populations to maximize yield. Figure 5 shows the yield response of hybrids to plant population grouped by CRM range in DuPont Pioneer trials conducted from 2006 to 2012.

Although this trend can still be detected when examining the response curves closely, it is a smaller difference than in the past. This change may be the result of different genetic backgrounds predominant in early maturities historically versus currently, or other unknown factors.

Hybrid Genetics: Yield response to plant population can also vary based on hybrid genetics. Figure 6 shows an example of two hybrid families with the same CRM that have been shown to differ in their response to plant population in DuPont Pioneer research trials. One hybrid family (Pioneer® hybrid P1142) has a plant population response that is typical of current 111 CRM hybrids, whereas the other (Pioneer® hybrid P1151) tends to achieve maximum yield at higher plant populations. DuPont Pioneer offers growers an online planting rate calculator that provides recommendations based on a selected hybrid, grain price, seed cost, and yield level.2

Yield Impact of High or Low Population

A plant population that is too high or too low can negatively impact yield. A low population may limit yield potential when growing conditions are favorable, while a high population may result in reduced performance and standability under stress conditions. In general however, modern hybrids tend to have a relatively wide margin of error when it comes to ideal population. For example, both of the hybrid families shown in Figure 6 could be as much as 4,000 plants/acre over or under the optimum population and still have less than 2 bu/acre variation in yield.

One reason for this is the improvements in stress tolerance that have resulted from decades of targeted breeding. A common stress response of older corn hybrids was “barrenness,” or the inability to produce an ear. Even as recently as 30 years ago, some of the best hybrids were prone to barrenness when population thresholds were exceeded. Modern corn hybrids are better able to produce an ear under moisture and density stress, even though ears are progressively smaller under increasing stress. This means that when plant density optimums are exceeded, yields tend to level off rather than drop abruptly. This hybrid characteristic has changed the risk/reward equation in the grower’s favor. Because the risk that excess populations will decrease yields under dry conditions is reduced, growers can more confidently plant higher populations that support increased yields when favorable conditions develop.

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4. ACHIEVE UNIFORM PLANT SPACING

Growers instinctively prefer corn stands with uniform plant-to-plant spacing. A “picket-fence” stand is both aesthetically pleasing and presumably higher yielding.

How is Plant Spacing Uniformity Measured?

Seeding specialists and agronomists have long used two related statistics, coefficient of variation (CoV) and standard deviation (SD), as the preferred metrics to quantify meter performance and plant spacing uniformity. A SD value of 2.0 inches or the corresponding CoV value of 0.33 are widely cited as the thresholds above which corn yield loss would be expected (Nielsen, 2001). The CoV is easily calculated by dividing the SD by the average plant spacing. For example, the SD corresponding to a CoV of 0.33 at an average spacing of 6.0 inches is 2.0 inches. More recently, engineers have also devised a “singulation” metric as an indicator of seed spacing uniformity, although there is no industry standard as to how it is calculated.

Spacing Metrics Poorly Correlated to Yield

Agronomists have long known that the various planting outcomes that result in increasing CoV and SD and declining singulation values can have widely different impacts on resulting individual-plant grain yield (Nafziger, 1996; Doerge et al., 2002; Nafziger, 2006). Thus, the use of easy-to-measure plant spacing metrics that are poorly correlated with individual plant yields has, unfortunately, created a tradeoff between convenience and accuracy. This has no doubt contributed to inconsistent results in past research seeking to explain the impact of within-row plant spacing on corn grain yield (Krall, 1977; Nafziger, 1996; Nielsen, 2001; Doerge and Hall, 2000; Doerge et al., 2002; Lauer and Rankin, 2004; Liu et al., 2004a, 2004b, 2004c; Nielsen, 2006).

Individual Plant Yield Determinations Provide New Insights

A 2002 DuPont Pioneer study (Doerge et al.) uniquely allows for quantifying the impacts of common and realistic non-ideal planting outcomes on grain yield. This study was conducted in 4 different environments (2 in Iowa, 1 in Missouri, and 1 in Minnesota), across a wide yield range — 109 to 206 bu/acre, and using hybrids with 3 very different genetic pedigrees. In this study, within-row spacing measurements and grain yields were determined on >6,000 individual plants.

Major Findings

1. As expected, differences in grain yields resulting from common non-ideal planting outcomes were indeed observed and are listed in Table 1.

2. These non-ideal planting outcomes typically, but not always, resulted in lower grain yield. The notable exception is that a double planting outcome slightly increased yield, but yield losses for all other planting outcomes varied over a rather wide range, from 0 to -0.26 lbs. grain for the 2- or 3-plant groupings depicted in Table 1.

Table 1. Corn grain yields resulting from various planting outcomes. Yield impacts are averaged across four study locations.

<table>
<thead>
<tr>
<th>Planting Outcome</th>
<th>Plant Spacing</th>
<th>Loss/Gain in Grain Weight**</th>
<th>Grain Yield***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect Spacing</td>
<td></td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>% yield*</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Skip</td>
<td>-0.26</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>% yield</td>
<td>110</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Double</td>
<td>0.13</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>% yield</td>
<td>100</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Seed Misplaced by ¼</td>
<td>0</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>% yield</td>
<td>98</td>
<td>101</td>
<td>104</td>
</tr>
<tr>
<td>Seed Misplaced by ½</td>
<td>-0.04</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>% yield</td>
<td>94</td>
<td>98</td>
<td>88</td>
</tr>
<tr>
<td>Seed Misplaced by ¾</td>
<td>-0.26</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>% yield</td>
<td>87</td>
<td>88</td>
<td>112</td>
</tr>
</tbody>
</table>

*% yield of individual plants compared to plants at perfect spacing.

**The gain or loss of yield of the 2-, 3-, or 4-plant groupings depicted in Table 1 compared to 3 plants at perfect spacing.

***The yield of the 2-, 3-, or 4-plant groupings depicted in Table 1 as a % of 3 plants at perfect spacing.
3. By far, a skip is the planting outcome that contributes the most to yield loss. Plants adjacent to a skip only partially compensate for the missing plant.

4. In general, yield loss due to misplaced plants is negligible if plants are displaced from their preferred location by no more than half of the normal plant-to-plant distance.

Conclusions

1. The CoV and singulation readings on the planter monitor are valuable real-time indicators of meter performance but poor predictors of the agronomic consequences of common, realistic non-ideal planting outcomes.

2. The planting outcome causing the greatest yield loss is percentage of skips. A skip is defined as an in-trench distance between seeds of ≥1.75 times the desired plant-to-plant distance (for example, at 34,848 plants/acre in 30-inch rows, the average distance between seeds or plants would be 6.0 inches, and a skip would therefore be a plant-to-plant distance of ≥1.75 × 6.0, or 10.5 inches).

3. Not all skips are caused by the planter. Missing plants resulting from unsuccessful germination or emergence will reduce grain yield just as much as planter skips and are to be equally avoided. Emerged plant spacing, along with population, gives the best prediction of yield performance.

4. Occasional doubles do not negatively impact yield. A true planter double, or two seeds held in one cell of the planter meter, is not necessarily a bad thing. First of all, there is at least enough increase in yield from a double to offset the cost of the extra seed that is being planted, and if having an occasional double (i.e. 1 to 2%) helps ensure fewer or no skips, then such an outcome would be preferred. This would be the case if adjusting the planter vacuum setting upward could reduce the occurrence of empty cells, even if the higher vacuum setting increases doubles slightly.

Table 2. The contribution of five common non-ideal planting outcome to two statistics used to describe seed and plant spacing uniformity, including Coefficient of Variation and Standard Deviation.

<table>
<thead>
<tr>
<th>Planting Outcome</th>
<th>Resulting CoV*</th>
<th>Resulting SD*</th>
<th>Resulting Yield Loss or Gain*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect Spacing</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1% Skips</td>
<td>0.10</td>
<td>0.78</td>
<td>-1.3</td>
</tr>
<tr>
<td>1% Doubles</td>
<td>0.10</td>
<td>0.78</td>
<td>+0.7</td>
</tr>
<tr>
<td>1% Seed Misplaced by ¼</td>
<td>0.04</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>1% Seed Misplaced by ½</td>
<td>0.07</td>
<td>0.55</td>
<td>0</td>
</tr>
<tr>
<td>1% Seed Misplaced by ¾</td>
<td>0.11</td>
<td>0.83</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

*Compared to perfect plant spacing.

Plant population assumed = 34,848/acre or mean spacing = 6.0 in.

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Past Inconsistent Research Results Explained

There are several explanations for the lack of agreement in the results from past plant spacing studies, which were all conducted by highly-qualified researchers. First of all, different planting outcomes that contribute to SD, CoV, or singulation can have completely different effects on individual plant yield (Table 2). Skips are highly detrimental to yield, doubles can be slightly positive, and misplaced plants have no effect on yield until plants are displaced from their preferred location by more than half the normal plant-to-plant distance. Second, no two fields can be expected to have the same amount or combination of non-ideal planting outcomes. Thus, it is no wonder that comparisons from aggregated, plot- or field-wide plant spacing studies are contradictory if the sources of plant spacing non-uniformity are not considered. Unfortunately, this lack of consideration has been true of most plant spacing studies.

Other sources of confounding include the manner in which some field experiments have been conducted. For example, some studies have used highly artificial groupings of plants to achieve pre-determined levels of plant spacing variability. In addition to being unrepresentative of “real-world” conditions, they often employ only different levels of misplaced plants (no skips or doubles) to achieve the desired spacing treatments. Tables 1 and 2 indicate that these types of plant arrangements will have little to no impact on yield. Other plant spacing studies may have been compromised by the use of overplanting and thinning to achieve the desired plant spacing arrangements and populations. These practices are potentially confounding because corn plants can sense the presence of neighboring plants beginning very shortly after emergence due to subtle differences in the ratios of red: far red light they receive (Liu et al., 2009). These light quality differences can act as an early signal of pending competition that can initiate a shade avoidance response in the remaining plants. Thus, overplanting and thinning can unintentionally result in plants that have been pre-conditioned to exhibit less favorable crop architecture and lower grain yield potential.

In contrast, when individual plant yields arising from different planting outcomes are considered, research results have been amazingly consistent. For example, Nafziger (1996) found that 10% skips in 4 Illinois experiments resulted in an average 8.1% decrease in yield (at 30,000 plants/acre) while the findings from the DuPont Pioneer study (Doerge et al., 2002) measured a corresponding 8.9% yield decrease (at a similar plant population). Likewise, the Illinois studies measured a yield increase of 4.2% for 10% doubles while the Pioneer data revealed a 4.7% yield increase. These similarities are notable since the genetics used in these two sets of experiments were released at least a decade apart.

Clearly, the key messages on within-row plant spacing uniformity are: 1) it does impact grain yield and can be explained, 2) whole-field impacts on grain yield are usually relatively small, averaging about 1 to 2%, and 3) growers should work to minimize or eliminate skips and not worry about occasional doubles or slightly misplaced plants.

SOURCES

To view authors and references, follow this link:

https://www.pioneer.com/home/site/us/agronomy/library/planting-outcome-effects/#/references
STRATEGIES AND CONSIDERATIONS FOR MULTI-HYBRID PLANTING

Farmers intending to replace old planters have a multitude of recent innovative features to consider, including planters with the ability to seed more than one hybrid or variety within a field. These new planters, often referred to as multi-hybrid or multi-cultivar planters, are configured with the equipment needed to automatically switch between two or more crop cultivars on-the-go. This technology allows growers to use prescription maps to match hybrids or varieties with specific field conditions and will likely be most beneficial in fields with variable landscapes. Initial implementation has largely focused on variable placement of corn hybrids, but the technology could potentially be used with any crop.

Precision farming pioneers have long envisioned that hybrid or cultivar would be an important input for variable management (Dudding et al., 1995). Extension agronomists consistently rate corn hybrid selection as one of the most important factors for maximizing yield (Coulter and Van Roekel, 2009; Elmore et al., 2006; and Thomson McClure, 2014). Variable cultivar planting takes this management decision to a higher level, allowing growers to choose the best-adapted cultivar for each part of the field.

Commercial availability of multi-cultivar enabled planters makes it easier than ever to deploy a zone-based management strategy for crop cultivar selection. This article will discuss strategies to identify candidate fields and develop appropriate multi-cultivar prescriptions, as well as review some potential applications for multi-cultivar planting in corn and soybeans. Although many of the principles discussed can be applied to numerous crop species, the focus of this article will primarily be multi-hybrid strategies for corn.

DERIVING VALUE FROM MULTI-HYBRID PLANTING

Two conditions are necessary for a multi-hybrid planting strategy to provide a yield advantage. First, there must be significant within-field variation in yield due to environmental or management factors, including landscape topography and other soil variables (i.e., the more uniform a field, the less likely that multi-hybrid planting will increase yield). Secondly, there must be a difference between hybrids in yield response to the within-field environmental variation.

A statistical technique originally developed in the 1960s (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) has commonly been used to describe yield stability of a corn hybrid across a range of environments. This method involves developing a linear regression of yield for a given hybrid versus the average yield of all hybrids tested across the same (multiple) environments. This provides a measure of relative yield stability for a given hybrid. A regression slope of 1 represents average yield stability with more stable hybrids (commonly referred to as “defensive” or “workhorse” hybrids) having a slope <1 and more responsive hybrids (commonly referred to as “offensive” or “racehorse” hybrids) having a slope >1 (Figure 1).

The average yield of all cultivars at a location is referred to as that location’s environmental index. Although originally developed to characterize yield stability across multiple locations, this same model can be applied to assessing hybrid response to variability within a field and evaluating the potential value of variable hybrid planting.

Figure 1. Corn hybrid yield stability model showing example linear regressions for offensive, stable, and defensive hybrids.

Figure 2 shows a hypothetical field in which yield performance is nearly (or “relatively”) constant across the entire field. In this scenario, yield would be maximized by planting the highest-yielding cultivar across the entire field.

Figure 2. Grain yield of two cultivars in a hypothetical field in which there is no spatial variation in yield due to environmental conditions.
This example visualizes a scenario in which the environmental factors in question have little or no influence on yield of either cultivar. In reality, all fields have some degree of spatial variation in yield due to environmental or management factors; the greater this variation, the more potential there is for differential placement of cultivars within the field to increase yield.

Figure 3 shows a hypothetical field in which yield varies due to environmental factors, but the two cultivars respond similarly to the environmental variation. The environmental index in this example could be reflective of any environmental factor or combination of factors that contribute to spatial variation and impact grain yield, such as drainage, disease pressure, or soil properties, or management factors such as tillage or crop history. Although this field has substantial variation in yield across the landscape, cultivar A still out-yields cultivar B across all environments in the field; therefore, yield would be maximized by planting the entire field to cultivar A. It is important to remember that substantial variability in yield across a field does not automatically mean that variable placement of two cultivars will provide a yield advantage.

Figure 4 shows a scenario in which both conditions are met for multi-cultivar planting to be advantageous: variation in yield due to environmental or management factors and differential cultivar response to this variation.

In this field, yield would be maximized by planting cultivar A in the higher-yielding regions of the field and cultivar B in the lower-yielding areas, a scenario represented by the solid lines in the figure.

DuPont Pioneer split-planter trial near Harlan, Iowa, in 2001. Split-planter trials have been used extensively over the past 20 years to study the value of variable hybrid placement.

