PIONEER GrowingPoint™

PIONEER®

AGRONOMY SCIENCES

RESEARCH SUMMARY 2019

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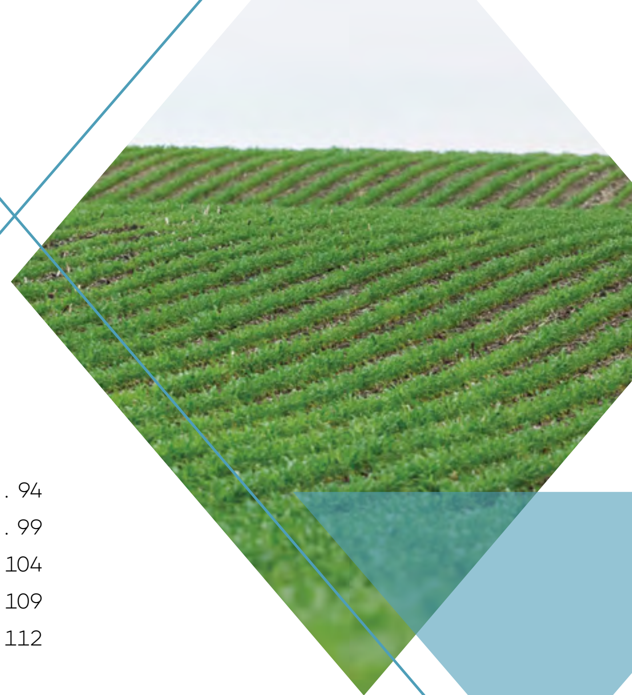
AGRONOMY SCIENCES

RESEARCH SUMMARY



Corn Fertility Management

Corn Harvest Practices

Soybean Planting Practices

Soybean Pest Management

Soybean Harvest - Weather Challenges

Forage Management

Sorghum Management

* Research conducted as a part of the Pioneer Crop Management Research Awards (CMRA) Program. This program provides funds for agronomic and precision farming studies by university and USDA cooperators throughout North America. The awards extend for up to four years and address crop management information needs of Pioneer agronomists and customers, and Pioneer sales professionals.

Pioneer Agronomy Sciences

The Pioneer Agronomy Sciences group supports and coordinates the efforts of agronomy field teams around the globe in order to provide Pioneer customers with the best possible management insights to help maximize productivity on their farms. Members of the Agronomy Sciences team bring together expertise on a wide range of agronomic specialties and experience in industry, academia, and agricultural production.

The current agronomy support and research structure at Pioneer can be traced back to the creation of the Technical Services Department at Pioneer in 1962. Initially consisting of five agronomists, the Technical Services team conducted winter corn production meetings that attracted thousands of farmers and provided customers with Pioneer Corn Services Bulletins, a major source of information about growing corn. In 1986, the Agronomy Services Support Department was created to provide information and crop management research support to the expanding team of Pioneer agronomists. This department continued to evolve into what is today called the Agronomy Sciences group. Many things have changed over the past 30 years, but the core mission of this group has remained the same.

Pioneer has product agronomists who work on IMPACT testing and provide product knowledge positioning insights and training to account managers, sales professionals, and dealers as well as field agronomists who lead agronomy training efforts and on-farm GrowingPoint™ Agronomy trials. The Agronomy Sciences team helps coordinate these trials and leads efforts to develop and archive agronomy information resources in the online Agronomy Library and the Pioneer® GrowingPoint™ agronomy app.

Paul Carter, Ph.D., *Agronomy Manager*

Paul earned his B.S. degree at North Dakota State University and his M.S. and Ph.D. degrees from the University of Minnesota and was Extension Agronomist and Professor at the University of Wisconsin-Madison before joining Pioneer. His research experience includes impacts of frost and wind damage on crop recovery, seeding practices, crop rotations, and tillage systems. Paul is a Fellow in both the American Society of Agronomy and the Crop Science Society of America and received the Agronomic Industry Award from the American Society of Agronomy.

Matt Clover, Ph.D., *Agronomy Manager*

Matt is responsible for helping guide on-farm trials planning, protocol development, analysis, and communication of trial results. Matt leverages his experience in soil fertility to bolster expertise of the Agronomy Sciences team and support Pioneer agronomists and sales teams and Encirca® services. Matt earned his Ph.D. in soil fertility from Iowa State University and his M.S. and B.S. degrees from the University of Illinois in Crop Sciences; he is a Certified Professional Soil Scientist (CPSSc). Matt came to Pioneer in April 2017 after a 9-year career in the fertilizer industry with various roles in agronomy and research and development.

Sandy Endicott, M.S., CPAg, *Agronomy Manager*

Sandy holds B.S. and M.S. Degrees from The Ohio State University in agronomy and weed science. Sandy started with Pioneer in 1989 as a Field Sales Agronomist in NW Ohio and NE Indiana; then in 2004, she joined the Pioneer research team in Hawaii where her role was to manage the agronomy programs at the Waimea (Kauai) and at Kunia (Oahu) research centers. From 2008-2018, Sandy lead the global agronomy teams in Africa, Asia, Canada, Europe, and Latin America and recently took on the role of Agronomy Manager for the Western Corn Belt and leads nearly 50 Pioneer Field Agronomists in their on-farm, agronomic, field trial work.

Matt Essick, M.S., *Agronomy Manager*

Matt is from a small community in Northwest Iowa and earned his B.S. in Agricultural Business and M.S. in Agronomy from Iowa State University. Matt joined Pioneer as a Management Assistant working at the Cherokee, Iowa, soybean production plant. He transitioned to a Pioneer Sales Representative where he gained hands-on experience in both sales and agronomy before becoming a Territory Manager for Pioneer. Matt transitioned to an Area Agronomist and then to a Product Agronomist before joining the Agronomy Sciences Team. Matt is responsible for the Northern U.S.

Eric Galdi, *Agronomy Systems Manager*

Eric is a native of Wisconsin and obtained his B.S. degree in Soils and Crop Science from University of Wisconsin – Platteville and is currently pursuing his M.S. degree in Agronomy from Iowa State University. He provided nutrient/manure management and precision agriculture services to growers in Wisconsin before joining Pioneer in 2009. He has held various roles at Pioneer in corn research and Encirca® Services before joining the Agronomy Science team.

Mary Gumz, Ph.D., *Agronomy Manager*

Mary is a native of northern Wisconsin and earned her B.S. in Agronomy from the University of Minnesota – Twin Cities and M.S. and Ph.D. in Weed Science from Purdue University. After working in the crop protection and seed industries as a Technical Service Agronomist, she joined Pioneer in 2008 as an Area Agronomist and later became Product Agronomist for northwest Indiana. She is now the Agronomy Manager for the Eastern U.S.

Mark Jeschke, Ph.D., *Agronomy Manager*

Mark earned his B.S. and M.S. degrees in Crop Sciences at the University of Illinois at Urbana-Champaign and Ph.D. in Agronomy at the University of Wisconsin-Madison. Mark joined Pioneer in 2007 and currently serves as Agronomy Manager. His primary role is development and delivery of useful and timely agronomy information based on Pioneer and university agronomy research. Mark authors and edits many of the agronomy resources available in the Pioneer agronomy library and through the Pioneer® GrowingPoint® agronomy app. Mark is originally from northern Illinois and is actively involved in the family corn and soybean farm near Rock City, Illinois.

Luke Northway, *Agronomy Systems Manager*

Luke double majored in Management Information Systems and Agricultural Business at Iowa State University and is currently pursuing his MBA from the University of Iowa. He started with Pioneer in 2007 as a support person for FIS and Pioneer® FIT Mapping System. He now works on the Agronomy Sciences team as Product Owner of Performance Explorer, Trials Planning, and mobile Trials Data Entry.

Dan Poston, Ph.D., *Agronomy Manager*

Dan holds a B.S. and M.S. from Clemson University and a Ph.D. from Virginia Tech. Dr. Poston grew up in the coastal plains of South Carolina. Most of his professional career has been spent as a soybean agronomist and weed scientist with Mississippi State University at the Delta Research and Extension Center in Stoneville, Mississippi. Dr. Poston joined Pioneer in 2008 as an Area Agronomist and transitioned to the Agronomy Manager role in 2010, supporting 13 southeastern states.

Brent Wilson, M.S., *Product Line & Agronomy Leader*

Brent Wilson serves as Leader of Product Management and Agronomy for the Pioneer brand in the US. In the past 30+ years with Pioneer, he has held various roles associated with crop management in both the sales and research areas. His current role is to support the team of Field and Product Agronomists with systems, processes, and information to advance the best products, learn those products, and position them with our customers with a high degree of crop management information. Brent holds a B.S. in Agronomy and Pest Management from Iowa State University and Master's of Agronomy from Iowa State University.

April Battani, *Graphics Specialist*

April earned both a B.A. in Graphic Design and a B.A. in Creative Advertising from Drake University in Des Moines, Iowa. She started with Pioneer in 2012 as a Publishing Assistant for Agronomy Sciences. She currently works as a Graphics Specialist for both the Agronomy Sciences and Sales and Agronomy Training teams. Her role includes the design, publication, and project management of web-based and printed materials, including the Agronomy Sciences Research Summary books produced annually. In addition, April provides individually tailored illustrations and charts for internal sales, marketing, and research clients.

Samantha Teten, *Agronomy Sciences Intern 2018*

Samantha is a senior at the University of Nebraska-Lincoln majoring in Agronomy with an emphasis in Integrated Crop Management and minor in Agribusiness. Samantha's internship project examined various soil health assessments on a long-term nitrogen rate study. Following her graduation in May 2019, Samantha will pursue a Master's degree in soil fertility and precision agriculture.