PREVIOUS RESEARCH

Even though commercial availability of multi-hybrid planting technology is relatively recent, the potential value of within-field variable hybrid placement has been studied extensively by DuPont Pioneer and university scientists for the past 20 years. Studies have typically involved using a conventional planter to plant two hybrids across a field using a split-planter arrangement. This method allows paired comparisons of two hybrids throughout an entire field to determine if they performed differently in different environments within the field. Numerous DuPont Pioneer on-farm split planter trials were conducted beginning in 1996 when the rapid adoption of yield monitors among growers made collection of spatial yield data across entire fields feasible for the first time (Doerge and Gardner, 1998; Figures 5 and 6).

Results of university split-planter studies generally have not supported widespread implementation of multi-hybrid planting. In the majority of studies, the hybrids responded similarly to within-field variation. A 3-year split-planter study conducted in 5 fields in New York found that spatial variability in yield differences between hybrids occurred in only 4 out of 15 site-years (Katsvairo et al., 2003). A study conducted from 1997 to 1999 in dryland production in eastern Colorado also found that the two hybrids tested responded similarly to in-field variation (Shanahan et al., 2004). Two studies conducted at multiple locations in eastern Illinois both found that there was no significant spatial variability in yield differences between hybrids in most fields tested (Miao et al., 2006a; 2006b).

A study was conducted by Pioneer and USDA researchers in the late 1990s using split-planter experiments to evaluate the potential yield benefits of variable hybrid planting in irrigated and dryland corn production in the far western Corn Belt (Doerge, 2000). Results showed that variation in grain yield across the landscapes in test locations was associated with site characteristics that do not change over time, such as elevation, pH, organic matter, soil color, and soil electrical conductivity; however, there was no evidence that hybrids responded differently to these site characteristics at either the dryland or irrigated locations in any year of the study.

Figure 3. Grain yield of two cultivars in a hypothetical field in which both cultivars respond similarly to spatial variation in environmental conditions.

Figure 4. Grain yield of two cultivars in a hypothetical field in which the cultivars have a differential response to environmental or management variation.
These results are consistent with the scenario shown in Figure 3, in which environmental variation exists but hybrids responded similarly to it, making the best management strategy to plant the higher performing hybrid across the entire field.

One noteworthy aspect of all of these studies is that the hybrids used generally were not selected based on any specific agronomic characteristics. In the study conducted by Shanahan et al., an early-maturity and late-maturity hybrid were compared. The other studies simply compared hybrids that were commonly used within their respective regions at the time. Even though the results of these studies did not show that variable hybrid planting would have provided much value in most cases, they do not rule out the possibility that a multi-hybrid management strategy using hybrids selected based on specific agronomic characteristics appropriate for certain field areas could be beneficial. The accumulated body of research in this area suggests that the greatest likelihood of success with multi-hybrid planting would be to target implementation to select highly-variable environments, using hybrids carefully selected based on yield-limiting factors in the field.

![Figure 5](image5.png)

**Figure 5.** Yield difference maps from a DuPont Pioneer split-planter study conducted in northern Illinois in 1996 and 1998, using the same two hybrids both years. Results from individual years suggested potential value for variable hybrid placement. However, the vastly different spatial patterns between years indicated a high degree of temporal variability relative to spatial variability in this field, which would make effective hybrid placement a challenge.

**CRITERIA FOR MULTI-HYBRID STRATEGIES**

Initial attempts at developing multi-hybrid planting prescriptions have often followed in the footsteps of strategies developed for variable rate seeding. Variable rate seeding prescriptions typically involve varying the seeding rate based on spatial variation in yield potential, where more productive areas usually receive a higher seeding rate (in the case of corn) and less productive areas a lower rate. Management zones are developed according to expected yield performance, often using past yield history as a basis or soil characteristics as a proxy for productivity (Butzen et al., 2009). Applications of this framework to multi-hybrid planting have typically involved splitting a field into higher-yielding and lower-yielding areas and then planting an “offensive” hybrid to the high yield areas and a “defensive” hybrid to the low yield areas.

This method of creating multi-cultivar prescriptions offers the advantages of being widely applicable and relatively straightforward to develop and execute. However, research suggests that it is unlikely to provide yield benefits in corn on a consistent basis for the simple reason that very few modern hybrids meet the criteria of being truly “offensive” or “defensive.” A recent review of performance data on over 2,500 corn hybrids tested in 7 or more environments found that only 6% met the definition of offensive (slope >1) and 8% met the definition of defensive (slope <1), while the vast majority of hybrids (86%) were classified as “stable” (Lauer and Hicks, 2005). These findings are not surprising given that modern corn breeding programs have largely focused on developing hybrids that will provide consistent performance across a wide range of environmental conditions (Pierce and Nowak, 1999).

**Consider Source of Yield Variation**

To realize a benefit from multi-hybrid planting, it will most likely be necessary to go beyond simply characterizing spatial yield variation – understanding the factor or factors driving that yield variation and selecting hybrids accordingly will be required. By comparison, variable rate seeding per se is generally simpler because the only one management criterion is under consideration: seeding rate, which is adjusted either higher or lower based on productivity or other factors. Modern hybrids are typically characterized for numerous agronomic traits, such as drought tolerance, disease resistance, root strength, etc., which provide a wide range of potential criteria for creating multi-hybrid prescriptions. As illustrated in Figure 4, one of the two conditions necessary for multi-hybrid planting to be advantageous is a differential hybrid response to variation in productivity. Knowing
both the field conditions and hybrid characteristics for success under those conditions is critical.

One of the environmental factors most likely to provide the basis for a successful multi-hybrid management strategy is soil moisture. This factor meets both the criteria for successful multi-hybrid planting: too much or too little soil moisture causes substantial variation in yields, and crop cultivars frequently differ in their response to insufficient or excessive moisture. Just as importantly, these differing responses are usually well-characterized. An example of recent research in this area is a collaborative study between DuPont Pioneer, Raven Industries, and South Dakota State University comparing conventional and variable planting at several locations in South Dakota. This study involved placing hybrids with greater tolerance to wet conditions in low landscape positions where there was likely to be excess moisture early in the season and more drought-tolerant hybrids at upper landscape positions likely to experience drought stress later in the season. Preliminary findings from the study have shown promise for this strategy, with yield benefits in the range of five to eight bu/acre at some of the study locations. (Sexton et al., 2013; 2014).

![Overhead view of a DuPont Pioneer multi-hybrid trial in 2015 with differing canopy color of the two hybrids clearly visible.](image)

**POTENTIAL APPLICATIONS FOR MULTI-CULTIVAR PLANTING**

There are many other possible applications and placement criteria for multi-cultivar planting. A multi-cultivar prescription could potentially involve multiple criteria, such as planting a drought tolerant hybrid on high ground prone to moisture stress and a disease tolerant hybrid on low ground prone to a foliar disease. In some cases, it may prove beneficial to select hybrids or varieties based on a predetermined multi-cultivar strategy, whereas in other cases the greatest benefit may be derived by first selecting the best available genetics and then using a multi-cultivar planter to optimize their placement.

Not all potential applications would necessarily require a multi-cultivar planter to execute but may be easier to implement with the ability to switch cultivars on the go. Some applications may have limited utility now but could become more valuable in the future with the development of new genetics and technologies. If multi-cultivar planting is widely adopted, it is possible that new technologies could be brought to market specifically to make use of this capability.

**Soil Moisture:** As previously discussed, soil moisture is probably the most obvious candidate to form the basis of a multi-cultivar strategy. Multi-cultivar planting could allow a more drought tolerant cultivar to be planted on hill slopes, sandy areas, or other areas prone to drought stress. Drought tolerant cultivars could also be planted in pivot corners in areas with central pivot irrigation. Conversely, a cultivar more tolerant to saturated soils or “wet feet” could be planted in low-lying or poorly-drained areas.

**Disease Resistance:** Hybrids or varieties with greater genetic resistance to disease could be placed on low-lying ground or other areas more prone to disease. Disease-resistant hybrids or varieties could also be placed in areas that are inaccessible for aerial applications of foliar fungicide, such as along treelines, near wind turbines or powerlines, or near populated areas.

**Stress Emergence:** Stress emergence ratings for Pioneer® brand corn products help categorize their genetic potential to emerge under stressful environmental conditions (including cold, wet soils or short periods of severe low temperatures) relative to other products. Multi-cultivar planting could be used to place a hybrid with a high stress emergence rating in areas of a field prone to poor emergence conditions, such as productive areas that may have high levels of residue, or low-lying areas that are slower to dry out and warm up in the spring.

**Insect Resistance / Refuge Placement:** Multi-cultivar planting would allow virtually limitless flexibility in placing structured insect refuges within a field. While this capability currently has limited utility in the Corn Belt due to the transition to blended refuge corn products, it could be useful in cotton-growing regions that require structured refuges, as a research tool, or possibly with a future insect protection technology in corn or other crops. Multi-cultivar planting would also allow selective placement of an insect-resistant hybrid or variety along fencerows or grass waterways to protect against insect pests that move in from field margins or in areas of a field at higher risk of insect damage due to prior cropping history or management practices.

**Herbicide Resistance:** With multi-cultivar planting, a hybrid or variety with additional herbicide resistant traits could be placed along field margins, field entrances, or grass waterways to allow spot-spraying for management of weed species moving in from seed brought in on machinery or from adjacent fields or fence-rows. Planting a herbicide-resistant hybrid or variety along a field margin could also be used to protect against herbicide drift from an adjacent field.

**Iron Deficiency Chlorosis Tolerance:** Soils with pH above 8.0 can result in alkalinity-induced chlorosis and reduced yield in corn and soybeans. Corn hybrids and soybean varieties both vary in their tolerance to elevated soil pH. Multi-cultivar planting would allow planting a hybrid or variety tolerant to chlorotic conditions in some areas of a field and another hybrid or variety that is more productive on lower pH soils. A DuPont Pioneer / University of Nebraska study conducted during 1998 to 2001 explored the possible value of multi-hybrid planting for increasing corn yield on high pH soils in Nebraska, although weather conditions during the study were generally not conducive to inducing chlorosis symptoms, and results were ultimately mixed (Doerge, 2002).
Standability: Multi-cultivar planting could potentially be used to help reduce the impact of lodging on yield. In the case of corn, this could involve planting a hybrid with stronger roots and/or stalks along field edges or other areas prone to wind lodging. For soybeans, a shorter stature variety could be placed on highly productive soils prone to lodging due to excessive plant height.

Maturity: Generally, planting of similar maturity hybrids or varieties would be an important component of a multi-cultivar strategy; however, in some cases, it could prove advantageous to selectively place products with differing maturities. A shorter maturity hybrid or variety could be placed in low lying areas or other parts of a field prone to slow maturity and drydown in the fall. A shorter maturity hybrid could also be placed in the end rows of a field to allow the field to be opened up earlier in the harvest season prior to harvesting the rest of the field.

Variable placement by hybrid or variety maturity could also be used to mitigate frost risk. Cold air accumulates in low-lying areas, putting them at a greater risk of frost damage. Placement of an earlier maturity hybrid or variety in these areas could reduce the risk of frost damage prior to physiological maturity, while allowing a fuller season hybrid or variety to be placed on higher ground less susceptible to early frost.

Seed-Applied Technology: Multi-cultivar planting could be used as a means to selectively place products based on seed-applied technology rather than genetics, or potentially based on both. As an example, this could involve placement of seed with a specific fungicide seed treatment in a part of a field prone to disease or an insecticide seed treatment in areas of a field at higher risk of insect damage due to prior cropping history or management practices. Populations of nematode species are known to vary by soil texture, with larger and more damaging species often more prevalent in sandy soils. Seed with a nematicide seed treatment could be placed in portions of a field at greater risk for nematode damage. With the rapid growth in seed treatment and seed-applied technologies, the potential applications for selective placement using a multi-cultivar planter will likely expand in the future.

Seed Production: Multi-cultivar planting technology could be useful in hybrid seed production, as it could allow greater flexibility and efficiency of planting male and female rows and border rows.

Potential Disadvantages

Although it is hypothetically possible that a poorly designed multi-cultivar prescription could actually result in yield loss, this outcome is probably unlikely in most cases. The more realistic risk for most growers would be that multi-cultivar planting provides no yield advantage or a yield advantage that is insufficient to offset the additional cost and complexity associated with multi-cultivar planting. Multi-cultivar planting would substantially increase the complexity of planting operations due to the need to create prescriptions and handle a larger number of cultivars. Multi-cultivar planting would also likely increase the frequency of planter fills, particularly if a prescription is heavily weighted toward one product, which would increase the amount of time needed for planting.
IS THE FUTURE OF CORN PRODUCTION IN NARROW ROWS?

INTRODUCTION

The vast majority of corn acres in the U.S. and Canada are currently planted in 30-inch rows, with narrow rows generally defined as any row spacing or configuration less than 30-inches. Narrow rows have proven beneficial in some scenarios but generally have not shown a consistent yield advantage in the central Corn Belt region that makes up the bulk of North American corn production. Consequently, adoption of narrow rows has remained low.

Despite being used on less than 5% of corn areas, interest in narrow-row production has persisted. This is largely due to the perception that evolving corn production practices will eventually favor a transition to narrower rows, similar to the past shift away from 36- to 40-inch rows into the current 30-inch standard. The purpose of this summary is to examine research that addresses: 1) the question of whether changes in corn production will eventually favor narrow rows and 2) if a wide-scale shift into narrow rows will be necessary at some point to continue to drive gains in corn productivity. Two factors that relate to row spacing, plant population, and plant leaf architecture will be examined in detail.

PROVEN BENEFITS OF NARROW ROWS

To evaluate the potential benefit of narrow row corn in the future, it is worth examining scenarios where they have already proven beneficial. Research has shown a strong relationship between improved yields in narrow row corn and increased light interception (Andrade et al., 2002). To maximize yield, the crop canopy needs to capture 95% or more of photosynthetically active radiation (PAR) during the critical period immediately before and after silking (Figure 1). Corn at a given density can intercept a greater percentage of solar radiation when planted in narrow rows, which can increase yield in cases where corn in 30-inch rows does not meet this threshold (Andrade et al., 2002).

Narrow rows can also improve nitrogen use efficiency of corn by increasing the ability of the crop to recover nitrogen from the soil (Barbieri et al., 2008). This can improve yield in nitrogen-deficient conditions; however, this advantage is reduced as nitrogen availability increases and may not result in increased yield when adequate nitrogen is available (Barbieri et al., 2000; Barbieri et al., 2008).

Yield benefits with narrow row corn have been observed more frequently in the northern portion of the Corn Belt in the area north of approximately 43°N latitude (a line running roughly through Mason City, IA; Madison, WI; and Grand Rapids, MI) (Lee, 2006). In a survey of several recent university studies comparing 15-, 20-, or 22-inch rows to 30-inch rows, an average yield advantage of 2.8% with narrow or twin rows was observed in northern studies, compared to no advantage on average (-0.2%) in the central Corn Belt (Jeschke, 2013). The lack of a consistent yield benefit in the central Corn Belt is likely because light interception and nitrogen uptake are generally not yield limiting in this area. Several studies have shown that corn in 30-inch rows can routinely capture over 95% of PAR in midwestern production (Figure 1) (Nafziger, 2006; Novacek et al., 2013; Robles et al., 2012; Sharratt and McWilliams, 2005; Tharp and Kells, 2001).

PLANT POPULATION

Long-Term Population Trends

It is generally assumed that optimum plant densities for corn will be significantly higher in the future than they are today. Examination of historical trends in plant population and corn yield show this assumption to be well-founded. Average corn yields have increased continually over the past 80 years as have average plant densities, increasing from around 12,000 plants/acre in the 1930s to over 30,000 plants/acre today (Duvick, 2005; DuPont Pioneer Brand Concentration Survey 2013). However, research has shown that yield potential per plant has not greatly increased over that time period. At low plant densities, current hybrids do not yield substantially more than hybrids of past decades (Duvick et al., 2004).

Figure 1. Percent of incident PAR intercepted by a corn canopy in central Iowa planted in 30-inch rows. Adapted from Puntel, 2012.

Figure 2. A corn canopy needs to intercept 95% or more of photosynthetically active radiation at silking to maximize yield.
Examination of more recent data supports these findings. Average corn yield in the U.S. has increased from 118 bu/acre in 1985 to 158.8 bu/acre in 2013 (USDA NASS, 2014). Average corn seeding rates have increased linearly over this period, from approximately 23,300 seeds/acre in 1985 to over 30,000 seeds/acre in 2013. When corn yield and seeding rate data are used to calculate average grain yield/plant, the resulting trend line shows that average yield per plant has remained relatively constant at around 0.3 lbs/plant.

Figure 3. Average grain yield per plant in the U.S. from 1985 to 2013, based on average corn yields (USDA-NASS, 2014) and average corn seeding rates* (DuPont Pioneer Brand Concentration Survey 2013). *Assumes harvest stand = 95% of seeding rate.

Higher plant density is not the only path to greater corn yields. In fact, growers who produced corn yields greater than 300 bu/acre in the 2013 NCGA National Corn Yield Contest did so over a wide range of plant populations. Harvest populations ranged from 29,000 plants/acre to 48,000 plants/acre, with the majority between 32,000 and 42,000 plants/acre (Jeschke, 2014).

Yield per plant varied widely as well, ranging from 0.36 lbs/plant to 0.64 lbs/plant. Grain yield per plant for these entries averaged around 0.5 lbs/plant, well above the current U.S. average. These data show that it is possible to increase corn yields per acre by increasing individual plant yield as opposed to plant density; however, this has not been achieved on a wide scale.

Why Might Narrow Rows be Favorable at Higher Populations?

The primary rationale for narrow corn row spacings is that reducing the crowding of plants within a row, will reduce competition among individual plants and allow the crop to better utilize available light, water, and nutrients. As plant density increases, plants are closer together within a row and it seems reasonable to think that, at some point, this crowding could become yield-limiting.

Table 1. Current average and high-end seeding rates and projected rates for 2035 and 2050 based on current trends.

<table>
<thead>
<tr>
<th>Seeding Rate</th>
<th>2013</th>
<th>2035 (projected)</th>
<th>2050 (projected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>31,000</td>
<td>37,000</td>
<td>42,000</td>
</tr>
<tr>
<td>High-End</td>
<td>38,000</td>
<td>44,000</td>
<td>49,000</td>
</tr>
</tbody>
</table>

The lack of a consistent yield benefit to narrow rows observed in most areas thus far suggests that this theoretical yield-limiting point has not been reached with current management practices. However, if such a point is reached in the future and higher corn yields continue to be driven by greater plant density, a wide-scale transition to narrower rows would then presumably be necessary to drive further gains. Several research studies may shed light on whether this theory is valid.

Narrow Row, High Population Research

A number of corn row spacing studies published during the last 15 years have included plant populations well above the current average (Table 2). If plant crowding within the row is indeed yield-limiting at high plant populations, then narrow rows would be expected to have a yield advantage over 30-inch rows in these studies.

Studies 1 through 5 in Table 2 are university studies that included plant populations over 40,000 plants/acre. Four of these studies, conducted in Nebraska, Iowa, Minnesota, and Indiana, did not show any yield advantage to narrow or twin rows at high populations (Table 2). The one study that showed an advantage was conducted in northern Minnesota where yield advantages with narrow rows have tended to be more consistent.

Studies 6 and 7 were recently conducted in Illinois and Indiana comparing 30-inch and twin rows at extremely high plant
populations of up to 65,000 plants/acre. In both of these studies, corn yield was actually significantly reduced in twin rows at high populations (Table 2). In the Indiana study, at populations of 50,000, 55,000, and 65,000 plants/acre, yield in twin rows was 8% less than in 30-inch rows. In the Illinois study, at 45,000 and 55,000 plants/acre, twin rows had 5% lower yield but significantly greater yield at the lowest population tested (25,000 plants/acre). The researchers hypothesized that the yield reduction with twin rows at high populations may have been due to increased air and leaf temperatures in the middle stratum of the canopy, leading to accelerated leaf senescence.

Will Higher Populations Require Narrow Rows?

Because it is not supported by research, the theory that corn production at higher populations will need to transition to narrower rows for continued gains is called into question. Row spacing studies with high populations have not shown an advantage to narrow or twin rows outside of the northern Corn Belt, where narrower rows have historically had a more consistent yield advantage. Additionally, a new corn yield record of 454 bu/acre was set in 2013 at 47,000 plants/acre in 30-inch rows, clearly demonstrating the potential to achieve much greater yields at high populations without the need for narrower row spacing.

HYBRID CHANGES IN LEAF ARCHITECTURE

The development of hybrids especially suited to a narrow-row, high-population environment is often cited as potentially favoring narrower rows in the future. The idea of optimizing hybrids for narrow-row production has most commonly focused on leaf architecture, specifically, that plants with narrower and more upright leaves may be more suited to narrow rows. Like plant population, plant architecture is another factor in corn production that has greatly changed over the past several decades, so it is not unrealistic to suggest that the future could bring further changes.

Changes in Leaf Architecture in the Hybrid Era

Continual selection for greater yield during the hybrid era has resulted in significant changes to many plant characteristics. For example, modern hybrids tend to be slightly shorter with lower ear placement. Tassel size and number of branches has been significantly reduced compared to early hybrids. However, the difference in leaf architecture, specifically a trend toward upright leaves (Figure 5), is perhaps the most visually apparent contrast between early and modern hybrids (Duvick, 2005).

The shift toward more upright leaf architecture began with the introduction of Iowa State University’s B73 inbred into breeding programs during the 1970s (Figure 6). Subsequent hybrids tended to have a more upright leaf angle and a greater length to the leaf flagging point compared to their predecessors (Duvick, 2005; Meghji et al., 1984; Lauer et al., 2012). Today, nearly all North American hybrids could be characterized as having upright leaves compared to those of the past.

Figure 5. Pioneer® hybrid 354 (introduced in 1953) and Pioneer P1365AMXTM (AMX, LL, RR2) brand corn (introduced in 2013) (Johnston, Iowa; July 16, 2013).

This industry-wide transition to more upright leaves is commonly considered to be an important factor that has enabled corn performance at higher plant densities. Upright leaves increase the distribution of light in the canopy; less light is captured by the uppermost leaves and more light penetrates further down where it is captured by lower leaves, thereby increasing photosynthetic efficiency. This improvement is greatest in corn canopies with a high leaf area index, generally associated with high populations. The canopy of a typical corn crop has greatly increased in leaf area index over the years, from approximately 2.4 m²/m² in the 1930s to 4.8 m²/m² or greater today (Lee and Tollenaar, 2007).

### Table 2. Yield advantage (%) of 15-, 20-, or 22-inch and twin rows compared to 30-inch rows observed in recent corn row spacing research studies in the Midwestern U.S. that included high plant populations (indicated in bold).

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Row Widths (inches)</th>
<th>Populations (1,000 plants/acre)</th>
<th>Row Width x Population Interaction?</th>
<th>Narrow Row Advantage at High Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minnesota</td>
<td>22 vs. 30</td>
<td>16.5, 22, 27.5, 33, 38.5, 44</td>
<td>Yes</td>
<td>4%</td>
</tr>
<tr>
<td>2</td>
<td>Nebraska</td>
<td>twin vs. 30</td>
<td>28, 33, 38, 42</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>Iowa</td>
<td>15 vs. 30</td>
<td>20, 28, 36, 44</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>Minnesota</td>
<td>20 vs. 30</td>
<td>16.5, 22, 27.5, 33, 38.5, 44</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>Indiana</td>
<td>twin vs. 30</td>
<td>28, 33, 38, 42</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>Indiana</td>
<td>twin vs. 30</td>
<td>35, 40, 45, 50, 55, 65</td>
<td>Yes</td>
<td>-8%</td>
</tr>
<tr>
<td>7</td>
<td>Illinois</td>
<td>twin vs. 30</td>
<td>25, 35, 45, 55</td>
<td>Yes</td>
<td>-5%</td>
</tr>
</tbody>
</table>

The extent to which changes in leaf architecture have actually directly contributed to increased corn yield is unclear, however. Several experiments on corn leaf angle conducted during the 1960s and 1970s produced variable results; some showed an advantage with upright leaves at higher plant densities (Lambert and Johnson, 1978; Pendleton et al., 1968; Pepper et al., 1977), and some did not (Hicks and Stucker, 1972; Russell, 1972; Whigham and Woolley, 1974). It is possible that increased light penetration in the canopy associated with upright leaves may provide indirect benefits via increased carbohydrate partitioning to the ear and delayed leaf senescence (Hammer et al., 2009).

Research Comparing Hybrid Response to Narrow Rows

Most research studies conducted during the past 25 years have not found consistent differences in hybrid response to narrow rows. Out of 15 university row spacing studies published between 1997 and 2013 that included more than one hybrid, only one reported a significant hybrid by row spacing interaction (Farnham, 2001). Furthermore, none of these studies showed a significant difference in hybrid performance in narrow rows that was specifically associated with a difference in leaf architecture.

Research conducted in Michigan compared performance of six hybrids in narrow rows (Widdicombe and Thelen, 2002). Of these hybrids, two were characterized as having erect leaf orientation, three with semi-upright leaves, and one with wide leaves. Average corn yield was significantly higher in narrow rows, but performance did not differ among hybrids. A study in Minnesota comparing two hybrids of differing leaf architecture also found no difference in yield response to narrow rows (Sharratt and McWilliams, 2005).

A 3-year DuPont Pioneer/University of Missouri study compared 11 hybrids in 15- and 30-inch rows. This study found a significant hybrid by row spacing interaction; however, hybrids with more upright leaves did not perform any better than other hybrids in narrow rows.

Can Hybrids be Designed for Narrow Rows?

The fact that most recent research studies have not found a significant difference in hybrid response to row spacing indicates that there is likely little variation among modern hybrids in their suitability to narrow rows, although the few studies that have found such a difference show that some variation does exist. Whether or not this variation could be exploited to design future hybrids for narrow rows and whether or not this would significantly increase corn productivity is unclear. The transition to more upright leaves in modern hybrids has likely contributed to improvement in corn yield associated with higher plant densities to some extent; however, research suggests it is unlikely that further changes in leaf angle offer a meaningful opportunity for yield improvement in the future (Lee and Tollenaar, 2007).

Past research on hybrids with extremely upright leaves has shown that narrow rows may increase productivity for hybrids that are unable to capture 95% of PAR in 30-inch rows. Extremely upright leaves that remain close to the stalk can have the negative effect of allowing light in the interrow to penetrate to the soil surface, an effect that narrower rows would tend to help mitigate. A research study including a Chinese hybrid with extremely upright leaves noted this effect (Stewart et al., 2003). A canopy photosynthesis model predicted that changing from 30-inch to 15-inch rows would significantly increase photosynthetic production with this hybrid, whereas minimal benefit was predicted for a comparative hybrid at a similar leaf area index.

Research has examined the potential of developing semi-dwarf hybrids for corn production in the far northern Corn Belt, the primary advantage of which would be earlier maturity than conventional hybrids (Schaefer et al., 2011; Combs and Bernardo, 2013). Such hybrids would require narrow rows and extremely high plant populations, similar to small grain production, to maximize productivity. Semi-dwarf hybrids could also potentially be advantageous in arid climates or in double-crop rotations, although their overall value for improving corn productivity has yet to be determined.

IS THE FUTURE OF CORN PRODUCTION IN NARROW ROWS?

It is possible that changes in corn production practices may eventually favor a transition away from the current 30-inch row spacing standard to narrower rows; however, research provides little evidence to suggest such a transition will be necessary or justified in the near future. Future yield gains will likely continue to be driven by higher plant populations, but research that has compared row spacing at populations from 40,000 to 65,000 plants/acre has generally not shown a yield advantage to narrow rows outside of the northern Corn Belt.

Modern hybrids typically have not differed in their response to narrow rows. When yield differences have been observed, they have not been associated with any particular characteristic of leaf architecture. Research with extremely upright-leaf hybrids and semi-dwarf hybrids has shown that narrow rows can be beneficial when 30-inch rows do not allow complete capture of PAR at silking. These studies indicate that development of hybrids optimized for narrow rows is possible; however, it is not clear if such hybrids could lead to greater productivity on a wide scale.

**SOURCES**

Enter this link in your browser to view sources:
https://www.pioneer.com/home/site/us/agronomy/corn-production-narrow-rows/#sources
ANALYTICS OF THE ENCIRCA\textsuperscript{SM} YIELD NITROGEN MANAGEMENT SERVICE

THE NITROGEN MANAGEMENT CHALLENGE

Nitrogen (N) management is among the most uncertain and costly aspects of modern corn production. Because soil nitrogen varies dynamically in response to the interaction between soils and weather, the optimal nitrogen application rate for any year or location varies widely (Figure 1; Scharf et al., 2005; Nafziger et al., 2008). As a result, nitrogen is often inadvertently over- and under-applied, reducing profitability (Lambert et al., 2006) and in some cases, leading to environmental contamination (Jaynes et al., 2001).

USING CROP MODELS TO GUIDE NITROGEN MANAGEMENT

Growers do not make corn nitrogen fertilizer rate decisions lightly, but yield goals (Hoeft et al., 2000) and generalized nitrogen response relationships (Sawyer et al., 2006) are often the best guidelines available to guide management. Neither of these approaches account for how variability in soils and weather affect crop growth and nitrogen availability at specific locations. Crop models offer one way to bring field and weather variability information into the nitrogen management decision-making process. While crop simulation models have historically been used for research purposes, advances in cloud computing and data management now make it possible to effectively extend crop models to commercial production systems. One of the major advantages of using crop models to guide nitrogen management decisions is that they can integrate the numerous, complex processes that affect soil nitrogen and provide actionable information that has meaning in a management context. Crop models can also incorporate weather information dynamically as it occurs so that nitrogen can be monitored and managed in real time.

ENCIRCA\textsuperscript{SM} YIELD NITROGEN MANAGEMENT SERVICE MODEL

The Encirca\textsuperscript{SM} Yield Nitrogen Management Service is based on a suite of crop and soil models developed by DuPont Pioneer scientists, using a combination of publicly available and proprietary data sources. Together, the components of the Encirca services nitrogen model estimate changes in soil nitrogen and crop nitrogen requirements that occur over time in response to weather, soil characteristics, crop growth, and management practices (Figure 2).

ENCIRCA SERVICES NITROGEN MODEL INPUTS

**Weather Data**

The Encirca services nitrogen model is updated daily with high-resolution weather data from an industry-leading rural weather network powered by DTN/\textit{The Progressive Farmer}, which links together thousands of on-farm weather stations. Growers that choose to enroll in Encirca View \textit{Premium} have a weather station installed on their farm.

**Soils Data**

Pioneer scientists have collaborated with scientists at the University of Missouri and the USDA-Agricultural Research Service (ARS) to create improved soil maps called Environmental Response Units (ERUs). ERUs reclassify the spatial distribution of soil properties

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**Figure 1.** Variability in corn economic optimum nitrogen fertilization rate observed over six years at seven locations in Illinois (adapted from Nafziger et al., 2008).
within fields based on high resolution digital elevation data and provide a more precise definition of the field-scale hydrological attributes that drive productivity and nitrogen availability.