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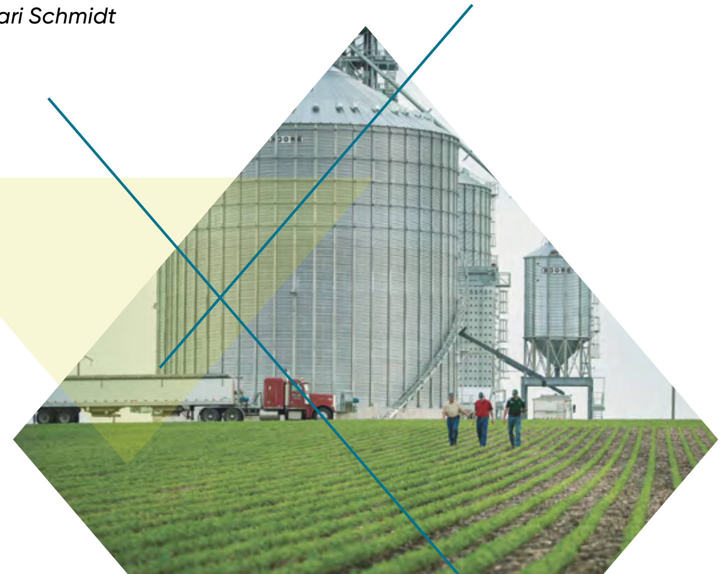

Insights on a Challenging Growing Season

The 2018 growing season will probably go down as a memorable one for many farmers and not for good reasons in many cases. The 2018 season was unusual right from the start as it was the first time since 1983 that planted acres of soybeans surpassed planted acres of corn in the U.S., a milestone noted with the photo of soybeans on the cover of this book. However, 2018 will mostly be remembered for the significant challenges many farmers faced throughout the season. A range of abnormal weather conditions affected the season from start to finish as well as some new and resurgent diseases and insect pests.

Planting was kept mostly at a standstill during the month of April due to record low temperatures. April temperatures in Iowa and Wisconsin were the coldest on record with near-record lows affecting most of the Great Plains, Midwest, Mississippi Delta, and Northeast. Weather quickly shifted to the other extreme in May as nearly all of the continental U.S. experienced abnormal heat, including eight states that had the hottest May on record. Planting proceeded quickly with the change in weather. Continued high temperatures in June accelerated crop development with corn silking extremely early despite the relatively slow start to the season. Temperatures moderated in July and August in much of the U.S., bringing some much-needed relief to the growing crops, except in the Northeast where temperatures remained high clear through maturity.

Overall, the May to October growing season was the hottest on record for the continental U.S., not primarily because of extreme maximum temperatures but because of record-high nighttime temperatures (Figure 1). Warm nights can be detrimental to corn yield; the reason they did not hurt yield more than they did in 2018 is because they mostly occurred early in the summer rather than during grain fill.

In addition to being extremely warm, the 2018 season was extremely wet (Figure 2). While portions of Missouri and Kansas suffered severe drought, too much rainfall was a more common problem than too little. The combination of abnormal heat and moisture set the stage for rampant crop disease problems. Poor stalk quality in corn was widespread as rapid development and low solar radiation forced plants to remobilize carbohydrates from stalks to fill the ears; additionally warm, wet conditions allowed stalk diseases to flourish. Excessive precipitation extended into the fall, making a seamless transition from rain to snow in some areas and causing significant harvest delays.

The 2018 season was also noteworthy for insect and foliar disease pressure. Western bean cutworm and Dectes stem borer were both significant pests in 2018. Grape colaspis, normally a sporadic secondary pest, caused crop injury in parts of Illinois. Gall midge emerged as a new pest of economic concern in soybeans. Bacterial leaf streak in corn expanded its geographic range with confirmed cases as far east as Wisconsin. What is more, tar spot made the transition from minor cosmetic disease to full-blown multistate epidemic in corn.

High night temperatures	Page 67
Corn stalk quality	Page 71
Western bean cutworm	Page 77
Grape colaspis	Page 81
Bacterial leaf streak	Page 89
Tar spot	Page 91
Soybean gall midge	Page 133
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Soybean pod and seed rot	Page 148

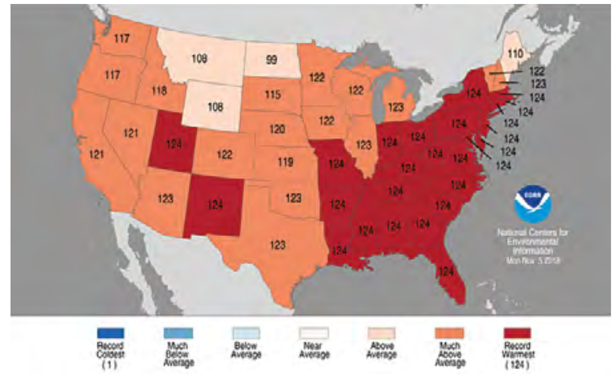


Figure 1. Statewide minimum temperature ranks (1895-2018) for May to October 2018 (NOAA).

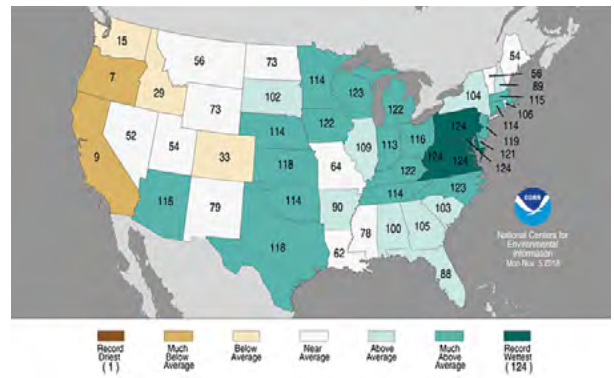


Figure 2. Statewide precipitation ranks (1895-2018) for May to October 2018 (NOAA).

2018 was the kind of year that calls to mind the words of General Dwight Eisenhower, "In preparing for battle I have always found that plans are useless, but planning is indispensable." The best-laid plans can quickly go by the wayside in an unpredictable growing season, but the ability to leverage crop management research and information as well as the expertise of knowledgeable advisors can help farmers adapt to new challenges and adjust plans for next year to reduce risk and improve the odds of success. This Agronomy Sciences Research Summary provides insights on numerous crop production topics; however, it represents just a small portion of the vast array of resources available in the Pioneer agronomy library and Pioneer® GrowingPoint™ agronomy app. We hope that resources available in this book and online will help you drive yield and profitability in 2019.

Mark Jeschke, Ph.D.
Pioneer Agronomy Manager

S.A.V.E. – A Pathway to Farming for Veterans and Servicemembers

*by **William McClure,** Technical Product Manager, and **Sandy Endicott, M.S.,** Agronomy Manager*

S.A.V.E.

- S.A.V.E. – Servicemember Agricultural Vocation Education – Farm is a non-profit organization that provides hands-on, immersion farm training for military servicemembers as they transition to civilian life.
- The S.A.V.E. teaching farm consists of 2,000 acres of crop land, livestock animals, orchards, horticulture, and apiaries in Kansas.
- This teaching farm will train over 100 veterans and servicemembers through an entire growing season cycle.
- Pioneer Tech Team members, Territory Managers, and Sales Representatives are volunteering time as well as resources to this effort.
- This ongoing effort is intended to ensure these veterans and servicemembers get the training they need to manage the crop through the entire cropping cycle.

Field Agronomist, Scott Dickey sharing crop management information with a S.A.V.E. participant in June.

Project Description

- Territory Manager Clint Pickard and Pioneer Sales Representative Mike Meier connected with a motivated new audience by partnering with S.A.V.E. Farm, an organization that helps military veterans and transitioning servicemembers learn agriculture and find job placement in the field.
- According to S.A.V.E. Farm founder Col. Gary LaGrange, U.S. Army, Retired, "There are 2.3 million post-9/11 veterans and transitioning military folks in the U.S. today, and 40 percent want to get into farming. At the same time, 63 percent of our farms are in the last generation. S.A.V.E. Farm was created to bridge the gap."
- LaGrange says his students find tremendous recovery and healing in farming, particularly those suffering from anxiety disorders or post-traumatic stress as a result of their service experience.
- "It's a healing thing for them to get out and work with soil, work with animals, work with plants in a relatively quiet environment."

Results

- Six Pioneer agronomists, one technical product manager, and three territory managers joined together to host a half-day workshop with seed, supplies, and technology provided by Pioneer.
- Held in June 2018 at a S.A.V.E. Farm field in Manhattan, KS, the workshop offered a basic introduction to row-crop agriculture, covering several topics related to both corn and soybeans:
  - Physiology
  - Life cycle
  - Weeds and pests
  - Yield success
  - Product selection
- "Don't underestimate the power of your teammates to sign onto your cause and unify behind Pioneer and Corteva to get some cool things done together," Clint Pickard says.
- ***"The fact that they are generous enough to donate materials and their time speaks volumes about, not just the importance of this work, but their values as a company."***

  \- Col. Gary LaGrange, Founder, S.A.V.E. Farm

Photos from Pioneer Training Events with S.A.V.E

Field Agronomist John Heimerman sharing agronomic management.

Territory Manager Clint Pickard sharing crop management information with a S.A.V.E. participant.

Territory Manager Ryan Harms sharing crop management information with a S.A.V.E. participant.

S.A.V.E. Features and Goals

From the S.A.V.E. Website:

- Healing center on site or adjacent for those in need of special treatment.
- Provide a home-like training center where they can learn to farm and heal.
- After training, transitioning servicemembers and veterans will be matched with mentor farms.
- Potential to work on, manage, or even own their farm.

www.thesavefarm.org/plan

Field Agronomist Ryan Steeves sharing crop management information with a S.A.V.E. participant.

S.A.V.E. participants gathered with the Pioneer team again in October of 2018 to evaluate their soybean crop, identify pests, and make plans for the 2019 crop management plan.

Ground-Truthing Satellite Imagery in Crop Production

*by **Ryan Clayton,** Field Agronomist, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Satellite imagery, such as that offered through Encirca® Pro from Encirca® services is a valuable tool for modern agriculture.
- There is an inherent tradeoff with satellite imagery between frequency and resolution – smaller, more numerous satellites are able to image an area more frequently but cannot accommodate the high-resolution optics of larger satellites.
- Satellite images can often reveal areas of higher or lower relative crop health but not necessarily identify the cause.
- Drone imagery and field visits can help "drill down" on areas in a field that differ from others in satellite images.

Objective

- Utilize satellite imagery, drone technology, and ground verification to analyze and solve field issues for farmers.

Study Description

- Pioneer Field Agronomists worked with their local Pioneer sales professionals across the state of Iowa in 2017 and 2018 to show farmers the value of satellite imagery as a diagnosis tool in identifying areas of concern within fields.
- Encirca services Crop Health Index was used to identify field challenges or evaluate field management treatments.
- When available, drones were used to further examine specific areas of concern or treatment evaluations within fields.
- Pioneer sales professionals then traveled to these areas and did a thorough analysis to assist the farmer in diagnosing any issue(s) and/or to evaluate field treatments.

Observations

Example 1 – Corn Fungicide Application (Figures 1-8)

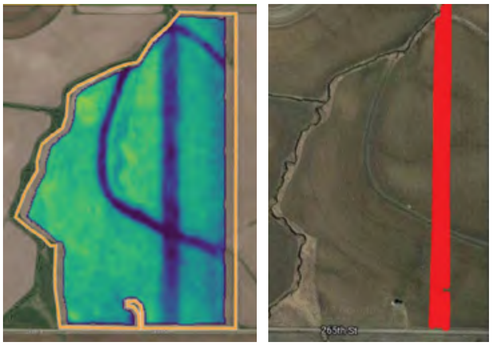


Figure 1. Encirca Pro satellite imagery and associated application map for VT corn fungicide application in Carroll County, IA, August 2018.

Figure 2. Drone field images captured in mid-September showing improved plant health in the corn fungicide treatment strip.

Figure 3. Improved plant health in the treated strip is still visible in a drone image taken in mid-October.

Figure 4. Differences in stalk strength and standability associated with fungicide treatment were apparent when scouting the field in October.

Figure 5. Ears sampled in October showed improved yield potential corresponding to better plant health in the fungicide-treated strip.

Treated: left

Untreated: right

Figure 6. Drone image showing fungicide treatment vs. non-treated area at harvest timing.

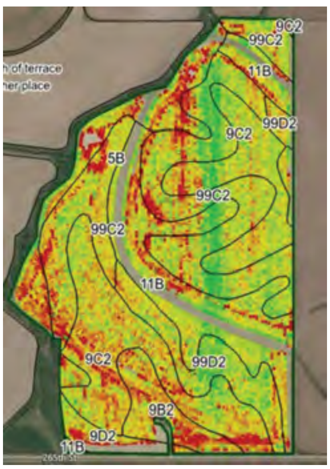


Figure 7. Harvest map of field showing increased yield levels in the fungicide-treated strip compared to the untreated areas of the field. The treated area had a 21.8 bu/acre yield advantage in this example.

Example 2 – Field Edge Effect (Figures 8-10)

- In 2017 and 2018, several growers noticed reduced yields on the edges of many corn fields.
- In some cases, growers anticipated this issue as they saw reduced crop health in the Crop Health Index images. Others were surprised by the results, and many were looking for answers as to why yields were reduced so much on the outside edges of many corn fields. Some key observations included:
  - » Damage was worse on fields bordered by a crop other than corn (soybeans or pasture).
  - » The south and west field edges tended to be affected more than north and east edges.
- Many growers suspected herbicide damage due to the close proximity to a different crop (soybeans/pasture) and the high frequency of yield loss associated with reduced crop health along the affected edges.
- Pioneer Field Agronomists used the Encirca® services Crop Health Index tool to determine that herbicide injury was not the primary cause of this field edge effect in most cases.
- In 2017, soybean post-emergence herbicides were typically applied in mid- to late- June when corn would have been at ~V10 stage of development. During the weeks following soybean herbicide application, no evidence or crop injury was observed in the corn. Review of Crop Health Index maps showed the damage did not start to show up until mid-July and progressed throughout the month of August (Figure 8).

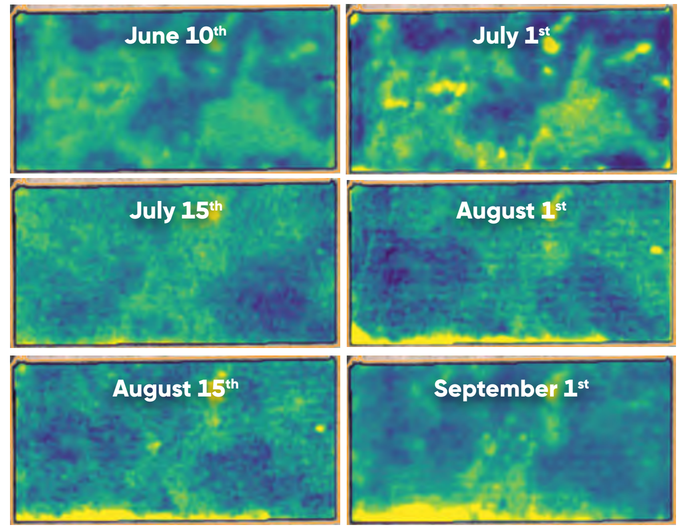


Figure 8. Sequence of Crop Health Index maps showing progression of affected area along a field edge from June 10 to September 1, 2017.

- By utilizing the Crop Health Index tool and scouting the affected and non-affected areas of the fields, Pioneer Field Agronomists were able to determine that a majority of the instances of reduced crop health and yield along field edges were associated with increased evapotranspiration levels during a critical dry spell that occurred around flowering time and into early grain fill.
- Corn is very sensitive to stress during late vegetative stages and just prior to silking.
  - » Nutrient and water demands are very high at this time.
  - » Most critical impacts from drought typically occur approximately two weeks prior to silking.
  - » Extra summer wind stress on the south and west field edges likely exacerbated water and nutrient stress in those areas.

Figure 9. Ears showing reduced kernel counts in affected area.

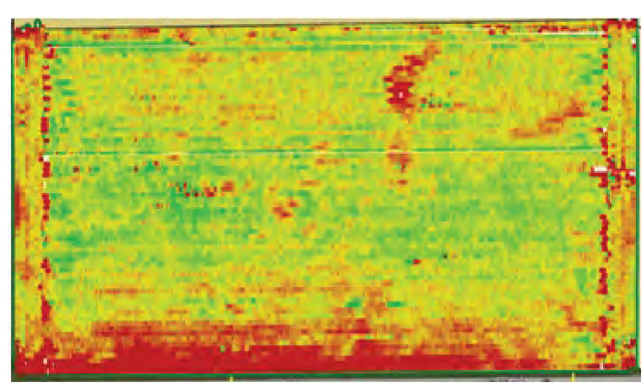


Figure 10. Yield map showing reduced yield levels in affected areas.

Example 3 – Fertilizer Application (Figures 11-12)

- In this example, the grower utilized the Encirca® services Crop Health Index tool to evaluate a sulfur application in a field that had shown signs of sulfur deficiency in the past.
- The grower established two sulfur treatment blocks in the field and evaluated the effect on corn yield in 2018.
- Sulfur was applied as ammonium sulfate in the spring of 2018 at a rate of 116 lbs/acre.

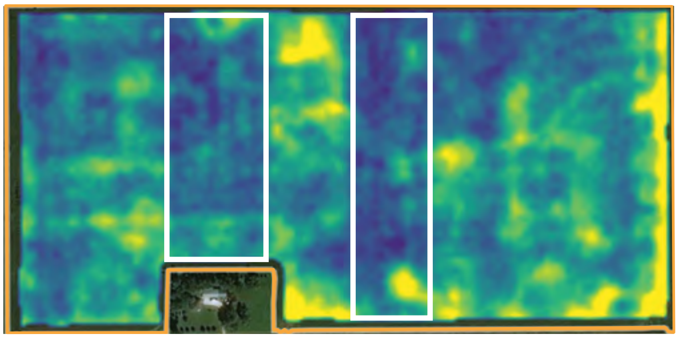
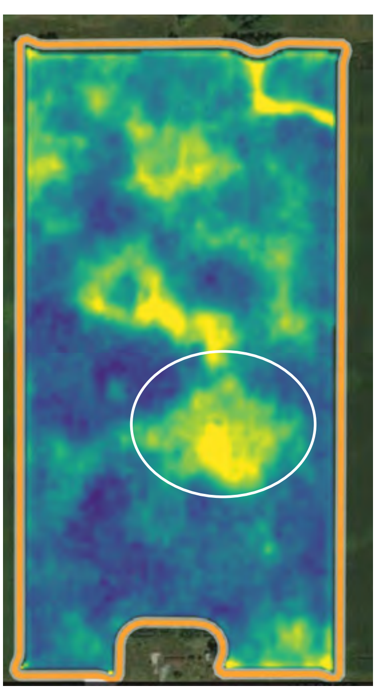


Figure 11. Crop Health Index image showing ammonium sulfate treatment blocks and associated improvement of plant health in July 2018.

Figure 12. Ear pictures for untreated (top) and treated (bottom) ammonium sulfate blocks (1/1000th of an acre) showing improved grain yield potential and grain quality.

Example 4 – Poor Plant Health Diagnosis (Figures 13-15)



- In this example, the Crop Health Index tool revealed an area of reduced crop health in the field.
- The grower was alerted of the area in early July via the Crop Health Index map to the left.
- Field visits to the corresponding areas found significant corn rootworm feeding and associated plant health concerns (drought stress and root lodging).

Figure 13. Crop Health Index image from early July 2017.

Figure 14. Roots sampled from the affected (left) and unaffected areas (right) showing severe corn rootworm feeding in the affected area.

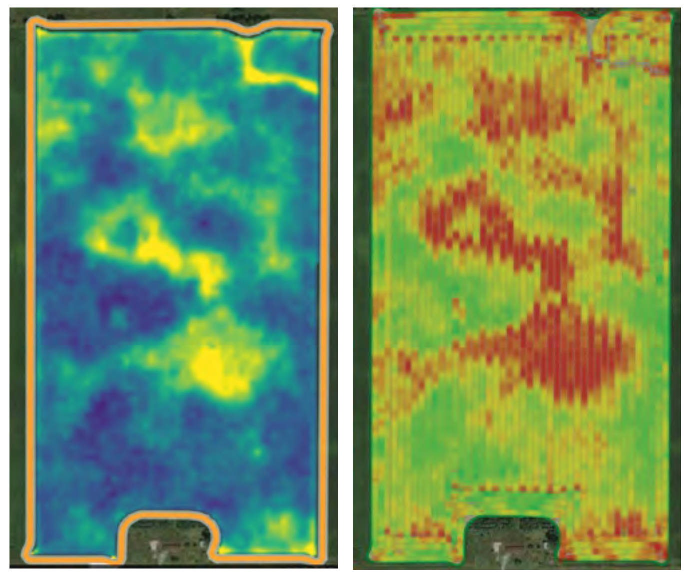


Figure 15. Crop Health Index map showing an area of reduced crop health caused by corn rootworm feeding and yield map showing a corresponding area of reduced yield.

- The grower and Pioneer sales team scouted the affected area revealed by satellite imagery and were able to diagnose the cause of reduced crop health.
- In this particular example, an isolated pocket of heavy corn rootworm feeding was the cause.
- Crop rotation and additional corn rootworm management practices were put into place to improve productivity in the future.

Conclusions

- The use of satellite imagery is a great starting point for discovering issues and evaluating treatments within a field.
- Combining this tool with other resources, such as drones and in-field scouting, allows sales professionals and growers to focus their scouting and management efficiently as well as effectively.
- Encirca® Pro from Encirca services provides valuable tools to help facilitate improved crop management.