**Operational Data**

Growers have the option to use their own historical yield data to help define productivity objectives for fields they enroll in the Encirca Yield Nitrogen Management Service.

**Management Practices and Objectives**

Growers work with their Encirca certified services agent or Pioneer sales professional to ensure that management practices and objectives in the model reflect reality.

**ENCIRCA® YIELD NITROGEN MANAGEMENT SERVICE MODEL COMPONENTS**

**Crop Growth and Nitrogen Uptake**

One of the core components of the Encirca services nitrogen analytics is a dynamic crop model that simulates corn growth, development, and nitrogen uptake (Figure 3). The crop model is driven by local weather and soils as well as management practices, including planting date and seeding rate, that are entered by the user. The rate of crop growth and development is also controlled by the relative maturity of the selected corn hybrid.

**Nitrogen Mineralization**

Mineralization describes the process by which soil microorganisms decompose organic matter (OM) and convert it into mineral components that are accessible to plants as nutrients. When mineralized, nitrogen in soil organic matter is first converted to ammonium (ammonification) and then to nitrate (nitrification). In the Encirca services nitrogen analytics, soil temperature, texture, drainage, organic matter, and previous crop are the primary factors that determine how much mineral nitrogen is released into the soil during the growing season and at what rate. Manure applications also affect N mineralization potential. All else equal, nitrogen mineralization will be greatest for warm, moist soils with high organic matter content (Figure 4).

**Nitrate Leaching**

Soil texture, soil temperature, drainage, precipitation, and crop growth all interact in the Encirca services nitrogen analytics to determine how much nitrate-nitrogen may be lost from the soil as a result of leaching. Well-drained soils and heavy precipitation may lead to excessive leaching, while little or no leaching may occur in the absence of precipitation or on poorly-drained soils (Figure 5). In most situations, leaching losses are confined to the first 30 to 60 days after planting. Soil temperatures prior to planting are generally too low for much of the nitrogen in the soil to be converted to nitrate. By 60 days after planting, crop nitrogen uptake is so rapid that little nitrate is typically available in the soil to be lost.
Denitrification represents the loss of nitrate-nitrogen that is converted to a gaseous form in the absence of oxygen. Denitrification most commonly occurs on low-lying field areas that pond after heavy precipitation. In the Encirca services nitrogen analytics, denitrification is driven by many of the same factors that cause leaching, but the effect of soil texture and drainage is reversed. Poorly-drained soils typically experience moderate to high levels of denitrification when saturated for an extended period of time, while little or no denitrification occurs on well-drained soils, even with heavy precipitation (Figure 5).

Ammonia Volatilization

Fertilizers containing urea are subject to a third form of loss called volatilization. Once applied, urea breaks down to ammonia and carbon dioxide in the presence of the ubiquitous urease enzyme. If ammonia is on the soil surface, it can be lost as a gas. In the Encirca services nitrogen model, the amount of ammonia volatilization depends on application method, soil temperature, pH, and soil water content. Volatilization losses are greatest when surface applied urea comes into contact with warm, dry soils (Figure 7). In contrast, cool, wet soils and/or urea incorporation greatly reduce the potential for volatilization. High pH soils can also have greater volatilization losses.
Figure 7. Model-estimated cumulative nitrogen volatilization for two surface-applied urea applications in Putman Co., OH, in 2007. See Table 1 for simulation details.

FRAMEWORK FOR RISK-BASED DECISION MAKING

The outcomes of nitrogen management decisions are inherently uncertain due to imperfect knowledge of future weather events that strongly influence crop growth and soil nitrogen levels. To account for uncertainty in nitrogen management, the Encirca services nitrogen analytics simulate historical and forecasted weather in conjunction with grower yield goals to provide estimates of the risk associated with planned management actions. The level of risk for a given management plan or set of plans is displayed in the Encirca Yield Nitrogen Management Service user interface using an intuitive color-coded system (Figure 8).

Figure 8. Risk associated with three hypothetical nitrogen management plans for 2015 based on simulations conducted on November 15, 2014. Green field areas represent low risk potential, while yellow and red field areas represent moderate and high risk potential, respectively.

VARIABLE RATE NITROGEN RECOMMENDATION MODEL

The Encirca services nitrogen analytics can be used to generate and export variable rate nitrogen recommendations for any desired application date, method, and product. The variable rate recommendation component of the model shares a common structure with the method described above for estimating nitrogen decision risk. The difference between the risk assessment framework and the variable rate recommendation logic is that the former shows the risk associated with currently planned applications, while the latter computes the rate of nitrogen required to minimize economic and other potential risk given all prior applications entered into the user interface as well as historical and forecast weather (Figure 9).

Figure 9. The Encirca services nitrogen model uses soil and weather information in conjunction with yield goals to generate variable rate nitrogen recommendations that minimize risk of yield loss from insufficient nitrogen.

Table 1. Details for model scenarios presented in Figures 3-7. All simulations were based on a 109 CRM corn hybrid planted at 34,000 seeds per acre on May 1. Soybean was the previous crop in all simulations.

<table>
<thead>
<tr>
<th>Scenario/Related Figure</th>
<th>State, County</th>
<th>Weather Year(s)</th>
<th>Soils</th>
<th>N Fertilization</th>
</tr>
</thead>
</table>
| Corn Growth/ N Uptake 3 | IA, Story     | 2007; 2012      | Webster clay loam | April 20: 150 lb N/acre^1  
                          |               |                 |                   | May 1: 30 lb N/acre^2 |
| Mineralization 4        | NE, Clay      | 2012; 2014      | Thurman loamy sand; Hastings silt loam | April 20: 150 lb N/acre^1  
                          |               |                 |                   | May 1: 30 lb N/acre^2  
                          |               |                 |                   | (32%) |
| Leaching 5              | IL, Woodford  | 2013, 2013^     | Plainfield sand; Sawmill silty clay | April 20: 150 lb N/acre^1  
                          |               |                 |                   | May 1: 30 lb N/acre^2 |
| Denitrification 6       | IL, Woodford  | 2013, 2013^     | Plainfield sand; Sawmill silty clay | April 20: 150 lb N/acre^1  
                          |               |                 |                   | May 1: 30 lb N/acre^2 |
| Volatilization 7        | OH, Putman    | 2007            | Toledo clay | March 20: 150 lb N/acre^1  
                          |               |                 |                   | April 20: 150 lb N/acre^2 |

^1Modeled as 2013 with each precipitation event reduced in magnitude by 50%.  
^2Injected NH3, ^3Broadcast UAN, ^4Broadcast urea.

SOURCES

Enter this link in your browser to view sources:
SOLAR RADIATION IN CORN PRODUCTION

SOLAR RADIATION AND CROP NEEDS

- Along with water and nutrients, solar radiation (sunlight) is an essential input for plant growth.
- Plant leaves absorb sunlight and use it as an energy source in the process of photosynthesis.
- A crop’s ability to collect sunlight is proportional to its leaf surface area per unit of land area occupied, or its “leaf area index” (LAI).
  » At “full canopy” development, a crop’s LAI and ability to collect available sunlight are maximized.
- From full canopy through the reproductive period, any shortage of sunlight is potentially limiting to corn yield.
  » When stresses, such as low light, limit photosynthesis during ear fill, corn plants remobilize stalk carbohydrates to the ear. This may result in stalk quality issues and lodging at harvest.
- The most sensitive periods of crop growth (e.g., flowering and early grain fill) are often the most susceptible to stresses, such as insufficient light, water, or nutrients.

CLOUD EFFECTS ON SOLAR RADIATION

- Plants are able to use only a portion of the solar radiation spectrum. This portion is known as “photosynthetically active radiation” (PAR) and is estimated to be about 43% to 50% of total radiation.
- Amount of PAR available to a crop is reduced proportionately to cloud cover (Figure 1).

Photosynthetically Active Radiation (PAR)

<table>
<thead>
<tr>
<th>Daily Weather Conditions</th>
<th>Daily PAR (mol / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainy (6/24)</td>
<td>21.8</td>
</tr>
<tr>
<td>Cloudy (7/13)</td>
<td>27.9</td>
</tr>
<tr>
<td>Partly Cloudy (7/17)</td>
<td>44.3</td>
</tr>
<tr>
<td>Sunny (7/12)</td>
<td>57.6</td>
</tr>
</tbody>
</table>

Figure 1. Daily PAR received in Johnston, IA, under rainy, cloudy, and sunny conditions on four different days in summer.

- As Figure 1 shows, PAR was reduced by 25% to 50% on partly cloudy to cloudy days and by over 60% on rainy days.
- It is not surprising, then, that cloudy, rainy periods during susceptible stages of crop development can have significant effects on yield.

EFFECT OF SHADE ON CORN YIELD

- A study using “shade cloth” reduced solar radiation by 55% during various crop stages (Liu and Tollenaar, 2009).
- Yield was significantly reduced by shading at the silking and post-silking stages (Table 1).

Table 1. Effect of shade treatments on yield (Tollenaar, 2009).

<table>
<thead>
<tr>
<th>Shade Period¹</th>
<th>Yield Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 weeks pre-silking¹</td>
<td>3.2% NS</td>
</tr>
<tr>
<td>3 weeks at silking²</td>
<td>12.6% **</td>
</tr>
<tr>
<td>3 weeks post-silking²</td>
<td>21.4% **</td>
</tr>
</tbody>
</table>

¹ Weeks relative to silking: a -5 to -1, b -1 to +2, c +2 to +5. NS=not significant, **= highly significant (Prob>F=0.05).

- In another study, solar radiation was reduced by 50% using shade cloth (Reed et al., 1988).
- Yield was significantly reduced by shading at the flowering and post-flowering stages.
- Shading during flowering reduced yield primarily through decreasing the number of kernels per row.
- Shading during grain fill reduced yield primarily through decreasing kernel weight.

Table 2. Effect of shade treatments on yield (Reed et al., 1988).

<table>
<thead>
<tr>
<th>Shade Period</th>
<th>Yield Reduction (%)</th>
<th>Change in Kernels/Rows</th>
<th>Change in Kernel Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetative</td>
<td>12%</td>
<td>-5%</td>
<td>+1%</td>
</tr>
<tr>
<td>Flowering</td>
<td>20%</td>
<td>-21%</td>
<td>+9%</td>
</tr>
<tr>
<td>Grain Fill</td>
<td>19%</td>
<td>-5%</td>
<td>-13%</td>
</tr>
<tr>
<td>LSD (.05)</td>
<td>7%</td>
<td>4.5%</td>
<td>6%</td>
</tr>
</tbody>
</table>
AVERAGE U.S. SOLAR RADIATION

- Daily light integral (DLI) is the total amount of solar radiation received at a location each day.
- The southern versus northern U.S. has higher DLIs in the fall and winter due to longer days and higher angle of the sun (Figure 2).
- From May through August, the primary DLI differences occur between the eastern and western U.S. (Figure 2).
  » Northern areas have longer days but a lower solar elevation angle, so DLI is about the same as in southern areas during most of the corn growing season.
- Elevation and regional weather patterns (primarily cloud cover and humidity) also contribute to regional differences.

![Map showing average daily light integral (DLI) by month](image)

**Figure 2.** Average U.S. daily light integral (DLI) by month (Korczynski, et al., 2002).

2015 GROWING SEASON AND SOLAR RADIATION

- Cloud cover and rainfall during vegetative, flowering, and early kernel development reduced solar radiation during these stages in 2015 (Figure 3).
- Flowering generally occurred from 7/10 to 7/25 in the central Corn Belt and from 7/20 to 7/31 in northern states and Ontario.
  » This period (R1) and the very early kernel development stage that follows (R2 or “blister”) are especially sensitive to environmental conditions.

![Map showing 2015 deviation from normal (2006-2015 avg.) solar radiation](image)

**Figure 3.** 2015 deviation from normal (2006-2015 avg.) solar radiation during the “lag phase” of development.

“Lag phase” is the time from pollination to the beginning of the linear phase of rapid dry matter accumulation in the kernel and corresponds with the R1 (silking) through R2 (blister) stages of development.

- Solar radiation during early kernel development in 2015 was well below the 10-year normal in many locations.
- Research (see Tables 1 and 2) indicates that inadequate sunlight during this stage can result in decreased yield, primarily due to less kernels produced per ear (“nosing back”).
- In addition to aborted ear tip kernels, lower sunlight during grain fill often results in lower kernel weights, poor stalk quality, and premature plant death.
  » Growers should monitor stalk quality and schedule harvest based on lodging potential, rather than just grain moisture.

REFERENCES


Corn Leaf Angle Response to Plant Density

Background and Objectives

- Previous research has shown that corn plants can alter their leaf angle in response to their environment.
- At greater densities, plant leaf angle tends to be more upright in order to optimize capture of sunlight.
- Plasticity of leaf angle in response to plant density have been shown to differ among hybrids.
- A research study was conducted in 2015 to evaluate leaf angle response to plant density with two Pioneer® brand corn products.

Study Description

Location: Johnston, IA
Replicates: 4
Plot Layout: Small plots (10 x 17.4 ft.), RCBD
Row Width: 30 inches
Planting Date: May 19, 2015
Factors:
- Pioneer® brand corn products
  Hybrid/Brand¹: P1151AM™ (AM, LL, RR2)
  P1311AMXT™ (AMXT, LL, RR2)
- Population: 30,000, 40,000, and 50,000 plants/acre

Leaf angle measurements were taken using a clinometer smartphone app.

Results

- Upper leaves tended to be substantially more upright for both corn products across all population densities (Figure 3).
- Angle of leaf 10 was significantly influenced by both plant density and corn product.
  - Average leaf angle was significantly more upright with greater population density (Figure 4).
  - The average angle of leaf 10 was significantly more upright for P1151AM™ than P1311AMXT™ (Figure 5).

¹All Pioneer products are hybrids unless designated with AM1, AM, AMRW, AMX, AMT and AMXT; in which case they are brands. 2015 data are based on average of all comparisons made in one location through August 17, 2015. Multi-year and multi-location is a better predictor of future performance. Do not use these or any other data from a limited number of trials as a significant factor in product selection. Product responses are variable and subject to a variety of environmental, disease, and pest pressures. Individual results may vary. PIONEER® brand products are provided subject to the terms and conditions of purchase which are part of the labeling and purchase documents.
Results (continued)

- There was a significant interaction between corn product and population density in their effects on angle of leaf 14.
- P1311AMXT™ had a greater response to density than P1151AM™.

**Figure 4.** Average angle of the 10th leaf (degrees from vertical) as affected by plant density.

![Graph showing average angle of the 10th leaf](image)

**Figure 5.** Average angle of the 10th leaf (degrees from vertical) by corn product.

![Graph showing average angle of the 10th leaf by corn product](image)

**Figure 6.** Average angle of the 14th leaf (degrees from vertical) by corn product and plant density.

![Graph showing average angle of the 14th leaf](image)

**Conclusions**

- The results of this study demonstrate the ability of corn plants to adjust their leaf angle in response to their environment.
- Future efforts to optimize the crop canopy for maximum light utilization and yield need to take this effect into account.
- Results suggest that attempts to optimize crop canopy through management may have limited benefit due to the inherent ability for plants to adjust themselves in response to their environment.