Soil Compaction in Agricultural Production

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager,*
and ***Nanticha Lutt,*** *Agronomy Sciences Intern*

Summary

- Soil compaction is the increase in bulk density and corresponding decrease in porosity of soil caused by loads applied to it.
- Soil compaction that negatively impacts crop growth can occur in a number of different ways and at different depths in the soil profile.
- The primary negative effect of soil compaction on crop production is a reduction in the ability of soil to supply water and nutrients to the crop.
- Compaction near the soil surface can significantly reduce yield under certain conditions but is generally more manageable and does not persist in the soil for very long.
- Deep compaction is more difficult to eliminate and can negatively affect crop growth and yield for years after the compaction took place.
- Restricted root growth, nutrient deficiencies, and poor water infiltration can all be signs of subsoil compaction.

"Soil compaction is often difficult to ***detect and measure*** and can **limit crop growth and yield** without presenting *any obvious symptoms."*

Soil Compaction in Crop Production

Soil compaction is one of the most serious forms of soil degradation caused by agricultural production. However, unlike other forms of soil degradation, such as erosion or salinization, compaction is often difficult to detect and measure and can limit crop growth as well as yield without presenting any obvious symptoms. When symptoms are present, such as stunted crop growth, nutrient deficiency, or poor water infiltration, they may be attributed to other causes.

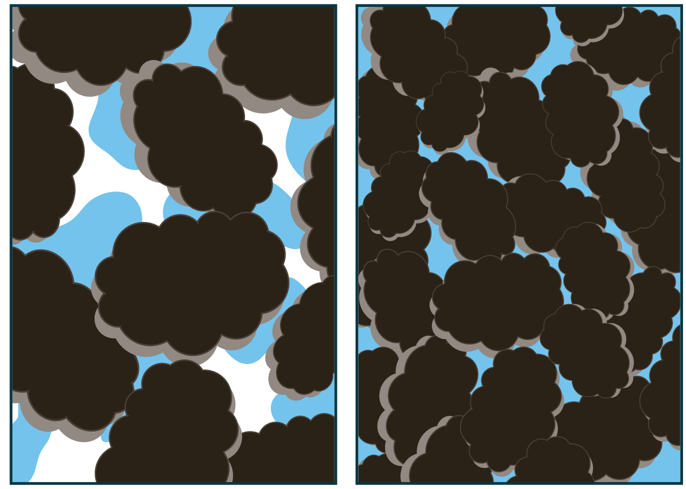
In general, compaction issues in crop production are becoming more prevalent. The size and weight of farm machinery has increased dramatically over the past several decades as farm operations have gotten larger and machines need to cover more acres. Earlier planting of corn to maximize yield can increase the likelihood of working fields in which portions of the field are too wet. Additionally, farm operations covering larger acreages spread over greater areas may come under greater pressure to operate in too-wet conditions, exacerbating the problem of compaction.

Figure 1. Corn seedling that has failed to emerge due to prolonged cold stress and compacted soil conditions. The coleoptile was unable to push upward to the soil surface and is twisted and malformed as a result.

Some degree of soil compaction is the inevitable consequence of modern crop production due to the need to move machinery through the field to plant, manage, and harvest a crop. Soil compaction likely cannot be eliminated entirely from modern agricultural systems, so it must be managed and minimized to the extent possible.

Compaction Effects on Soils and Crops

Soil compaction is defined as the increase in bulk density and corresponding decrease in porosity of soil caused by loads applied to it. Soil compaction can have numerous negative effects on crop production, including restriction of root growth and reduced water-holding capacity. Highly productive, well-aggregated, agricultural soils tend to consist of about 50% solids and about 50% pore space with an equal distribution of macropores and micropores in this pore space (Brady, 1990). This ratio of macropores to micropores allows soil to store ample water for plant growth while allowing for gaseous exchange in the soil profile to provide oxygen to plant roots. Soil minerals have a particle density of about 2.65 g/cm^3, so a medium-textured soil consisting of 50% pore volume will have a bulk density near 1.33 g/cm^3 (USDA-NRCS, 2008).



Normal Soil

- Bulk density = 1.3
- Firm condition
- Few large pores
- Moderate aeration
- Typical silt loam following normal traffic

Compacted Soil

- Bulk density = 1.6
- No large pores
- Small pores are water-filled
- Crushed aggregates

Figure 2. Characteristics of normal and compacted soils (adapted from Wolkowski, 2010).

Finely textured soil and soil high in organic matter have lower bulk density, whereas sandy soils have less pore space and consequently have a higher bulk density. The range of bulk density that is favorable for plant growth differs based on soil texture as does bulk density that is restrictive to plant growth (Table 1).

Table 1. General relationship of soil bulk density to root growth based on soil texture (USDA-NRCS, 2008).

Soil Texture	Ideal Bulk Density for Plant Growth	Bulk Density that Restricts Root Growth
	g/cm³	*g/cm³*
Sandy	< 1.60	> 1.80
Silty	< 1.40	> 1.65
Clayey	< 1.10	> 1.47

Soil compaction that negatively impacts crop growth can occur in a number of different ways and at different depths in the soil profile. Surface compaction from heavy rains, sidewall compaction from wet conditions at planting, and hard pans at the bottom of the plow layer can all restrict root growth as well as reduce crop yield. From a management perspective, however, the most serious form of compaction is that caused by wheel loads from machinery operating in the field. Compaction caused by heavy axle loads can extend from the soil surface down into the subsoil where it can persist for years and is difficult or impossible to remediate.

The primary negative effect of soil compaction on crop production is a reduction in the ability of soil to supply water and nutrients to the crop. There are multiple aspects of compaction that contribute to this outcome. Compacted soils limit the ability of plant roots to grow into surrounding soil to extract water and nutrients, effectively reducing the amount of the soil profile that is available to contribute to supplying water and nutrients for crop growth (Figure 3). The reduction of pore space in the soil also reduces the overall water-holding capacity of the soil, meaning less water is available for plant uptake.

Figure 3. Root growth of corn plants (V5 growth stage) growing in soil compacted to different bulk densities before corn seeds were planted (Strachan and Jeschke, 2017).

Compaction reduces the rate at which water moves downward through the soil profile (Figure 4). This lower rate of infiltration can reduce the proportion of water from a rainfall event that penetrates the soil and becomes available for crop uptake as well as increase the proportion lost to runoff. Increased runoff can have the additional negative effect of greater risk of soil erosion.

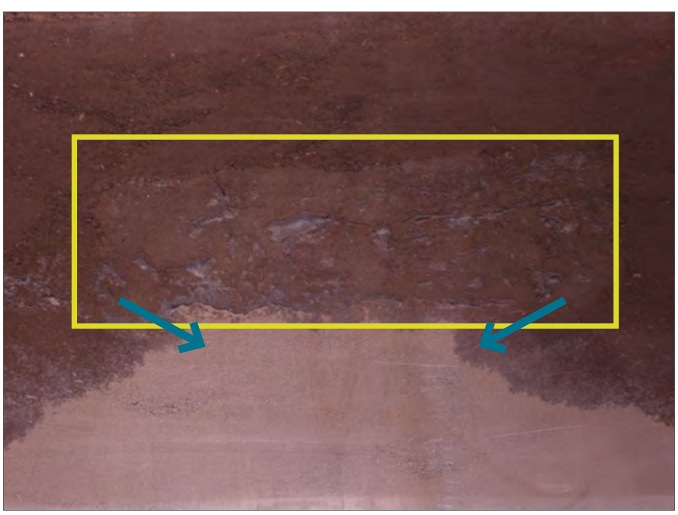


Figure 4. Water as it drains through the soil profile is limited by a zone of highly compacted soil (outlined by the yellow box). Water drains through less compacted soil more quickly and eventually begins to move below the zone of high compaction (Strachan and Jeschke, 2017).

Reduced infiltration rate also means that, once saturated, compacted soils are slower to drain. This can negatively affect crop growth by reducing the availability of oxygen needed for proper growth to plant roots. Slower drainage can also reduce the rate at which soils warm up in the spring as well as increase the amount of time after a rainfall event needed for the soil to dry out and become suitable for field work.

Soil Factors That Influence Compaction

Soil Moisture

Soil moisture is the most important factor influencing the risk of soil compaction (Soane and Van Ouwerkerk, 1994). Drier soils can sustain heavier loads without becoming compacted. Soils with moisture levels at or above field capacity have the greatest potential for compaction. Water acts as a lubricant between soil particles that allows soil to be pushed together. As more air space is replaced with water, the potential for compaction increases up to a maximum point referred to as the "plastic limit." At soil saturation levels above this point, the compactive potential of the topsoil declines since water cannot be compressed. However, this results in the compactive force being directly transferred to the subsoil, increasing the risk of subsoil compaction (Duiker, 2004). Additionally, trafficking very wet soils often results in extensive smearing of the topsoil, which reduces hydraulic conductivity and may be even more detrimental to crop root growth than compaction (Raper and Kirby, 2006).

There are some simple in-field tests that can be used to make a rough determination if the soil is too wet to work without a high risk of compaction. One such test is the "ribbon test," which involves digging down four inches into the seed bed, grasping a handful of soil, and squeezing it tightly in your hand. If the soil forms a "ribbon" when squeezed between the thumb and forefinger, it is in a condition for compaction to occur (Figure 5).

Figure 5. The "ribbon test" can be used to assess soil moisture and determine if soil is at high risk for compaction.

Soil Texture and Structure

Soil texture (% of sand, silt, and clay in a soil) has some effect on compaction potential. Soils that consist of particles of equal size have less compactive potential than soils that have particles of varying sizes. Smaller particles can fill spaces between larger particles, thereby increasing soil density. A sandy loam soil is the most susceptible to compaction, while pure sands, clays, and silt soils are least susceptible. Soil texture can also influence the pattern of compaction in the soil. Compaction in coarser soils tends to penetrate vertically downward into the soil profile, while in finer texture soils, compaction tends to penetrate downward and outward laterally in the soil profile (Ellies et al., 2000).

Compaction potential is also influenced by soil structure. Natural processes in the soil, including wetting and drying; freezing and thawing; and bacterial, fungal, and root growth, result in the formation of aggregates. Aggregates are groups of soil particles that bind more tightly to each other than to adjacent particles. Collectively, the stability of these aggregates is referred to as *soil structure*. Soil structure provides an important defense against soil compaction. Without good structure, individual soil particles are more susceptible to compaction from external pressure. Soils higher in organic matter generally have better soil structure and resist compaction better than low organic matter soils.