**Authors:** Mark Jeschke and Adelyn Uppena

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**AcreMax® AcreMax AcreMax**

AM - Optimum® AcreMax® Insect Protection system with YGCB, HX1, LL, RR2. Contains a single-bag integrated refuge solution for above-ground insects. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax® Xtra products. AMKT - Optimum® AcreMax® XTreme contains a single-bag integrated refuge solution for above- and below-ground insects. The major component contains the Agrisure® RW trait, the YieldGard® Corn Borer gene, and the Herculex® XTRA genes. In EPA-designated corn growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax® Xtra products. HX1 - Contains the Herculex® I Insect Protection gene which provides protection against European corn borer, southwestern corn borer, black cutworm, fall armyworm, western loopers, western corn rootworm, larval corn stalk borer, southern corn stalk borer, and raggedstems borers, and supereemer corn rootworms. HXX - Herculex® XTRA contains the Herculex® I and Herculex® RW genes. YGCB - The YieldGard® Corn Borer gene offers a high level of resistance to European corn borer, southwestern corn borer and southern cornstalk borer; moderate resistance to corn earworms and common stalk borers; and above average resistance to fall armyworms. LL - Contains the LibertyLink™ gene for resistance to Liberty® herbicide. LL2 - Contains the RoundUp Ready® Corn 2 trait that provides crop safety for over-the-top applications of labeled glyphosate herbicides when applied according to label directions. LibertyLink™ is a registered trademark of Dow AgroSciences and Pioneer Hi-Bred. Herculex® and the HX logo are registered trademarks of Dow AgroSciences LLC. YieldGard®, the YieldGard® Corn Borer design and RoundUp Ready® are registered trademarks used under license from Monsanto Company. Agrisure® is a registered trademark of, and used under license from, a Syngenta Group Company. Agrisure® technology incorporated into these seed is commercialized under a license from Syngenta Crop Protection AG. Liberty®, LibertyLink™ and the Water Droplet Design are registered trademarks of Bayer.

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Corn Leaf Orientation Response to Plant Density

Background and Objectives

- Previous research has shown that corn plants can alter their leaf orientation in response to their environment (Girardin, 1992; Maddonni et al., 2001; Maddonni et al., 2002).
- Leaves may preferentially orient toward the inter-row in order to optimize capture of sunlight.
- A research study was conducted in 2015 to evaluate leaf orientation response to plant density with two Pioneer® brand corn products.

Study Description

<table>
<thead>
<tr>
<th>Location:</th>
<th>Johnston, IA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replicates:</td>
<td>4</td>
</tr>
<tr>
<td>Plot Layout:</td>
<td>Small plots (10 x 17.4 ft), RCBD</td>
</tr>
<tr>
<td>Row Width:</td>
<td>30 inches</td>
</tr>
<tr>
<td>Row Direction:</td>
<td>North-south</td>
</tr>
<tr>
<td>Plating Date:</td>
<td>May 19, 2015</td>
</tr>
<tr>
<td>Factors:</td>
<td></td>
</tr>
<tr>
<td>- Pioneer® brand corn products</td>
<td></td>
</tr>
<tr>
<td>Hybrid/Brand¹:</td>
<td>P1151AM™ (AM, LL, RR2) P1311AMXT™ (AMXT, LL, RR2)</td>
</tr>
<tr>
<td>Population:</td>
<td>30,000, 40,000, and 50,000 plants/acre</td>
</tr>
</tbody>
</table>

Leaf Measurements

- Leaf orientation measurements were taken on the 2nd, 6th, 10th, and 14th leaf of ten plants in each plot.
- Leaf orientation was measured using a compass smartphone app.
  - 0° and 180° = parallel to the row
  - 90° and 270° = perpendicular to the row

Results

- Leaf orientation distribution did not significantly differ between corn products or among population densities.
- Leaves tended to orient more toward the inter-row with successive growth stages (Figure 1).
  - Preferential orientation toward the inter-row was apparent at leaf 6, indicating that plants were responding to neighboring plants at relatively early stages of vegetative growth.
  - These results are consistent with previous research that has also detected nonisotropic structure in corn plants as early as the 6th leaf (Girardin, 1992).

Figure 1. Distribution of azimuthal orientation for leaf 2, leaf 6, leaf 10, and leaf 14 averaged across corn products and population densities.

¹All Pioneer products are hybrids unless designated with AM1, AM, AMRW, AMX, AMT and AMXT, in which case they are brands. 2015 data are based on average of all comparisons made in one location through August 17, 2015. Multi-year and multi-location is a better predictor of future performance. Do not use these or any other data from a limited number of trials as a significant factor in product selection. Product responses are variable and subject to a variety of environmental, disease, and pest pressures. Individual results may vary. PIONEER® brand products are provided subject to the terms and conditions of purchase which are part of the labeling and purchase documents.
These results suggest that leaf orientation response of corn plants to

- Orientation of leaf 10 showed a much stronger relationship to the orientation of leaf 6 (Figure 3), as did leaf 14 to leaf 10 (Figure 4).
- These results suggest that leaf orientation response of corn plants to neighboring plants occurred largely during early vegetative growth between V2 and V6, after which leaf orientation was relatively static.

Conclusions

- The results of this study demonstrate the ability of corn plants to adjust their leaves in response to their environment.
- Future efforts to optimize the crop canopy for maximum light utilization and yield need to take this effect into account.
- Results suggest that attempts to optimize corn leaf orientation through seed positioning at planting may have limited benefit due to the inherent ability for plants to adjust themselves in response to their environment.

References


Authors: Mark Jeschke and Adelyn Uppena
CORN YIELD GAINS DUE TO GENETIC AND MANAGEMENT IMPROVEMENTS

One of the great success stories of modern history has been ever-increasing crop yields, which have helped to feed a growing global population, compensated for shrinking farm acres, and provided a source of not only food and feed, but also fuel and fiber. No crop has made more impressive gains than corn, which has more than doubled in yield in the last half century. These gains have been due to improvements in both corn genetics and crop management practices.

Whether farmers and scientists can continue to make yield gains at the same rate as in the past has been a point of recent debate. Some speculate that gains will necessarily level off as corn yields approach the “theoretical maximum” yield estimated by computer growth models. Others point to modern breeding techniques, including use of transgenic traits, genetic markers, doubled haploids, improved information technology, and other advances that may actually increase the rate of genetic gain. Crop management gains are also a certainty as new technologies evolve.

Addressing the “rate of yield gain” question is important because the future potential of crop yields has profound impacts for farmers, landowners, consumers, input suppliers, policymakers, and others. For this reason, DuPont Pioneer researchers conducted studies to help determine the genetic component of corn yield increases over time. These studies were designed to measure genetic progress throughout the entire period of hybrid corn culture in the U.S. This article discusses the yield gains documented in those studies as well as those resulting from improvements in crop management practices.

HYBRID CORN ADOPTION IN THE UNITED STATES

- U.S. farmers began to evaluate the performance of hybrid corn vs. “open-pollinated” varieties during the early 1930s.
- Adoption rates of hybrids reached 50% of corn area in Iowa during 1938 and 100% by 1942.
- Adoption rates in the U.S. reached 50% during 1943 but only approached 100% by 1960 (Duvick, 2001).

DESIGNING TESTS TO MEASURE GENETIC GAIN

By maintaining historic parent lines, hybrids from the past can be recreated and tested against modern hybrids. In controlled experiments in which all other variables are held constant, yield differences between these “era hybrids” can be attributed to genetic differences, and genetic progress achieved over time can be determined. However, plant density requires special treatment in this kind of study. Because optimal plant populations have increased as hybrid genetics have improved over time, subjecting older hybrids to currently used populations would place them at a disadvantage. Instead, several populations are tested, allowing researchers to determine the yield of each era hybrid at its most optimal population and to use this value when comparing to hybrids of different eras. This metric has been the norm for reporting genetic gain from “era” studies and can be interpreted as the rate of gain that would apply if genetic x density-based improvement was substituted for pure genetic-based improvement (Smith et al., 2014).

DuPont Pioneer initiated studies to measure genetic gain in 1972 and has regularly updated these studies. In addition to the newest hybrids, the latest iteration has included both irrigated and drought conditions facilitated by the use of “managed stress environments.” These test sites (Woodland, California, and Viluco, Chile) are located in irrigated areas that receive very little rainfall, allowing researchers to impose either high yield or drought stress conditions at will. This enables the measurement of hybrid performance and genetic gain at both ends of the yield spectrum.

Genetic, physiological, and morphological data are collected in DuPont Pioneer “era” studies. This allows researchers to observe the collateral impact on various traits of selection for yield and formulate testable hypotheses about how changes in these traits may contribute to yield improvement.

IMPROVEMENTS IN CORN YIELD DUE TO MANAGEMENT

In addition to genetic gains, corn yields have benefited from improvements in management practices. Those most beneficial and widely adopted by growers include:

- Earlier planting, which reduces moisture stress during pollination and ear fill and lengthens the growing season
- Use of seed treatments that contain a fungicide and insecticide and may also include a nematicide, growth promoter, or other active ingredient
- Increasing use of foliar fungicides to limit leaf diseases
- Use of improved planters to achieve:
  - More consistent depth and coverage of seed, resulting in more uniform stand emergence
  - More equal plant-to-plant spacing to reduce competitive effects among plants
  - Timely planting of a higher percentage of corn acres to increase yield potential (achieved by using larger planters and those designed to operate at higher ground speeds)
- Improvements in irrigation practices and an increase in acres of irrigated production
• Improved fertility practices, including higher rates of nitrogen fertilizer
• Variable-rate technology that allows growers to focus resources where they are most beneficial
• Narrower row spacings
• Improved drainage (increase in systematic tiling)

These improvements, along with improved genetics, have enabled U.S. growers to improve corn yields by about 1.8 bu/acre per year since 1930 (Figure 1).

![Figure 1. U.S. corn yields, 1930-2014. Source: USDA-NASS.](image)

**PIONEER ERA STUDY DESCRIPTION AND RESULTS**

Recent Pioneer studies documented genetic gain by growing hybrids from different eras together in studies conducted over multiple environments. Hybrids chosen were the top-selling central Corn Belt hybrids of their era from 1930 to 2011. Beginning in 1997, many hybrids included in the study contained transgenic insect protection traits or trait stacks of insect and herbicide resistance. Thus, any yield gain from insertion of these genes is treated as part of the genetic gain accrued in those hybrids. Likewise, any yield “drag” associated with insertion of the genes would subtract from the overall gain. Results are shown in Figure 2. (Studies conducted to identify yield gains from insect resistance traits alone are reported later in this article.)

- Genetic gain was 1.4 bu/acre per year for hybrids released from 1930 to 2011 and planted at optimum density in their target production environment (TPE).
- Genetic gain was similar when studies were conducted in well-watered environments — 1.3 to 1.5 bu/acre per year.
- When studies were conducted in drought stress environments, genetic gain was 0.8 to 0.9 bu/acre per year.

These studies included all hybrids (single, 3-way, and double crosses) predominant in their era. When a subset of only single-cross hybrids was considered (1963 to 2011 era), genetic gain estimates were slightly higher (Figure 2):

- 1.5 bu/acre per year in both their target production environment and in well-watered environments
- 1.0 bu/acre per year when measured in drought-stressed environments

Results were similar to previous studies that tested a set of era hybrids dating from 1930 to 1980. Grown at their optimum plant density, those hybrids also demonstrated a genetic gain of 1.5 bu/acre per year (Figure 2). Another previous study, however, showed lower genetic gain of 1.2 bu/acre per year for the period of 1930 to 2001. Both of these prior studies were not confined to single-cross hybrids, and environments were not “grouped” by stress level (Figure 2).

**GENETIC GAIN IN DUPONT PIONEER STUDIES**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Previous Studies</th>
<th>Current Study (1930 - 2011, 1936 - 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930 - 1980</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1990 - 2001</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Well-Watered Loc 1</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Well-Watered Loc 2</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>SX  Only (1963-2011)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Drought Loc 1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Drought Loc 2</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>SXs Under Drought</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**HAS THE GROWING ENVIRONMENT CHANGED OVER TIME TO INFLUENCE YIELD GAINS?**

Yield gains can be attributed to genetics, management, and growing environment, as well as interactions between these components. The growing environment includes weather, biotic, and soil factors. If weather patterns, such as prevailing temperature and rainfall; biotic factors such as insect and disease pressure; and soil characteristics, such as organic matter content, change directionally over time, yield trends could be impacted. For this reason, DuPont Pioneer researchers looked closely at environmental factors to evaluate their impact on yield trends.

Weather patterns if trending in a single direction (warmer or colder, wetter or dryer) have potential to impact yields over time. Increased weather variability within single seasons could also affect yield trends. Using the EnClass® system, the DuPont Pioneer propriety software, researchers were able to evaluate historic weather patterns and model their expected impacts on yield from 1950 to 2011. This thorough analysis of weather records determined that the effects of weather on yield trends were minimal, contributing an upward bias of only 0.02 bu/acre per year during the period.

Insect and disease pressures change from year to year, depending primarily on weather conditions, but may also change depending on host susceptibility or resistance. For example, transgenic (Bt) traits have been developed that give excellent protection against European corn borer (ECB), a major pest of corn. Use of this
trait in nearly all hybrids where this pest is endemic in North America has reduced natural populations to a small fraction of their previous levels. Until the advent of Bt technology, hybrids had poor resistance to ECB. Thus, the older non-Bt hybrids in the study also benefited from this change in the growing environment. The reduction in ECB pressure created a potential downward bias to protecting the genetic gain determined in the study. (More discussion of the genetic gain due to insect resistance traits is included in a later section.)

**GENETIC OR NON-GENETIC YIELD GAINS?**

Theoretically, by comparing genetic yield gain to overall yield gain, % genetic gain can be computed:

\[
\text{Genetic yield gain / Total yield gain} = \% \text{ Genetic gain}
\]

In reality, apportioning gains is much more complex than the equation indicates. That is because of the interactions between genetics and management that are inherent in yield improvement. Perhaps the best example involves plant density. The main genetic component is breeding new hybrids able to withstand the stress of higher populations and therefore produce higher yields. However, that advantage would not be realized unless the management practice of growing the crop at higher populations is also imposed. In our calculation of yield gain, plant population is included on the genetic side of the ledger, but there is obviously a management component as well.

Another example is early planting to increase yields. Genetic components may consist of improved stress emergence, better resistance to seedling diseases, and full-season hybrid maturity. Management components include planter improvements, use of seed treatments, and planting earlier.

Because genetic and management gains are not completely distinct, calculating “percent genetic gain” may be somewhat misleading. Nevertheless, it is instructive to compare estimates of genetic gain to various metrics of overall yield gain to evaluate their relationship under a variety of environments – general growing conditions, irrigation, and drought.

**GENETIC YIELD GAINS VS. OVERALL YIELD GAINS**

Overall yield gains may be represented by several metrics, such as the average annual U.S. yield as reported by the USDA (Figure 1) or average annual yields in top corn states, such as Iowa (Figure 3).

In this comparison, genetic gain was 1.47 bu/acre per year, and overall gain (Iowa-based gain) was 1.97 bu/acre per year. Percent genetic gain is calculated as 1.47/1.97, or 75%. The calculation demonstrates that a preponderance of total yield gain can be attributed to genetic gains, bearing in mind that genetic and management gains cannot be completely separated.

**GENETIC VS. TOTAL YIELD GAINS UNDER IRRIGATION**

Overall yield gains under irrigation can be best represented by annual mean yields under irrigation in Nebraska, where most irrigated acres are located (Figure 4). Genetic yield gains under irrigation were documented by era studies conducted at DuPont Pioneer irrigated test sites (Figure 4).