Tillage, falling rain, and compaction are the primary mechanisms by which soil aggregates are destroyed. Tillage operations that combine shearing action with substantial down pressure cause the most damage to soil structure due to the destruction of soil aggregates and the tendency to form a tillage pan at the bottom of the plow layer. Compaction from heavy loads applied to the soil can be both a cause and consequence of poor soil structure. Compaction can cause granular structure in the topsoil to break down and reform as blocky or platy structure.

Types of Soil Compaction

There are a number of different forms of soil compaction that can occur in crop production and negatively affect crop growth as well as yield. Some forms of compaction, such as surface crusting and sidewall compaction, can significantly reduce yield under certain conditions but are generally less of a management concern due to the fact that the compaction generally does not persist in the soil for very long, and there are various management options available to prevent or mitigate their effects. Other forms of compaction, such as tillage pans and subsoil compaction, can persist for years and are much more challenging to manage.

Surface Crusting

Surface crusting is a form of soil compaction that reduces seed emergence and water infiltration rates. It is caused by the impact of raindrops on surface soil particles. Heavy impact causes soil particles to sift together. Rapid soil drying increases potential of surface crusting. Soils with higher organic matter or sand content have less potential for crusts to form. Reduced- and no-tillage systems are generally at lower risk of surface crusting due to better soil structure and greater amounts of crop residue on the soil surface. Rotary hoes can be used to break up crusts and improve emergence as well as stand establishment.

Sidewall Compaction

Sidewall compaction typically results from planting into soils that are too wet and/or applying too much down pressure on the row units. The action of the planting disc openers shearing into wet soils can cause seed furrow sidewalls to become hard after planting (Figure 6). The result can be poor crop emergence and poor root development out of the seed furrow. The consequences of restricted root development can be magnified if conditions turn drier and the crop encounters drought stress later in the season. Severe sidewall compaction reduced corn yield by 50% in a University of Kentucky Extension demonstration (Lee, 2011). The use of spiked closing wheels may help reduce sidewall compaction by tilling in the soil around the seed and breaking up the sheared sidewall face but is unlikely to completely eliminate its effects.

Figure 6. **Left:** Compaction of the seed furrow sidewall due to double-disk openers slicing through the soil in wet seedbed conditions. **Right:** Corn roots showing the effects of sidewall compaction due to wet field conditions at planting.

Topsoil Compaction

Topsoil compaction occurs from the soil surface down through the normal tillage zone. This type of compaction is typically caused by wheel traffic or animal traffic. Effects of topsoil compaction on crops can vary depending on weather conditions and are generally worse in wet growing seasons. Topsoil compaction is usually temporary and can be partially remediated by normal tillage. Natural processes, such as freeze-thaw cycles, wet-dry cycles, microbial activity, and plant root growth, will also tend to alleviate topsoil compaction over time and rebuild soil structure.

Tillage Pan

A tillage pan is a layer of subsoil compaction only a few inches thick right beneath the normal tillage zone. This type of compaction is caused by repeated tilling at the same depth, particularly with tillage implements that shear and compress the soil at the bottom of the plow layer, such as discs, moldboard plows, and sweep-type implements. Deep tillage may help break up tillage pans under certain conditions but can also make the problem worse if the soil is too wet or is immediately recompacted.

Deep Compaction

Deep compaction lies beneath the tillage zone and is caused by high-axle weight loads applied to the soil. Harvest equipment, such as grain carts and combines, have high-axle loads and most often are the biggest contributors to deep compaction. Heavy loads can compact soil more than two feet down into the soil profile. Deep compaction is the most difficult to eliminate and can negatively affect crop growth as well as yield for years after the compaction took place, so prevention is important.

Detecting and Measuring Compaction

Crop Symptoms

Soil compaction can result in malformed root growth, including stubby, flat, thin, or twisted roots. Roots growing into a tillage pan can grow horizontal rather than vertical and will have flat, shallow root systems. Above-ground growth is directly related to below-ground root growth. If root growth is being impaired, vegetative growth above ground will likely be stunted.

Look for specific patterns or areas in fields such as wheel track patterns, particularly when associated with very heavy loads, such as combines, grain carts, or liquid manure spreaders (Figure 7). In some cases, a specific pattern is not visible. These areas can result from repeated overlapping of the same areas with different tillage passes that, over time, have an additive effect on areas within the field.

Figure 7. Corn field with uneven emergence due to compaction in wheel tracks. *Photo courtesy of Jim Boersma.*

Nutrient stresses on crops can be another sign of compaction. Since roots are the avenues for soil nutrients to the crop, root restrictions can decrease interception of nutrients in the soil. Phosphorous, potassium, and nitrogen deficiencies can be secondary symptoms of soil compaction.

Lack of Water Infiltration

Standing water or excessive water erosion can be caused by soil compaction. Compaction reduces pore space within soil, so water is not absorbed into soils as readily. Increased power requirements for field operations can be a sign of compaction as well. If field tillage operations encounter certain areas in a field where the tractor "pulls down," this can signal a compacted area.

Figure 8. Measuring soil compaction with a soil penetrometer.

Measuring Soil Compaction

Sidewall, surface crusting, and tillage-pan compaction are the easiest forms to detect with a shovel or other type of digging device. Deep soil compaction is harder to find since it occurs deeper in the soil.

Cone-tipped penetrometers can be used to locate compaction (Figure 8). These have limitations, however. Penetration resistance is a function of soil density and moisture content. Compacted and non-compacted soils of equal moisture and texture need to be compared. Therefore, there is no specific numerical value of resistance (psi) that identifies compaction. Comparative values need to be evaluated (Duiker, 2002). Constant rates of push also must be maintained to give accurate readings. Motor drive penetrometers, which penetrate the soil at a fixed rate, give the most accurate readings.

Soil probes are another useful tool. These are also subject to moisture content and soil density. A drier soil will probe harder than a wet soil; clays will probe harder than loam soils for instance. Soil probes can be used effectively to monitor differences in the soil moisture profile. If the top foot of soil is extremely dry but the second foot is very moist, this suggests that crop roots are not penetrating into the second foot, possibly because of compaction.

The best indicator of compaction is viewing root growth patterns into the soil profile. This is accomplished by using a spade or shovel to dig holes or trenches alongside the existing crop. Holes should be dug alongside the existing crop in suspected compaction areas.

Machinery Options for Reducing Soil Compaction in Crop Production

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Summary

- Heavy modern farm machinery and the need to sometimes operate in wet conditions have increased the risk of soil compaction issues in agricultural production.
- The primary negative effect of soil compaction on crop production is a reduction in the ability of soil to supply water and nutrients to the crop.
- Compaction in the topsoil is primarily determined by contact pressure, whereas, subsoil compaction is primarily determined by axle load.
- Research has shown that axle loads greater than approximately 10 tons can cause compaction that penetrates into the subsoil.
- Larger tires, duals, lower tire pressure, and rubber track systems are all effective options to reduce contact pressure and minimize topsoil compaction; however, heavy axle loads still can cause subsoil compaction.
- Research shows that 80% of wheel traffic compaction occurs on the first pass, so growers should try to limit the number of trips across fields and use the same traffic pattern whenever possible.
- Future developments in autonomous machinery offer the potential for reducing soil compaction with smaller machines and precisely controlled traffic patterns.

Introduction

Soil compaction is a pervasive problem throughout modern agriculture. The need to move machines through the field to conduct planting, harvest, and other tasks makes some degree of soil compaction nearly unavoidable. Soil moisture is the most important factor influencing the risk of soil compaction (Hamza and Anderson, 2005; Lindstrom and Voorhees, 1994), so the best solution to compaction is simply to avoid operating when soil is too wet and compaction risk is high. However, the realities of getting crops planted and harvested often mean growers have essentially no choice but to sometimes operate when portions of a field are too wet. Given this situation, it is important to evaluate the full range of options available to minimize compaction, manage soil to be more resilient against compaction, and remediate or manage compaction that has already occurred. This article will focus specifically on machinery options for managing compaction.

High axle loads of large agricultural machines, such as tractors, combines, and grain carts, can create compaction deep into the soil profile when operating in wet conditions.

A Growing Challenge to Crop Production

One of the most significant factors that has contributed to increasing soil compaction issues has been the dramatic increase in the size and weight of farm machinery over the past several decades (Figure 1). Even just within the last 20 years, the weight of some of the largest machines has gone up dramatically. The largest combine in the Case IH lineup in 1998 was the 2388, weighing in at 28,329 lbs. With an 8-row corn header and a full grain tank, the maximum weight tops out at 44,311 lbs. Compare that to a maximum weight of 77,020 lbs for the largest combine in 2018 (Table 1). Larger machines have facilitated much greater efficiency by allowing one operator to cover more acres, but the greater loads being applied to the soil have increased the potential for compaction that is both more severe and extends deeper into the soil profile.

Additionally, some growers may face greater pressure to conduct field operations when conditions in at least part of the field are too wet. Research has shown the benefits of planting corn (Jeschke and Paszkiewicz, 2013) and soybeans (Van Roekel, 2018) as early as practical to extend the growing season and maximize yields, but this means spring tillage operations may be pushed earlier when soils are more likely to be wet. The need for machines to cover more acres on larger and more geographically dispersed operations during the spring and during harvest can also increase the likelihood of being forced to operate in suboptimal conditions. Trends toward greater annual precipitation, particularly in the spring, and more intense precipitation events in the U.S. Corn Belt driven by climate change are likely to add to the problem (U.S. EPA, 2016).

International Harvester 1086

1976-1981

12,715 lbs

Case IH Magnum 7130

1987-1993

17,540 lbs

Case IH Magnum MX285

2003-2006

21,630 lbs

Case IH Magnum 380

2014-2017

32,200 lbs

Figure 1. Examples of tractors that would have been commonly used for field work in their respective eras, showing increasing tractor weight over the past 40 years.
Tractor weights from www.tractordata.com.

Soil Compaction Effects on Crop Growth and Yield

The primary negative effect of soil compaction on crop production is a reduction in the ability of soil to supply water and nutrients to the crop. Compacted soils limit the ability of plant roots to grow into new soil to extract water and nutrients, effectively reducing the amount of the soil profile that is available to contribute to supplying water and nutrients for crop growth. The reduction in pore space in the soil also reduces the overall water-holding capacity of the soil, meaning less water is available for plant uptake. Compacted soils can delay crop emergence, reduce stand establishment, inhibit crop growth, and ultimately reduce yield.