As the graph indicates, average yield gains under irrigation in Nebraska are about 1.96 bu/acre per year from 1965 to 2011.

**FUTURE YIELD GAINS**

The primary importance of era studies is in the insights they provide regarding possible corn yield increases in the future. Another way to gauge future corn yield potential is by evaluating yield trends in the highest yielding environments under top management. Yields achieved in the National Corn Growers Association (NCGA) National Corn Yield Contest are often considered the best estimate of current yield potential in corn. Researchers and growers, among others, are interested in whether those contest yields are increasing at a consistent rate, leveling off, or perhaps even increasing at a higher rate of gain. NCGA yield contest trends are shown in Figure 5.

NCGA irrigated yields are increasing at a rate of about 2.5 to 3.0 bu/acre per year and non-irrigated yields by about 3.0 bu/acre per year. By comparison, Nebraska irrigated farm yields and Iowa farm yields are increasing by about 2.0 bu/acre per year. Thus, it is apparent that NCGA contest yields, which represent a small sample of growers using the very best genetics and management...
European Corn Borer (ECB): The optimal method for measuring a trait effect is to evaluate pairs of hybrids that are genetically identical except for the trait in question (i.e., “isogenic” hybrids). DuPont Pioneer researchers tested 15 isogenic pairs of hybrids with adaptations spanning the predominant maize maturity zones in North America. Each hybrid pair had either no transgene or a +Cry1Ab transgene that confers protection against ECB. Hybrids were planted in plots 15 feet long by 2 rows wide arranged in a randomized complete block design. Tests were conducted at 3,739 locations where isogenic pairs of Pioneer® brand hybrids were tested to measure the effects of ECB resistance provided by the Cry1Ab trait.

and moth flights have been negligible” since 2006 (Steffey and Gray, 2008). Consequently, as long as protection remains resilient, future studies in the U.S. regarding genetic protection against the ECB if reliant on natural infestations alone will underestimate the positive effects provided by insect resistant hybrids.

Corn Rootworm (CRW): Across maize growing regions of the U.S., Alston et al. (2002) estimated average yield increase factors resulting from the use of CRW resistant maize hybrids (in comparison with untreated conditions) ranging from:

- 1.0 to 1.165 under low CRW pressure (i.e., yields ranging from no advantage to 16.5% higher than untraited hybrids),
- 1.076 to 1.269 under moderate CRW pressure, and
- 1.164 to 1.393 under high CRW pressure.

Significant interactions exist between soil type, water, and insect biotype. CRW infestation is more prevalent in wet clay soils, but if water and nutrient availability can be maintained, then yields might not suffer.

Two methods were used to compare the rates of genetic yield gain in U.S. corn contributed by simply inherited traits with the advances made by breeding with “base” germplasm. The results showed that native germplasm accounted for 93% of genetic gain in 1 method of analysis and 77% in another (Smith et al., 2014). While these calculations are speculative, they suggest that multigenic mediated yield gain is overwhelming compared to that of monogenic sources.

**HOW HAVE HYBRIDS VISIBLY CHANGED TO PRODUCE MORE YIELD?**

Morphological data collected in DuPont Pioneer era studies include harvest index, tassel size, leaf angle, anther-silk interval (“silk delay”), stalk and root lodging, barrenness, and staygreen. Previous studies reported that the mean harvest index (grain dry weight/total plant dry weight) increased from 0.46 for 1961 era hybrids to 0.49 for 2004 released hybrids (with maxima of 0.53) (Duvick, 1984, 2005a, 2005b; Duvick et al., 2004a, 2004b). In other words, grain weight has become a higher percentage of total plant weight over time. Of those traits categorized as contributing to increased harvest index, the current study found a continued trend toward reduced tassel size. In contrast, a trend toward more upright leaves plateaued in the 1990s.
Duvick (1984, 2005a, 2005b) also categorized several morphological changes associated with higher planting densities. The current study detected a continuing trend toward shorter anther-silk intervals (less “silk delay”) and a lessening of stalk lodging, plus a slight but consistent improvement in root lodging resistance. In contrast, resistance to plant barrenness (failure to produce grain) and greater staygreen plateaued in the 1990s. Other studies using a computerized “crop modeling” approach suggest that root architecture improvements (deep, vertical roots rather than more shallow, horizontal roots) may contribute more to yield gains than leaf architecture improvements (more erect leaves) (Hammer et al., 2009). Among all changes to the corn plant, however, the one deserving primary credit for corn yield gains over time is the ability to endure stresses imposed by higher plant populations and still produce an ear, resulting in more yield per unit area.

CONCLUSIONS

• In DuPont Pioneer era studies conducted since 1972, corn yields showed no signs of plateauing.
  » This includes corn grown under irrigation, drought, and natural rainfed conditions.
• Increases in corn yields are due to genetic and management improvements and their interactions.
• Genetic gains are primarily responsible for yield improvements; those gains are interconnected with management gains.
• Transgenic insect resistance traits have helped protect the genetic gains contributed by breeding.
• As hybrids have been developed for higher yield, plant morphology and physiology have changed as well.
  » The largest contributor to genetic gain is increased stress resistance to higher planting densities.
• Hybrid improvements are predicted to continue into the foreseeable future.
  » Recent increases in breeding efficiencies will likely further increase the rate of genetic gain.
  » Plant breeding research, crop management research, new information technologies, and other technical innovations must continue to be supported.
  » Agronomy collaborations with plant breeders must remain a top priority.

SOURCES

To view authors and references, follow this link:

MAXIMIZING THE VALUE OF FOLIAR FUNGICIDES IN CORN

Over the span of only a few years, foliar fungicide treatments have progressed from a mostly new and untested practice to a trusted component of many growers’ management systems. This has occurred as research results and grower experience have demonstrated that fungicides can be very effective tools for managing foliar diseases and protecting yield in corn. However, studies have also shown that fungicide applications do not always result in an economic benefit for growers. Extensive DuPont Pioneer research conducted over the last eight years has demonstrated that the value of fungicide applications depends on disease pressure, hybrid susceptibility, previous crop, and tillage.

This article summarizes the key findings of three major foliar fungicide research projects conducted between 2007 and 2014. These studies involved several different foliar fungicide products and included both aerial and ground applications, but all were focused on application timings between tasseling and brown silk (VT – R2).

• On-farm fungicide trial survey: Survey of on-farm foliar fungicide side-by-side trials conducted between 2007 and 2014.
• Pioneer small-plot research: 2009 study conducted to identify factors influencing yield response of multiple hybrids to foliar fungicide application across several Midwestern sites.
• University of Tennessee/Pioneer small-plot research: 2006 to 2008 study comparing foliar fungicide response among hybrids with differing levels of genetic resistance to gray leaf spot at a site chosen specifically due to its history of high GLS pressure.

Table 1. Average corn yield response to foliar fungicide treatment at Pioneer small-plot research locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Previous Crop</th>
<th>Tillage</th>
<th>Yield Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mankato, MN</td>
<td>Soybean</td>
<td>Conv.</td>
<td>6.4</td>
</tr>
<tr>
<td>Waltham, MN</td>
<td>Soybean</td>
<td>Conv.</td>
<td>4.6</td>
</tr>
<tr>
<td>Janesville, WI</td>
<td>Soybean</td>
<td>Conv.</td>
<td>0.6</td>
</tr>
<tr>
<td>Minburn, IA</td>
<td>Corn</td>
<td>Strip</td>
<td>10.6</td>
</tr>
<tr>
<td>Breda, IA</td>
<td>Corn</td>
<td>Conv.</td>
<td>11.5</td>
</tr>
<tr>
<td>Alleman, IA</td>
<td>Soybean</td>
<td>Strip</td>
<td>8.0</td>
</tr>
<tr>
<td>Seymour, IL</td>
<td>Soybean</td>
<td>Conv.</td>
<td>11.8</td>
</tr>
<tr>
<td>Macomb, IL</td>
<td>Soybean</td>
<td>Conv.</td>
<td>7.1</td>
</tr>
<tr>
<td>Windfall, IN</td>
<td>Corn</td>
<td>Conv.</td>
<td>5.8</td>
</tr>
<tr>
<td>Gwynneville, IN</td>
<td>Soybean</td>
<td>No-Till</td>
<td>22.6</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>8.9</td>
</tr>
</tbody>
</table>
YIELD RESPONSE TO FUNGICIDE TREATMENT

Between 2007 and 2014, DuPont Pioneer researchers conducted a total of 780 on-farm fungicide trials comparing yield and moisture of non-treated corn to corn treated with a foliar fungicide between tasseling and brown silk. Across these trials, the average yield response to fungicide application was an increase of 6.9 bu/acre (Figure 1).

A positive yield response to fungicide application occurred in 80% of the trials. Yield response varied widely among many of the trials, as was expected given differences in weather conditions, disease pressure, and trial locations.

Pioneer small-plot research found similar results, with an average yield response to fungicide treatment of 8.9 bu/acre across 10 research locations in 2009 (Table 1). Average yield response varied among locations, ranging from 0.6 to 22.6 bu/acre, largely due to differences in disease pressure.

The economic viability of a fungicide application can vary greatly according to the price of corn and cost of the fungicide and application. Higher corn prices and lower treatment costs reduce the break-even yield response, while lower corn prices and higher costs increase it (Table 2).

At a break-even yield response of 4 bu/acre, 60% of the DuPont Pioneer on-farm trials conducted over 8 years would have seen an economic benefit from fungicide application (Figure 1). However, at a break-even point of 7 bu/acre, the success rate drops to only 45%.

Table 2. Yield response necessary to cover the cost of fungicide and application over a range of costs and corn prices.

<table>
<thead>
<tr>
<th>Fungicide + Application Cost/Acre</th>
<th>Corn Price/Bu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3</td>
</tr>
<tr>
<td>$22</td>
<td>7.3</td>
</tr>
<tr>
<td>$24</td>
<td>8.0</td>
</tr>
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<td>$26</td>
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<td>$28</td>
<td>9.3</td>
</tr>
<tr>
<td>$30</td>
<td>10.0</td>
</tr>
<tr>
<td>$32</td>
<td>10.7</td>
</tr>
</tbody>
</table>

FACTORS INFLUENCING YIELD RESPONSE

Disease Pressure

Pioneer research has shown that one of the most important factors determining the value of a foliar fungicide application is disease pressure. Foliar diseases can occur anywhere corn is grown in North America but are more common in the warmer, more humid growing areas of the South and East. Most widely grown hybrids have at least moderate resistance to the major leaf diseases, which may be sufficient protection against low to moderate disease pressure. However, in years when weather conditions are very conducive for disease, a fungicide application can provide a substantial economic benefit.
There are two basic types of disease cycles among the fungal diseases that infect corn leaves. Most of the pathogens, such as northern leaf blight, overwinter in diseased corn leaves, husks, and other plant parts. Spores are produced on this crop residue when environmental conditions become favorable in the spring and early summer. These spores are spread by rain splash and air currents to the leaves of new crop plants, where primary infections are produced. Secondary spread then occurs from plant to plant and from field to field as spores are carried long distances by the wind. As the plants die, the fungi remain in the dead plant tissue.

The rust diseases have a different cycle because they do not overwinter in crop residue and cannot survive the winters throughout much of the Corn Belt. Instead, disease starts in corn fields in the Southern United States, and spores are windblown long distances into the Corn Belt. Disease onset depends on weather systems that carry the spores northward combined with favorable conditions for infection. Secondary spread occurs similarly to the other leaf diseases.

Foliar infections can occur at any growth stage, and the earlier lesions develop, the more leaf area is reduced and the more damage results. However, plants are generally more susceptible to infection after silking. Damage may include yield losses due to decreased photosynthesis and harvest losses if secondary stalk rot infection and stalk lodging accompany loss of leaf area.

Pioneer on-farm research trials conducted in Iowa from 2007 to 2014 demonstrated the extent to which corn yield response to foliar fungicides can vary year to year due to weather conditions. Disease pressure is generally lower under drought conditions, as development and spread of several common foliar diseases is favored by moisture and humidity. 2011 and 2012 were both abnormally dry years in Iowa, whereas 2007 to 2010, 2013, and 2014 all experienced normal to above-normal precipitation in most parts of the state. The average yield response to foliar fungicides in on-farm trials conducted during the two drought years of 2011 and 2012 was well below the average response observed in years with greater precipitation (Figure 3).

![Image](image_url)

**Figure 2.** A hybrid susceptible to common rust (3 on a 1-9 scale) treated with a fungicide (left) compared to the same hybrid, non-treated, showing severe common rust symptoms (right). As expected, yield was greatly improved by the fungicide application due to high disease pressure at this DuPont Pioneer research study near Seymour, IL.

DuPont Pioneer small-plot research trials conducted in 2009 demonstrated the degree to which yield response to foliar fungicides can vary due to differences in disease pressure. The wide variation in yield response to fungicide application among locations was largely attributable to differences in common rust pressure. Common rust was prevalent at several Iowa, Illinois, and Indiana locations in 2009. Average yield response across locations in these states was 11.4 bu/acre (Table 1). Conversely, average yield response at Minnesota and Wisconsin locations where common rust was less prevalent was only 3.9 bu/acre. At sites with high common rust pressure, yield response to foliar fungicide application was greatest among hybrids with a low level of genetic resistance to the disease (Figure 2).

**Figure 3.** Average corn yield response to foliar fungicides in Iowa on-farm trials in drought years (2011-2012) compared to years with normal or above-normal precipitation (2007-2010 and 2013-2014).

### Hybrid Disease Susceptibility

In Pioneer and university studies with multiple hybrids of varying disease resistance, the probability of using a fungicide profitably has often been directly related to the susceptibility of a hybrid to the predominant leaf diseases. Pioneer® brand hybrids are rated on a scale of 1 to 9 for their level of genetic resistance to major foliar diseases, with 1 to 3 indicating a susceptible hybrid, 4 to 5 moderately resistant, 6 to 7 resistant, and 8 to 9 highly resistant. In cases where a foliar disease is not severe, a foliar fungicide application may not provide an economic benefit with a resistant or highly resistant hybrid. Hybrids that are susceptible to a common foliar disease are more likely to benefit from a fungicide application and should be monitored for disease symptoms, particularly when weather conditions are favorable for disease development.

A research project was conducted over three years at the University of Tennessee Research and Education Center at Milan. The primary goal of this study was to determine the yield benefit associated with foliar fungicide management of gray leaf spot in hybrids with differing levels of genetic resistance. The research site was specifically chosen due to a history of high gray leaf spot pressure. The plot area was in irrigated no-till corn production for four

**Figure 4.** Corn leaf showing symptoms of gray leaf spot.
years prior to the start of the study, with a high level of gray leaf spot each year. Three Pioneer brand corn hybrids with differing levels of resistance to gray leaf spot were included in the study (Table 3).

Table 3. Gray leaf spot resistance ratings of Pioneer® brand hybrids used in a 3-year foliar fungicide study at the University of Tennessee.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Hybrid GLS Resistance</th>
<th>GLS Rating*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Susceptible</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Moderately Resistant</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Resistant</td>
<td>7</td>
</tr>
</tbody>
</table>

* See GLS CI (2009).

Results of the study demonstrated the potential for gray leaf spot to cause substantial reductions in yield when disease pressure is very high. Hybrid resistance was effective in mitigating a large portion of yield loss due to gray leaf spot; however, even with the most resistant hybrid, the yield benefit of the foliar fungicide application was great enough to likely cover the cost of product and application (Figure 4). Under more moderate disease pressure, a fungicide application would likely not provide an economic benefit on a resistant hybrid.