Table 1. Machine, header, and maximum grain weights for a top-end Case IH combine in 1998 and 2018.

1998	Weight (lbs)
Combine – Case IH 2388	28,329
8-row corn header (model 1063)	4,222
210 bu grain tank (full)	11,760
Total	**44,311**
2018	**Weight (lbs)**
Combine – Case IH 9240	42,205
16-row corn header (model 4416)	11,855
410 bu grain tank (full)	22,960
Total	**77,020**

Deep compaction caused by heavy loads is the most challenging form of soil compaction for crop production. Equipment with extremely high axle loads, such as fully loaded grain carts, can compact soil more than three feet down into the soil profile. Effects of deep compaction on crop growth and yield can persist for years and often go undetected, resulting in growth and yield issues often attributed to other factors. Compaction created by high axle loads can reduce crop yields by more than 15% in the first year with yield reductions of 3 to 5% persisting as many as 10 years after the initial compaction event (Duiker, 2004). Compacted areas due to machinery traffic in a field often run parallel to the rows, making yield effects difficult to detect and measure from yield monitor data since all harvest passes tend to be affected. Additionally, deep compaction is difficult or impossible to fix once it occurs.

Factors that Influence Compaction Severity & Depth

In order to effectively manage compaction, it is necessary to understand how the soil is affected at different depths by loads applied to it. Compaction in the topsoil is determined by contact pressure. Compaction in the upper portion of the subsoil is determined by both contact pressure and axle load. Compaction in the lower subsoil is determined primarily by axle load (Figure 2). The number of passes and load-dwelling time (i.e., how fast the machine is moving) will also influence how the load affects the soil.

Axle Load

Axle load is the total weight carried by one axle, typically expressed in lbs, kg, or tons. For machines or implements with more than one axle, the average axle load can be calculated by dividing the total weight by the number of axles. The maximum axle load will be some fraction of the total weight and varies depending on how the machine is balanced. For example, combines typically carry most of their weight on the front axle, whereas 4WD tractors have a more even weight distribution (Table 2). Thus, for a combine and a 4WD tractor of equal weight, the average axle load would be the same, but the maximum axle load would be greater for the combine.

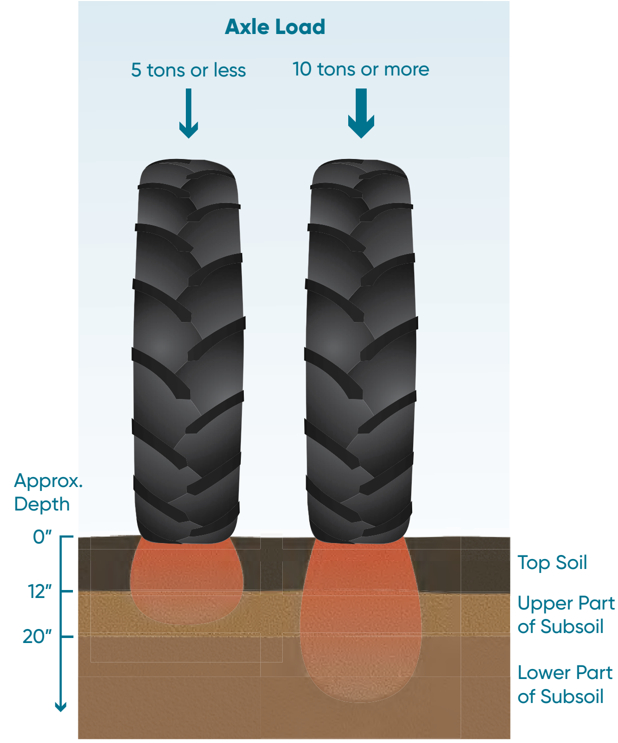


Figure 2. Greater axle load will produce compaction deeper into the soil profile. Axle loads over 10 tons can create compaction in the subsoil that may persist for years (Adapted from Duiker, 2004).

Table 2. Approximate weight balance of modern combines and tractors (Hoeft et al., 2000).

Machine	Front Axle	Rear Axle
2WD Tractor	25-30%	70-75%
MFWD Tractor	35%	65%
4WD Tractor	51-55%	45-49%
Combine	80-85%	15-20%

Research has shown that axle loads greater than approximately 10 tons can cause compaction that penetrates into the subsoil (Voorhees et al., 1986). Compaction caused by axle loads less than five tons is generally limited to the topsoil and does not extend into the subsoil. Modern tractors, combines, and grain carts often greatly exceed the 10-ton threshold (Table 3) and therefore run the risk of causing subsoil compaction in susceptible soils.

Table 3. Approximate axle loads for field equipment (DeJong-Hughes, 2018).

Field Equipment	Axle Load (tons/axle)
Slurry tanker, 4,200 gal	10-12
Slurry tanker, 7,200 gal	17-18
Class 9 combine, 590 hp, 360 bu capacity	20
12-row combine, full with head	24
Grain cart, 720 bu, full, 1 axle	22
Grain cart, 1,200 bu, full, 1 axle	35-40
Terra-Gator, rear axle	12-18
4WD Tractor, 200 HP, front axle	7.5
4WD Tractor, 325 HP, front axle	13
4WD Tractor, 530 HP, front axle	18

Contact Pressure

Contact pressure is the axle load divided by the surface area of contact between the load and the soil and is measured in pounds per square inch (psi) or kPa and is the primary factor determining topsoil compaction. Reducing contact pressure will reduce compaction in the topsoil. This can be achieved by lowering tire pressure or by increasing the contact area between the load and the ground, such as by using wider tires (Figure 3).

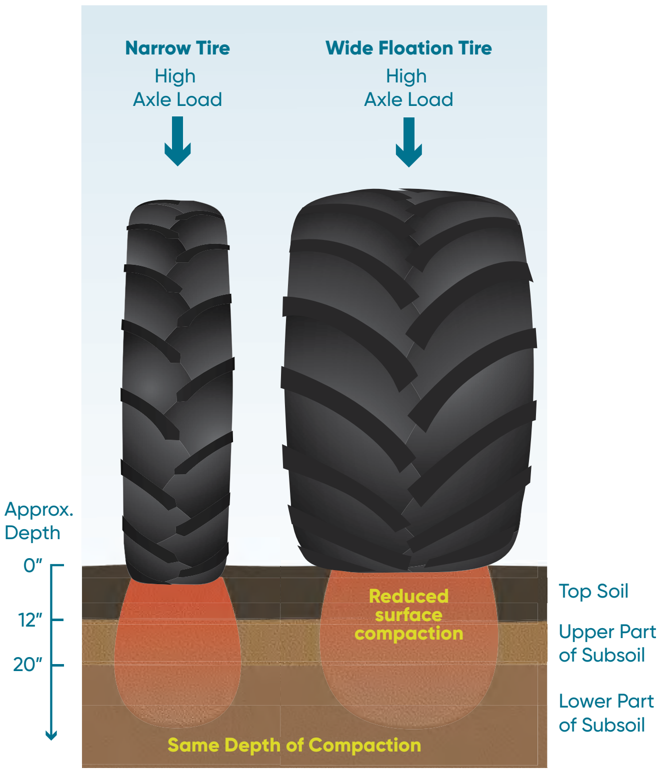


Figure 3. Increasing the surface area of contact by using wider tires, duals, or tracks can reduce compaction in the topsoil layer but does not eliminate the risk of subsoil compaction with high axle loads (adapted from Duiker, 2004).

Contact pressure for radial agricultural tires is generally 1 to 2 psi above inflation pressure. The use of low-pressure radial tires can help reduce topsoil compaction. Grain trucks and other vehicles with high axle loads and high-pressure road tires can cause much more severe topsoil compaction.

Larger tires, duals, lower tire pressure, and rubber track systems are all effective options to reduce contact pressure and minimize topsoil compaction; however, axle loads greater than 10 tons still can cause subsoil compaction.

Table 4. Maximum pressure at a range of soil depths associated with different tire inflation pressures (Arvidsson and Keller, 2007).

Inflation Pressure	Maximum Pressure at Soil Depth			
	4 in	12 in	20 in	28 in
psi	psi			
22	25	16	3	3
15	20	15	4	3
10	16	15	4	3

Research has shown that lower contact pressure can reduce compaction in the upper soil profile (Table 4) but that it has little to no effect on subsoil compaction, which is primarily determined by axle load (Table 5).

Table 5. Maximum pressure at a range of soil depths associated with different wheel loads (Arvidsson and Keller, 2007).

Wheel Load	Maximum Pressure at Soil Depth			
	4 in	12 in	20 in	28 in
lbs	psi			
7,400	24	22	6	5
3,400	19	11	3	2
2,500	17	12	3	2

Number of Passes

Conventional wisdom for managing soil compaction holds that the majority of compaction occurs on the first pass over the soil, so growers are better off concentrating repeated traffic into the same travel lane rather than spreading traffic out over a greater portion of the field. This is true; research shows that 70 to 80% of compaction effects happen on the first pass (Wolkowski and Lowery, 2008). However, this does not mean that effects of repeated passes are inconsequential. The compaction caused by repeated passes may cause as much damage to crop growth because the incremental increases in soil density are being applied to a soil that is already above optimum bulk density (Duiker, 2004). The compactive effects of lower axle loads applied repeatedly can eventually exceed the effects of fewer passes with a heavy axle load as well as extend into the subsoil (Balbuena et al., 2000).

This can be important when considering the value of tandem or triple axles vs. single axles on heavy equipment, such as slurry tankers and grain carts. Adding an additional axle cuts the axle load in half and doubles the surface area of contact, both of which can help reduce compaction. However, it also effectively adds a pass since the same track is being trafficked twice instead of once, which is likely to offset some of the aforementioned benefits (Raper and Kirby, 2006) (Figure 4).

Figure 4. Increasing the number of axles carrying a heavy load increases the surface area of contact and reduces maximum axle load but also increases the number of times pressure is applied to soil in the wheel track.

Load Dwelling Time

Travel speed of machines operating in a field can influence the amount of compaction they cause. Longer dwelling times of loads applied to the soil increase the amount of compaction they cause. Increasing travel speed will decrease the load-dwelling time and consequently, the severity of compaction.

Machinery Options for Reducing Compaction

Tire Pressure and Configuration

Soil compaction in the upper part of the soil profile is greatly influenced by the contact pressure, so lower tire inflation pressure can help reduce compaction. From a practical standpoint, conducting field operations at the lowest recommended tire pressure can be challenging as proper tire pressure for road speeds can be two to three times higher than optimal pressure for field conditions. New lower-pressure agricultural tires have been introduced by multiple tire manufacturers in recent years, expanding options available to growers for reducing compaction. On-board compressor systems have also been developed that allow growers to reduce tire pressure when entering fields and then re-inflate tires before traveling on roads.

Duals and triples can also help reduce compaction. Additional tires on a machine increase the total surface contact area and also reduce inflation pressure necessary to carry the axle load. A study comparing compactive effects of single and dual wheels found that duals reduced compaction in the upper part of the soil profile but that the advantage of duals over singles narrowed at greater depths (Figure 5). Duals and triples have the disadvantage of increasing the width of the trafficked area.

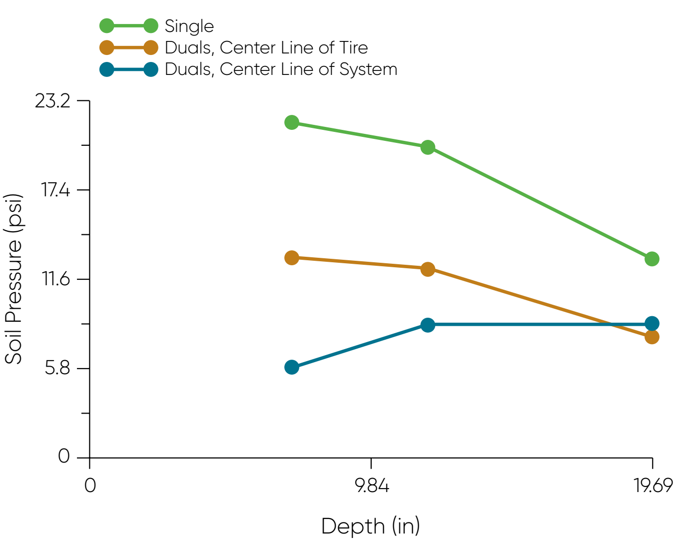


Figure 5. Soil pressures measured beneath single and dual tires (Taylor et al., 1986).

Tracks

The availability of factory and aftermarket rubber track systems for farm machines has greatly expanded in recent years, making them one of the most readily-available equipment options for managing soil compaction. A variety of track options are now available for tractors, combines, grain carts, sprayers, and planters (Figure 6). There are a number of factors to consider in assessing the value of tracks versus tires, and research has not necessarily shown a clear across-the-board advantage for tracks in mitigating soil compaction under wet conditions.

Figure 6. Examples of some of the numerous factory and aftermarket track options on display at the 2018 Farm Progress Show.

Tracks generally increase the surface contact area of a load relative to a comparable wheeled configuration, which can help reduce topsoil compaction and formation of ruts. Also, since tracks expand the surface contact area longitudinally within the path of travel, they do so without increasing the area of the field that is trafficked in contrast to other options, such as duals, that increase the width of the compacted path. However, it is important to realize that surface contact pressure is not uniform across the entire track area. Rather, a zone of higher pressure is created under each wheel. As a track moves, it will create multiple pressure spikes corresponding with each wheel passing over the soil. In that sense, tracks can be thought of as a form of multi-axle configuration – there are more axles carrying the load and the surface contact pressure is reduced, but the soil in the machine path is subjected to repeated pressure applications and greater total load-dwelling time (Duiker, 2004).

Table 6. Soil compaction of a four-wheel drive and tracked tractors at different soil depths (Abu-Hamdeh et al., 1995a).

	Cone Index			
Soil Depth	Duals[1] (24 psi)	Tracks[2] (24-inch)	Tracks[3] (36-inch)	Duals[4] (7 psi)
inches	psi			
4-8	87.7	78.2	62.3	51.9
8-12	73.9	65.4	46.8	42.2
12-16	72.9	49.5	38.4	32.4
16-20	35.5	26.2	20.7	10.9

[1] John Deere 8870 with 710/70R38 duals overinflated to 24 psi.
[2] Cat Challenger 65 with 24-inch rubber track.
[3] Cat Challenger 75 with 36-inch rubber track.
[4] John Deere 8870 with 710/70R38 duals inflated to 6 and 7 psi (front and rear).

Table 7. Soil compaction (reduction in soil porosity) from a John Deere 9600 combine with various tire and track configurations (Abu-Hamdeh et al., 1995b).

Soil Depth	Decrease in Soil Porosity				
	Single 34 psi[1]	Track[2]	Duals 26 psi[3]	Wide 24 psi[4]	Wide 15 psi[5]
inches	%				
4-8	16.3	13.9	10.5	8.1	6.1
8-12	14.1	12.0	9.8	7.2	5.6
12-16	13.2	9.8	7.3	5.1	2.9
16-20	8.1	5.9	4.1	1.8	1.3

[1] Single 30.5L32 tires at 34 psi.
[2] Half-track system with an average psi of 10.
[3] Dual 18.4R38 tires at 26 psi.
[4] Wide 68x50.0-32 tires overinflated at 24 psi.
[5] Wide 68x50.0-32 tires at the correct pressure of 15 psi.

The question of whether tracks provide an advantage over tires in reducing soil compaction is not one that necessarily has a straightforward answer. Research has generally indicated that it depends on the specific tire and track configurations being compared. An Ohio State study comparing compaction down to a depth of 20 in caused by tracked and wheeled tractors found that the best result for minimizing soil compaction was achieved with duals running at low inflation pressure (Table 6). Another Ohio State study compared half-tracks and four different tire configurations on a combine. This study also showed that tires at a low inflation pressure provided the best results (Table 7). For machines where the tires typically have a higher inflation pressure, such as sprayers or planters, tracks would likely provide a greater advantage relative to tires. For the heaviest machines, such as combines and grain carts, tracks may provide an advantage in reducing surface compaction and rut formation but will not eliminate the risk of subsoil compaction associated with heavy-axle loads.

Controlled Traffic

Controlling wheel traffic in a field is a tactic available to all growers to help reduce soil compaction. Research shows that 80% of wheel-traffic compaction occurs on the first pass, so growers should try to limit the number of trips across the field and use the same traffic pattern whenever possible. During harvest, try to follow combine wheel paths as much as possible when running the grain cart rather than cutting diagonally across the field between the combine and the grain trucks. Try to keep grain trucks confined to the edges of fields or out of the fields altogether, if possible, as the heavy-axle loads combined with high inflation pressure road tires can cause significant compaction.

Autonomous Machines

Multiple farm machinery manufacturers are currently developing autonomous farm machinery technology, and it is likely that the first autonomous farm machines will become commercially available in the near future. Initial experimental prototypes and concept vehicles have often resembled current tractors without the need for an operator and in some cases, without a cab or operator controls on the machine at all (Figure 7).

Figure 7. Case IH autonomous concept vehicle introduced at the 2016 Farm Progress Show.

As autonomous technology progresses, however, it may move away from resembling current operator-based vehicles to take advantage of the inherent advantages of the technology, specifically the ability to run more machines simultaneously without additional operators and the ability for a machine to run 24 hours a day. Replacing a single, large, operator-controlled machine with multiple, smaller autonomous machines could provide significant advantages in reducing soil compaction. Additionally, the ability to precisely manage traffic patterns across a field throughout the season could reduce the proportion of the field subject to compaction by concentrating traffic into regular paths.

Soil Health and Management in Agricultural Systems

*by **Samantha Teten,** Agronomy Sciences Intern*

Summary

- The term *soil health* has gained prominence in agriculture to refer to chemical, physical, and biological attributes of a soil and the ways in which they can influence crop productivity.
- Increased interest in soil health is being driven in part by expanding knowledge of soil biology, specifically the effects of bacterial and fungal communities in the soil on crop productivity and the ways in which crop management practices can either help or harm these species.
- In order to optimize crop management practices for improved soil health, it is necessary to develop a system to quantify soil health so that management effects over time can be measured.
- The Soil Health Institute has developed a list of 19 soil health Tier 1 indicators that are quantitatively measurable, effective across regions, and have thresholds for expected outcomes, such as yield or environmental effects.
- Several multi-faceted soil health assessments have been developed to provide a comprehensive evaluation of the overall soil condition.
- Many challenges hinder the wide adoption of soil health tests, including expense, scalability, correlation to productivity, and replicability in different environmental conditions.

Introduction

Soil plays a critical role in regulating many essential elements for crop growth. A productive soil stores water and nutrients for plant accessibility and contains pore space for the oxygen needed for root respiration. The ability of a soil to carry out these functions and provide utility for its intended purpose is the basis for the concept known as *soil health*. More specifically, soil health has been defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994).

Our understanding of soil management has greatly evolved over the course of a century, a fact that is well-illustrated by a 1909 statement attributed to the Federal Bureau of Soils, "The soil is the one indestructible, immutable asset that the nation possesses. It is one resource that cannot be exhausted, that cannot be used up." Few at the time understood the risk to sustainable productivity posed by soil degradation and erosion. Soil conservation and management did not become a priority until the U.S. experienced the devastation of the 1930s Dust Bowl. The combination of excessive tillage, eroded bare ground, and extreme drought resulted in severe soil degradation, in some cases making land unproductive for many years to come.

Since that time, soil management has markedly improved with the help of agencies, programs, and education. The terms *soil tilth* and *soil quality* quickly emerged following the Dust Bowl era as research and education projects were initiated to improve land management practices. Tilth generally referred to the soil's physical characteristics, including aggregate stability, erosion, and water-holding capacity. Soil quality became more widely accepted to encompass all attributes related to land properties and management. Within the last two decades, the phrase *soil health* has gained traction. This better exemplifies the increasing understanding and recognition of the importance of biological aspects of soil in addition to chemical and physical attributes.

The objective of soil health management is to optimize management practices so the soil can reach its maximum potential for a specific goal. For agriculture, this goal is often yield, but it may also include other desired outcomes, such as minimized nitrate leaching. For a pasture or buffer strip, the goal may be increased vegetation or decreased erosion potential. Increased interest in soil health is being driven in part by expanding knowledge of soil biology, specifically the effects of bacterial and fungal communities in the soil on crop productivity, and the ways in which crop management practices can either help or harm these species. In order to optimize crop management practices for improved soil health, it is necessary to develop a system to quantify soil health so that management effects over time can be measured.