Figure 4. Average yield increase of hybrids susceptible, moderately resistant, and resistant to gray leaf spot due to foliar fungicide application in a 3-year University of Tennessee/DuPont Pioneer research study.

Another example is the small-plot study described previously where common rust was prevalent at some of the locations. Yield response to foliar fungicide application in this study was greatly influenced by genetic resistance of hybrids to this disease. Among locations with high common rust severity in Illinois and Indiana, yield response to fungicide application was much greater for susceptible hybrids compared to hybrids with a moderate level of resistance (Figure 5). At Minnesota and Wisconsin sites with low common rust severity, a fungicide application could still have been profitable on susceptible hybrids (depending on prices) but most likely would not have been profitable on moderately resistant hybrids.

Figure 5. Average fungicide yield response of hybrids with low resistance (3 on a 1-9 scale) and moderate resistance (4-6) to common rust in DuPont Pioneer small-plot trials.

Common rust was prevalent at a trial at Macomb, IL, along with low to moderate levels of gray leaf spot and northern leaf blight. Notable differences in disease symptoms and yield response to fungicide were observed at this location (Figure 6). These research results from 2009 demonstrate the value of foliar fungicides in protecting yield when disease outbreaks occur; however, genetic resistance of hybrids may also provide adequate protection and should be considered in fungicide treatment decisions.

Figure 6. Two hybrids treated (left) and non-treated (right) with fungicide at Macomb, IL. The fungicide helped to protect yield in hybrid A (above) but provided little benefit on hybrid B (below), which had minimal disease.
Research results have clearly shown that corn-following-corn fields are at a higher risk and more likely to benefit from a fungicide application than corn-following-soybean fields. Survival of diseases in corn residue can lead to earlier infection and higher disease incidence and severity in the subsequent corn crop. Many common diseases, including gray leaf spot, northern leaf blight, southern leaf blight, eyespot, and northern leaf spot, overwinter in corn residue, providing a source of inoculum to infect corn planted the following season.

The 2009 DuPont Pioneer small-plot trials also included different cropping sequences and tillage practices among locations (Table 1). Average yield response to fungicide application tended to be higher among locations planted to corn the previous year and locations using no-till or strip-till practices; however, high yield response at some locations was driven primarily by common rust pressure. Common rust does not overwinter in crop residue so would not be affected by crop rotation or tillage practices.

**OTHER CONSIDERATIONS**

**Grain Moisture**

One concern with fungicide treatments in corn is the potential for increased grain moisture at harvest, resulting in higher drying costs. Observations have varied among university trials with some showing a small increase in moisture in treated versus non-treated corn and some showing no difference. Among Pioneer on-farm trials, grain moisture of fungicide-treated corn was only slightly higher (+0.3 points) than non-treated corn. This difference was not greatly affected by overall moisture level at harvest. In trials where harvest moisture of the non-treated corn was greater than 25%, treated corn averaged 0.36 points wetter.

One possible reason a fungicide application could increase grain moisture at harvest is that disease pressure in the non-treated corn was severe enough to cause premature death of the plant. In such a case, the increase in moisture would probably be accompanied by an increase in yield, which may more than offset any additional drying costs. There is some evidence of this trend among the Pioneer on-farm trials. Among those trials in which the harvest moisture of the treated corn and non-treated corn was similar (treated corn 0 to 0.3 points wetter), the average yield response to fungicide application was 5.9 bu/acre. In trials where the treated corn was more than 2.0 points wetter, the fungicide yield advantage was 8.8 bu/acre. Finally, in the small number of trials where the treated corn was more than 2.5 points wetter, the average yield response was 14.3 bu/acre.

**Hybrid Maturity and Planting Date**

Hybrid maturity and planting date have also been found to influence susceptibility to yield loss from foliar diseases (data not shown). These factors are important relative to the timing of disease development. Later planted fields and/or later maturing hybrids can be more vulnerable to yield loss because they are still filling grain while disease development is peaking in late summer. Therefore, these later fields are often more likely to benefit from a fungicide application.

Survey results from 374 on-farm trials where previous crop and tillage practices were reported showed an inverse relationship between tillage intensity and yield response to foliar fungicide application in both corn following corn and corn following soybean (Figure 7). Rotation away from corn to a different crop, such as soybean, is often recommended as a way to manage corn diseases by reducing inoculum levels. These results support that recommendation and indicate that rotation with soybean does have a positive impact on reducing disease pressure; however, residue levels still appear to have an impact on disease pressure in corn following soybean.

The 2009 DuPont Pioneer small-plot trials also included different cropping sequences and tillage practices among locations (Table 1). Average yield response to fungicide application tended to be higher among locations planted to corn the previous year and locations using no-till or strip-till practices; however, high yield response at some locations was driven primarily by common rust pressure. Common rust does not overwinter in crop residue so would not be affected by crop rotation or tillage practices.
NORTHERN LEAF BLIGHT

DISEASE DEVELOPMENT AND SYMPTOMS

Northern corn leaf blight (NLB) is caused by the fungus Exserohilum turcicum, also known as Setosphaeria turcica and previously known as Helminthosporium turcicum (Figure 1). The disease organism overwinters as mycelia and conidia in diseased corn leaves, husks, and other plant parts (Figure 2). Spores are produced on this crop residue when environmental conditions become favorable in spring and early summer. These spores are spread by rain splash and air currents to the leaves of new crop plants, where primary infections are produced. Infection occurs when free water is present on the leaf surface for 6 to 18 hours and temperatures are 65 to 80°F.

Secondary spread occurs from plant to plant and field to field as spores are carried long distances by the wind. Infections generally begin on lower leaves and then progress up the plant. However, in severe NLB outbreak years (that have high spore levels), infections may begin in the upper plant canopy. This can occur when weather systems deposit spores from southern growing areas, such as Mexico and the Caribbean. In recent years, weather patterns with large storms moving from south to north over the North American continent have spread the NLB organism into additional northern regions.

Heavy dews, frequent light showers, high humidity, and moderate temperatures favor the spread of NLB. Development of disease lesions on the ear leaf or above and significant loss of green leaf area can result in yield loss.

RACES OF NLB

There are multiple races of Setosphaeria turcica documented in North America; Race 0, Race 1, and Race 23N are the most prevalent. Ferguson and Carson (2007) reported a survey of NLB races that indicated that frequency of Race 0 isolates decreased from 83% in 1974 to 50% in the 1990s. During this same period, Race 1 isolate frequency increased. Low levels of Race 23 and 23N were present throughout the 20-plus years. The authors attribute the decrease in Race 0 frequency to the widespread use of the Ht1 gene, which has provided control of Race 0 but not of Race 1, by the sweet corn and hybrid corn industries.

The resistance genes available to corn breeders are named “Ht” based on the previous NLB fungal name (H)elminthosporium (t)urcicum. The common sources of resistant Ht genes are dominant genes and provide resistance to the various key races of Exserohilum turcicum (Et) as shown in Table 1.

Table 1. Common sources of resistance Ht genes.

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Host (Ht) Reaction to Each Race</th>
</tr>
</thead>
<tbody>
<tr>
<td>Et Race</td>
<td>Ht1 Gene</td>
</tr>
<tr>
<td>0</td>
<td>R</td>
</tr>
<tr>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>2</td>
<td>R</td>
</tr>
<tr>
<td>12</td>
<td>S</td>
</tr>
<tr>
<td>23</td>
<td>R</td>
</tr>
<tr>
<td>23N</td>
<td>R</td>
</tr>
<tr>
<td>123N</td>
<td>S</td>
</tr>
</tbody>
</table>

DuPont Pioneer Breeders Target Multiple NLB Races

To provide disease resistance to NLB when multiple races might be present, two or more Ht genes may be needed. For example, a combination of Ht1 and Ht2 genes would provide resistance to Races 0, 1, and 23N, the predominant races of NLB in the U.S. and Canada. Because of these multiple races of NLB, DuPont Pioneer breeders are incorporating additional Ht genes in their hybrid development programs (i.e., a “multigenic” approach). Resistant phenotype and inheritance of NLB resistance genes are shown below (Table 2).

Table 2. “Ht” resistance genes (Welz and Geirger, 2000).

<table>
<thead>
<tr>
<th>Gene</th>
<th>Resistant Phenotype</th>
<th>Inheritance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ht1</td>
<td>Chlorosis</td>
<td>Dominant</td>
</tr>
<tr>
<td>Ht2</td>
<td>Chlorosis</td>
<td>Dominant, suppressed by sht1 gene¹</td>
</tr>
<tr>
<td>Ht3</td>
<td>Chlorosis</td>
<td>Dominant</td>
</tr>
<tr>
<td>Ht4</td>
<td>Chlorosis halo</td>
<td>Recessive</td>
</tr>
<tr>
<td>Htm1</td>
<td>Latent period prolonged</td>
<td>Dominant</td>
</tr>
<tr>
<td>NN</td>
<td>Complete resistance</td>
<td>Dominant</td>
</tr>
</tbody>
</table>

¹sht1 is a dominant inhibitor of Ht2, Ht3, and Htm1 (but not of Ht1) in some parent lines.

The resistant phenotype, which appears with Ht1, Ht2, and Ht3 genes, is tissue chlorosis, where normal green color begins to change to a yellow hue in leaf lesions (Figure 3, left). These NLB lesions are slower to develop, and there are fewer spores produced per lesion.
With the Ht4 gene, a chlorotic “halo” appears around the lesions, which are somewhat smaller in size and fewer in frequency.

The Htn1 gene prolongs the latent period before lesions occur; fewer and smaller lesions develop with fewer spores produced per lesion. The plant is able to maintain its health longer even with the disease organism present (Figure 3, right).

The Htm1 and NN genes provide complete resistance, and minimal lesions are noted in plants with these genes present.

Susceptible and resistant reactions are shown in Figures 4-6.

**Figure 3.** Left: Ht1 “chlorotic” reaction – slower to develop and fewer spores produced per lesion. Right: HtN type reaction – fewer, smaller lesions develop and fewer spores produced per lesion.

**Figure 4.** Susceptible response, early lesions. Plant has no resistance, but lesions have not had time to fully develop.

**Figure 5.** Susceptible response, later lesions. With time, lesions have expanded to form large areas of necrotic tissue. Entire leaves may eventually become necrotic.

**Figure 6.** Resistant response. Note chlorotic halo surrounding lesions and restricted development of lesions, indicative of resistant response.

**Figure 7.** Illustration of DuPont Pioneer scoring system for NLB.

When photosynthesis is limited by loss of green leaf area due to disease lesions, corn plants remobilize stalk carbohydrates to developing ears. When this occurs, stalk quality is reduced, often resulting in harvest losses. Hybrids with higher leaf disease scores tend to maintain leaf health and overall plant health longer into the grain filling period. This maintenance of plant health results in higher yields, better stalk standability, and increased grain harvestability.

**MANAGING NLB IN CORN PRODUCTION**

Effective management practices that reduce the impact of NLB include selecting resistant hybrids, reducing corn residue, timely planting, and applying foliar fungicides.

**Resistant Hybrids**

Selection of resistant hybrids based on disease reaction characterization scores is an important first step in managing this disease. The Pioneer NLB rating reflects the hybrids’ expected...
performance against the major NLB races predominant in your area. As race shifts inevitably occur, continued testing by DuPont Pioneer researchers may result in a rating adjustment for some hybrids. Use of multigenic resistance by breeders increases hybrid stability as NLB races shift over time.

Hybrids should be selected based on all important traits needed for a field. In addition to NLB resistance, select hybrids with high yield potential, appropriate insect resistance traits, suitable (usually full-season) maturity for the area, and consistent performance demonstrated through data from multiple locations and years. Strong emergence, stalk strength, and drought tolerance are other agronomic characteristics to consider to help optimize stands and harvestable grain yields.

Reducing Previous Corn Residue

Reducing corn residue decreases the amount of NLB inoculum available to infect the subsequent crop. Crop rotation is one effective method of reducing residue. In addition, any form of tillage that places soil in contact with corn residue promotes decomposition and decreases the amount of residue that survives to the subsequent cropping season. Stover harvest for cellulosic ethanol production or animal feed is another means to reduce corn residue and disease inoculum. However, reducing corn residue does not protect against spore showers carried into a field on wind currents.

Timely Planting

Timely planting can often help hybrids escape the most severe damage from NLB if crop development outpaces normal disease progression. The latest-planted corn in an area may be infected when plants are smaller, resulting in the disease progressing more rapidly relative to the crop. However, in cases of high disease incidence, both early- and late-planted corn may be severely damaged.

Fungicide Application

Various foliar fungicides are available to help control or suppress NLB development (Table 3). Though fungicides are routinely used by growers to protect against several common leaf diseases, NLB may not always be controlled as completely as some other diseases. This is due to the more rapid life cycle of NLB, which may be as short as one week under favorable conditions. Because NLB sporulates so rapidly, it is more difficult to time a single fungicide application. Consequently, selecting resistant hybrids is a crucial first step in managing NLB where incidence is historically high.

Decisions to use a fungicide must be based on the disease risk factors of the field, including hybrid susceptibility, cropping sequence, tillage system, location, disease history, yield potential, the price of corn, and expected weather during reproductive development. In fact, weather conditions anticipated during ear fill are a primary factor for disease development and often have the most impact (along with hybrid disease rating) on the profitability of fungicide applications.

Survey results from 374 on-farm trials where previous crop and tillage practices were reported showed an inverse relationship between tillage intensity and yield response to foliar fungicide application in both corn following corn and corn following soybean (Figure 8). These results indicate that rotation and tillage have a positive impact on reducing disease pressure.
Objectives

• Evaluate and monitor corn rootworm protection of Pioneer® brand corn products with the Herculex® RW (HXRW) trait in the central and northern Corn Belt, specifically targeting fields where HXRW has been used in two or more consecutive growing seasons.
• Estimate corn rootworm population levels in fields in the central and northern Corn Belt using Pherocon® AM/NB sticky traps.

Study Descriptions

Study 1: Evaluate and monitor corn rootworm protection

• Years: 2014 and 2015
• Locations: 136 fields in IA, IL, IN, MN, NE, SD, and WI
• Sampling Methods:
  o Targeted fields for sampling with a history of continuous corn and continuous use of HXRW trait (Table 1)
  o All fields were planted with a Pioneer brand corn product with Optimum® AcreMax® 1, Optimum® AcreMax® Xtra, or Optimum® AcreMax® XTreme insect protection in the year that sampling took place.
  o Sampled 10 roots per location (five 2-plant clusters)
  o Roots were washed and corn rootworm injury rated using 0-3 Node Injury Scale (NIS)

Results

Study 1: Evaluate and monitor corn rootworm protection

• Corn rootworm injury was low at all locations in the study; average node injury score less than 1.0 (one node removed).
• Corn rootworm injury did not differ based on HXRW trait history (Table 2).

Table 1. Locations by state and history of fields sampled for evaluation of corn rootworm protection efficacy in 2014 and 2015.

<table>
<thead>
<tr>
<th>Field History</th>
<th>IL</th>
<th>IN</th>
<th>IA</th>
<th>MN</th>
<th>NE</th>
<th>SD</th>
<th>WI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Reported</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Years HXRW</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Years HXRW</td>
<td>9</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>4 Years HXRW</td>
<td>14</td>
<td>3</td>
<td>2</td>
<td>14</td>
<td>1</td>
<td>9</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>5 Years HXRW</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
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<tr>
<td>≥6 Years HXRW</td>
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<td>5</td>
<td>11</td>
<td>7</td>
<td>25</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Competitive Trait Problem Field</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HXRW/Soy Rotation</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>3</td>
<td>20</td>
<td>39</td>
<td>2</td>
<td>1</td>
<td>24</td>
<td>136</td>
</tr>
</tbody>
</table>

Study 2: Estimate corn rootworm population levels

• Year: 2015
• Locations: 638 fields in IA, IL, MN, SD, and WI
• Sampling Methods:
  o Sticky traps placed in field beginning at blister stage (R2)
  o Sticky traps placed per field: 1 or 6
  o Beetles counted on each trap at 7-day intervals
  o If weekly count averaged more than 50 beetles/trap, trapping was discontinued
  o If the beetle count was below 50 beetles/trap average, new traps were placed in the field and for another 7 days
  o Trapping continued for 4 consecutive weeks, or until traps averaged >50 beetles per trap, whichever came first
Corn rootworm population levels were categorized at zero, low, moderate, or high for each sampling location in 2015:

- **Zero** = no beetles collected
- **Low** = traps average <21 beetles/week
- **Moderate** = traps average 21-50 beetles in a single week
- **High** = traps average >50 beetles in a single week

Corn rootworm beetle population levels observed (Figure 1):

- 3.9% of locations had high populations
- 11.3% of locations had moderate populations
- 78.1% of locations had low populations
- 6.7% of locations had zero adults collected

**Management Considerations**

- Corn rootworm protection of Pioneer® brand corn products with the Herculex® RW trait was extremely consistent across all sampling locations in 2014 and 2015 and was not influenced by HXRW trait use history.

**Figure 1.** Population levels observed at corn rootworm beetle trapping locations in 2015.

- Although this study has shown that the HXRW trait remains an effective tool for corn rootworm management, DuPont Pioneer and university research suggests that continuous, uninterrupted use of the same corn rootworm Bt technology can lead to decreased corn rootworm susceptibility to that technology, and may result in reduced product efficacy against these insects.

- To help maintain the efficacy of Bt corn rootworm products, it is essential to develop a multi-faceted rootworm control management plan.

- Your DuPont Pioneer Sales Professional or your local Extension professionals can assist you in developing best management practices for your farming operation.

- Please contact your authorized Pioneer Representative or consult with your local University Extension for more information regarding insect resistance management guidelines, best management practices and to understand whether there has been insect resistance documented in your area.

Authors: Jeff Mathesius, Marlin Rice, Ryan French, Brad Van Kooten, Mark Jeschke, and DuPont Pioneer Field Agronomists
SCOUTING FOR CORN ROOTWORM BEETLES WITH STICKY TRAPS

ESTIMATING ROOTWORM POPULATIONS

- Counting corn rootworms in the summer allows growers to make better informed decisions regarding management options the following season.
- Pioneer and university research has shown that yellow sticky traps are an easy, convenient, and reliable method for estimating corn rootworm populations within a cornfield.

USE YELLOW STICKY TRAPS

- **PHEROCON® AM/NB traps** (no bait) are the preferred product for trapping corn rootworm adults.
- Trapping should begin at the blister stage (R2) after silking.
- Count the beetles on each trap at 7-day intervals.
  - If the count averages more than 50 beetles, no more trapping is needed.
  - If the beetle count is below a 50 beetle per trap average, place new traps in the field and continue another 7 days.
  - Continue trapping for 4 weeks, or until traps average >50 beetles per trap, whichever comes first.

TRAP PLACEMENT

- Place 6 traps per field, arranged down one row and the length of the field.
- Traps should be at least 100 feet from the edge; beetle populations at field edges may not accurately represent the overall field population.
- Attach the trap to the stalk directly above the ear.
- Fold the trap with the sticky side out around the stalk and fasten using a twist tie; lock the trap tab in the lower corner of the trap.
- Remove nearby leaves that may get caught on the trap.
- Mark the row where the traps are located.

**CORN ROOTWORM IDENTIFICATION**

- **Western Corn Rootworm**
- **Northern Corn Rootworm**

**ACTION THRESHOLDS**

- **Traps average <21 beetles** per trap per week.
  - **Low** rootworm populations are anticipated next year.
  - Select an option for low populations:
    - Rotate to another crop.
    - Plant a non-Bt rootworm product with Pioneer® P1250.
    - Plant a non-Bt rootworm product with soil insecticide.
    - Plant a corn rootworm Bt corn product.
- **Traps average 21 to 50 beetles** per trap per week.
  - **Moderate** rootworm populations are anticipated next year.
  - Select a control option for moderate populations:
    - Rotate to another crop.
    - Plant a corn rootworm Bt corn product.
    - Apply soil insecticide at planting for larvae.
    - Apply foliar insecticide in the current year to control adult beetles prior to egg-laying.
- **Traps average >50 beetles** per trap per week.
  - **High** rootworm populations are anticipated next year.
  - Select a control option for high populations:
    - Rotate to another crop (best for soybean variant beetles or extended diapause beetles).
    - Apply foliar insecticide in the current year to control adult beetles prior to egg-laying, and use a rootworm resistant Bt corn or soil-applied insecticide the following year.
    - Plant a corn rootworm Bt corn product, and consider adding a soil-applied insecticide.
    - Use a pyramided corn rootworm Bt product; if in Cry3Bb1 or mCry3A problem areas, consider adding a soil-applied insecticide.

*DuPont Pioneer is not the supplier of PHEROCON® AM/NB (no bait) traps, makes no warranties, express or implied, relating to their accuracy, performance, suitability, or merchantability.

For further assistance please refer to Great Lakes IPM, INC. at 1-800-235-0285 or http://www.greatlakesipm.com/trecetraps.html for item # TR-330650.
Insect Protection Technologies for Corn Rootworm Management

**Objective**
- Research trials were conducted in 2013, 2014, and 2015 to evaluate corn rootworm (CRW) protection efficacy of insect protection technologies available in Pioneer® brand corn products under various levels of CRW feeding pressure.

**Study Description**

**Years:** 2013, 2014, 2015

**Locations:** 9 in 2013, 11 in 2014, 15 in 2015; research locations in IA, IL, IN, MN, NE, SD, and WI

**Plot Layout:** Small research plots, 4 rows each

**Replications:** 3 per location

**Hybrid Platforms:** 4 or 5 per location

**Insect Protection Technologies – Pioneer brand products:**
- Qrome™ products
- Optimum® AcreMax® XTreme (AMXT)
- Optimum® AcreMax® Xtra (AMX)
- Optimum® AcreMax® TRIsect® (AMT) with Poncho® 1250 + VOTIVO® insecticide

**CRW non-protected check (HX1, LL, RR2):**
- Evaluated CRW feeding damage on 5 plants per plot
- Samples did not exclude refuge plants
- CRW feeding damage rated using the Iowa State 0-3 node injury score (Oleson et al., 2005)
- Research locations were selected and managed specifically to create high CRW pressure environments, with some sites utilizing trap crops and/or manual CRW infestations

**Site Characterization**
- Research locations were categorized as having low, moderate or high CRW feeding pressure based on the average CRW node injury in the CRW non-protected check:
  - Low: 0 - 0.75
  - Moderate: 0.75 - 1.75
  - High: 1.75 - 3.00

**Results**
- Across all three years of the study, a total of 14 locations had moderate to high CRW pressure (0.75 - 3.00) The average CRW node injury score of the CRW non-protected check was 1.77 across these 14 locations (Figure 1).
- All CRW protection technologies had excellent CRW protection efficacy, with average CRW node injury scores significantly lower than the non-protected check, ranging from 0.22 to 0.38.

**Figure 1.** Average CRW node injury by insect protection technology at moderate and high CRW pressure locations, 2013-2015. N = 14 locations with ~1000 observations/treatment.

See your local Pioneer sales representative to better understand which products make sense on your farm.

A decrease of susceptibility to certain technology traits in corn has been observed in some CRW populations, which may result in lower efficacy as depicted in this chart. Please contact your authorized Pioneer sales representative or consult with your local University Extension for more information regarding insect resistance management guidelines, best management practices, and to understand whether there has been insect resistance documented in your area.


Authors: Murt McLeod, Steven Paszkiewicz, and Mark Jeschke
Performance of Pioneer® Brand Soybeans with ILeVO® Fungicide Seed Treatment Against SDS

Background and Objective

- **ILeVO** fungicide (active ingredient: fluopyram) is a seed treatment that provides protection of soybean seedlings from *Fusarium virguliforme* infection, the causal agent of Sudden Death Syndrome (SDS).
- DuPont Pioneer soybean research trials were conducted in 2012, 2013, and 2014 to evaluate ILeVO fungicide seed treatment performance in soybeans across a broad range of environments (SDS and non-SDS locations).

Study Description

**Years:** 2012, 2013, & 2014

**Locations:** 80 (total)

**Plot Design:** Replicated small-plot research trials

**Seed Treatment:**
1. FST/IST (fungicide seed treatment/insecticide seed treatment)
2. FST/IST + ILeVO 600 FS @ 1.18 fl oz/140k unit

**SDS:** If late-season SDS symptomology was present then locations were characterized as SDS locations; if no SDS symptomology was present then locations were characterized as non-SDS locations.

Results

- Over 3 years & 80 locations, the addition of ILeVO fungicide to the FST/IST check increased soybean grain yield 2.8 bu/acre (positive response at 73% of locations).
- The addition of ILeVO fungicide to the FST/IST check increased soybean yield by 0.9 bu/acre across non-SDS locations (n=63) and 9.8 bu/acre across the 17 SDS locations.

2012-2014 data are based on average of all comparisons made in 80 locations through Nov 1, 2014. Do not use these or any other data from a limited number of trials as a significant factor in product selection. The foregoing is provided for informational use only. Please contact your Pioneer sales professional for information and suggestions specific to your operation. Product performance is variable and depends on many factors such as moisture and heat stress, soil type, management practices and environmental stress as well as diseases and pests pressures. Individual results may vary. Pioneer® brand products are provided subject to the terms and conditions of purchase which are part of the labeling and purchase documents.

ILeVO® is a registered trademark of Bayer.
PPO INHIBITOR HERBICIDES

There are several herbicide families classified as PPO inhibitors. Inhibition of the PPO enzyme ultimately leads to accumulation of peroxidative agents that cause the breakdown of cell membranes. For this reason, the PPO inhibitors are also called cell membrane disruptors. The Herbicide Resistance Action Committee and the Weed Science Society of America classify seven herbicide families in this group. These families are the diphenylethers, N-phenylphthalimides, oxadiazoles, phenylpyrazoles, thiadiazoles, triazolinones, and triazolopyridinones.

The first PPO inhibitor herbicides were introduced in the 1970s and early 1980s. The diphenylethers were the first widely used family of PPO inhibitor herbicides. These herbicides have been labeled primarily for preemergence and postemergence annual broadleaf weed control. However, some of these herbicides also have limited preemergence grass activity. They are widely registered for many agronomic and horticultural crops.

PHYSICAL AND CHEMICAL PROPERTIES

Many of the PPO inhibitors are foliar-applied, contact-type herbicides. Plant absorption is increased with high relative humidity. Most of these herbicides require spray additives to improve foliar coverage and leaf absorption. Spray additive recommendations should be followed closely because using the wrong additive can lead to greater crop response. The PPO-inhibiting herbicides have low volatility, low toxicity to mammals, and very favorable environmental impact profiles. Most of the herbicides in these families are fairly immobile in soil through strong adsorption to soil organic matter and clay. These herbicides are primarily degraded by sunlight (photodegradation) and microbial action. The soil-active members of these herbicide families have somewhat short half-lives with short to moderate residual activity in the four to six week range.

SYMPTOMS

The PPO inhibitor herbicides are primarily foliar-applied and have limited soil activity. They are contact-type herbicides that primarily affect only the sprayed plant tissues. The leaves of susceptible plants will quickly become chlorotic (yellow), then desiccated and necrotic (brown) within one to three days. The youngest leaves of tolerant plants may show yellow or reddish spotting (called “bronzing”), and plants can be temporarily stunted. Soil-applied PPO inhibitors cause rapid yellowing, necrosis, stunting, and death of germinating susceptible plants.

The degree of plant response will vary with application rate, stage of plant growth, plant species, plant (or crop) variety, and environmental conditions. Plant response tends to be more severe and common with high humidity and extremely cool or hot temperatures.

Plant response to the soil-applied PPO inhibitors tends to be greater with saturated soils or following high intensity rainfall.
that splashes treated soil onto young seedlings. These herbicides can cause yellowing, burning, girdling, stunting, and stand loss of plant seedlings under severe environmental conditions.

**DIFFERENTIAL RESPONSE IN SOYBEAN VARIETIES**

University of Arkansas and Auburn University researchers discovered differences in susceptibility among soybean varieties to sulfentrazone. Their research indicated susceptible varieties lacked a gene for tolerance to PPO-inhibiting herbicides. Additional research conducted by DuPont Pioneer and the University of Arkansas confirmed that the gene for resistance was a single dominant trait. Pioneer has published charts that identify Pioneer® brand soybean varieties as having reduced tolerance to PPO herbicides with more potential for exhibiting crop injury. Screening for PPO tolerance is an on-going program at Pioneer.

![Soybean leaf bronzing due to acifluorfen.](image)

**GUIDELINES FOR USING PPO INHIBITING HERBICIDES IN SOYBEAN AND CORN PRODUCTION**

The PPO-inhibiting herbicides are valuable broadleaf weed control tools in soybean and corn production systems. Important herbicides in this group can provide quick control of many difficult-to-control broadleaf weed species, including morningglory, Palmer amaranth, waterhemp, and velvetleaf. The contact-type herbicides require good foliar coverage. The soil-applied herbicides require rainfall for good “activation.” Herbicide performance is enhanced by using higher spray volumes to maximize coverage. Weed control is also improved under good growing conditions and higher relative humidity.

The level of crop tolerance to PPO-inhibiting herbicides varies with the specific herbicide, crop genetics, and environmental conditions. Most crop responses to these herbicides occur during extended periods of high humidity, very low or high temperatures, and/or wet soils. Crop response is mostly cosmetic and short-lived since there is very little translocation within the plant. Applying these herbicides at the correct growth stage, using only recommended spray additives, and avoiding conditions of crop growth stress will minimize crop response and provide the greatest level of weed control.

To view authors, references, and a list of PPO herbicide families and active ingredients, follow this link:

AMX - Optimum® AcreMax® Xtra Insect Protection system with YGCB, HXX, LL, RR2. Contains a single-bag integrated refuge solution for above- and below-ground insects. In EPA-designated cotton growing counties, a 20% separate refuge must be planted with Optimum AcreMax Xtra products.

LL - Contains the LibertyLink™ gene for resistance to Liberty® herbicide. Liberty®, LibertyLink® and the Water Droplet Design are trademarks of Bayer.

RR2 - Contains the Roundup Ready® Corn 2 gene that provides crop safety for over-the-top applications of labeled glyphosate herbicides when applied according to label directions.

YGCB - The YieldGard® Corn Borer gene offers a high level of resistance to European corn borer, southwestern corn borer and southern cornstalk borer; moderate resistance to corn earworm and common stalk borer; and above average resistance to fall armyworm. Contains the YieldGard® Corn Borer gene. YieldGard®, and the YieldGard Corn Borer design are registered trademarks used under license from Monsanto Company.

HXX - Herculex® XTRA contains the Herculex I and Herculex RW genes. Herculex® Insect Protection technology by Dow AgroSciences and Pioneer Hi-Bred. Herculex® and the HX logo are registered trademarks of Dow AgroSciences LLC.

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