Soil Health Indicators

The Soil Health Institute is an independent, nonprofit organization comprised of leaders in industry, farming operations, government agencies, non-governmental organizations, and universities established to conduct research, outreach, and education related to soil health. In 2017, the Soil Health Institute developed a list of 19 soil health Tier 1 indicators that are quantitatively measurable, effective across regions, and have thresholds for expected outcomes, such as yield or environmental effects (Figure 1). These indicators were adopted following a 3-year national scientific collaboration and additional measurements continue to be evaluated for potential inclusion in Tier 1. The next step of the organization is setting forth a framework for Tier 2 and Tier 3 measurements. Tier 2 will focus on the development of indicators for improvements or degradation of soil along with creating thresholds for regions and how management factors influence the measurements. The mission for the Tier 3 indicators is to quantify soil processes and land management effects on a large scale.

Figure 1. Chemical, physical, and biological indicators designated as Tier 1 Soil Health Indicators by the Soil Health Institute.
https://soilhealthinstitute.org/2017-tier-measurements/

Chemical indicators are the characteristics of soil that are most easily affected in the short term by vegetative growth, leaching, mineralization, fixation, and inputs. Nitrogen, phosphorus, and sulfur quantities fluctuate throughout a growing season. Other chemical characteristics, such as potassium, pH, and micronutrients, are more stable but can be amended through lime, fertilizer, and manure applications.

Physical indicators are more related to the inherent properties of soil, such as texture, but can still be influenced through management practices over the long term. Tillage, erosion, and compaction can degrade the physical characteristics of soil, which then take longer to rebuild.

Biological indicators are a more recent development in the understanding of soil health with increasing knowledge of microbial communities and their impact on crop productivity. This third component of soil health is often the most challenging to characterize as temperature and moisture can greatly affect short-term variability in biological activity. Management of these characteristics is done indirectly by balancing or improving the chemical and physical soil properties. For this reason, many soil health tests rely heavily on measuring biological indicators since they can be indicative of limitations in other areas. For example, the biological indicator of crop yield may be negatively impacted by low pH. In the same way, a slow rate of carbon mineralization could be indicative of low soil nitrogen and high bulk density.

In addition to being a promising indicator for soil health, the biological aspects of soil play an often-underappreciated role in crop growth. Soil ecosystems encompass a broad diversity of organisms, such as earthworms, insects, nematodes, algae, fungi, bacteria, and plant materials like roots. A primary function of soil organisms that is relevant to crop production is the breakdown of organic matter to form humus, which is correlated to important soil properties like cation exchange capacity and water-holding capacity. These organisms also play a role in forming stable aggregates to improve soil structure for root growth. Bacteria are vital for many of the chemical processes in the soil matrix, such as nitrification, nitrogen fixation, and sulfur oxidation.

In addition to the 19 indicators selected by the Soil Health Institute, overall soil health characteristics important to a producer may include other factors like the quantities of weed seed, disease inoculum, soil insect pests, and microbial communities. These factors can all influence crop productivity and can be affected by management practices.

Indicator Testing Methods

Ideally, soil health is a comprehensive assessment of the collective effects and interactions of soil characteristics; however, measuring single characteristics independently can alleviate some expense and time while identifying specific areas in need of improvement. These single indicator tests are common components of comprehensive soil health assessments and can help determine yield-limiting factors.

Physical Indicators

An infiltration test measures the rate at which water is absorbed by the soil. Sandy textured or well-aggregated soils will have a faster infiltration rate than clay or poorly structured soils. Often this test is conducted on-site instead of in a laboratory. This test uses a 6-inch diameter by 5-inch tall ring to restrict the testing area, a timer, and water. Infiltration rate is an important characteristic since a well-aggregated soil with higher infiltration will be less prone to water runoff during rainfall events.

The bulk density of a soil is found by dividing the oven-dried weight of a soil sample by the volume of the sample taken. Thresholds are different for each soil type with sandy soils having the highest bulk density (Table 1). Bulk density is directly related to porosity and highly correlated with compaction.

Table 1. General relationship of soil bulk density to root growth based on soil texture (USDA-NRCS, 2008).

Soil Texture	Ideal Bulk Density for Plant Growth	Bulk Density that Restricts Root Growth
	g/cm^3	*g/cm^3*
Sandy	< 1.60	> 1.80
Silty	< 1.40	> 1.65
Clayey	< 1.10	> 1.47

Aggregate stability is another indicator of soil health, defined as how well soil particles hold together. This is highly variable based upon organic matter and clay percentages and is influenced by management practices. Strong aggregates create soil structure leading to the increase of macro-porosity for water and gas exchange. If the aggregate stability is poor, the risk of erosion and surface crusting increases. Testing for aggregate stability can be done in a lab or in-field using a small sample in a fine-mesh strainer or terry cloth and then saturating the soil. Strong aggregates will remain in the strainer and can be quantified, comparing before and after weights.

Many soil physical characteristics that directly impact yield can be studied simply through observations of a soil profile. Top-soil depth and rooting depth can illustrate compaction layers and give an indication of nutrient accessibility. Soil texture and penetration resistance can be estimated by physical touch or measured using a soil penetrometer.

Chemical Indicators

The chemical balance in the soil matrix influences characteristics in both the biological and physical areas. Electrical conductivity is a test to measure the salts in the soil solution, including cations like Ca^{2+} and Na^{+} and anions like NO_3^{-} and SO_4^{-}. Some salts are necessary for plant growth, but high levels limit plant growth and microbial activity. Another chemical characteristic that influences several soil factors is pH. An acidic or basic soil environment can limit the availability of nutrients and the activity of microorganisms. By properly managing pH levels, many other aspects of soil health also improve. Since one of the primary goals of soil health is the improvement of water quality, testing nitrate levels can be a useful indicator. Soil nitrate amounts can help determine nitrogen fertilizer needs as well as ensuring that nitrate levels are not excessively high for the area.

Biological Indicators

Earthworms are a commonly-used indication of healthy biological activity. With their size, they are accessible to count with minimal effort and then can be compared to earthworm quantities of a different area. They are beneficial to creating channels and pores in the soil for aeration and drainage as well as breaking down organic matter.

Crop yield is the only single test measurement that can indicate how the chemical, physical, and biological aspects of the soil are collectively working together. However, crop yield is highly dependent on other factors, such as moisture, temperature, pest pressure, genetics, etc., making it inconsistent in results over years or locations. Crop yield, along with most other soil health tests, does not consider the maximum health potential of different soils types. Instead, it is primarily influenced by inherent properties, such as soil texture, drainage, and organic matter, which are difficult to manage.

Soil Health Assessments

Testing or characterizing individual Tier 1 indicators can elucidate one piece of the larger picture of processes occurring in the soil but may fail to detect other limitations to soil productivity. The objective of a multi-faceted soil health assessment is to provide a comprehensive evaluation of the overall soil condition. Researchers have proposed over 65 different soil indicators to include in a complete assessment (Bünemann et al., 2018). This complete list would be prohibitively time-consuming and expensive to include in a comprehensive soil health evaluation; consequently, soil health assessments developed to date focus on a select subset of attributes (Table 2).

Soil Fertility Test

The most commonly used soil assessment is for soil fertility, looking at only the chemical indicators of soil. A grower can learn the organic matter, cation exchange capacity, pH, macronutrients, and micronutrients with a small bag of soil cores. Fertilizer and liming recommendations can be made specifically for that location based upon calibrated response curves or other nutrient management strategies. Managing fertility can increase crop yield and improve other biological processes in cases where there is a deficit.

Solvita Tests

The Solvita field test is a soil respiration test that measures carbon dioxide emission from a soil sample, providing an assessment of soil biological activity. Carbon dioxide is emitted by respiration of micro- and macro-organisms and live roots in the soil. Greater carbon dioxide emission is indicative of greater biological activity, which is generally a positive characteristic of a healthy soil. This test involves filling a small jar with soil either sampled at field capacity moisture or dried then rewetted to a consistent moisture so biological activity will be at its peak. A gel probe is placed in the enclosed jar, and a reading can be taken based on the color 24 hours later. This simple soil health test can produce quick results but is reliant on one indicator. The laboratory version of this test, the Solvita CO_2 Burst Test, can be conducted alongside Solvita's stored organic nitrogen test, called SLAN (Solvita Labile Amino-Nitrogen), and their volumetric aggregate stability test, called VAST.

Table 2. Overview of common soil assessments.

Test	Measurement	Indicators	Expense/ Sample
Soil Fertility Test	Cation exchange capacity, organic matter, pH, buffer index, base saturation, nitrogen, phosphorus, potassium, micronutrients	Chemical	$10-$25
Haney Test	pH, soil respiration, soluble salts, organic matter, soil respiration, nitrate, organic carbon to organic nitrogen	Chemical, biological	$50-$60
Cornell Compre-hensive Assessment of Soil Health (CASH)	Available water capacity, aggregate stability, organic matter, protein index, respiration, active carbon, pH, phosphorus, potassium, minor elements	Chemical, physical, biological	$60, $110, $170 depending on package selected
Extension Soil Health Evaluations	Self-assessment of structure, crusting, compaction, earthworms, decomposition, infiltration, water holding capacity, plant health	Physical, biological	No cost
Solvita	CO_2 concentrations, aggregate stability, nitrogen fertility	Biological, chemical, physical	$60 for biological test, $90 for entire package
Tea Bag or Underwear Test	Decomposition activity	Biological	<$10

The combination of these three test provides an overall soil health assessment that includes physical, chemical, and biological characteristics.

Haney Test

The Haney Test, named for the developer Rick Haney, combines five measurements into one equation for a soil health score. The elements include the Solvita 1-day CO_2 test (respiration measurement), water extractable organic carbon, water extractable organic nitrogen, organic carbon, and organic nitrogen. This creates a carbon to nitrogen ratio, which quantifies how easily plant residue can be decomposed. The completed score from the equation is an indication of mineralization for future availability of nutrients, such as nitrogen and phosphorus. This send-in laboratory test pairs well with a standard fertility test but does not incorporate physical characteristics.

Cornell Comprehensive Assessment of Soil Health

Cornell University's Comprehensive Assessment of Soil Health (CASH) uses 12 measurements spanning chemical, physical, and biological characteristics (Figure 2). Each measurement is rated on a scale and then given an overall score. A sample of soil is submitted to the lab along with soil compaction penetrometer readings for the complete analysis. This soil health testing method has the advantages of consistency and replicability; ease of sampling; and extensive interpretation of the soil health segments. The scalability of this test is currently limited by its relatively high cost.

Comprehensive Assessment of Soil Health

From the Cornell Soil Health Laboratory, Department of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. http://soilhealth.cals.cornell.edu

Grower:
Mark Jeschke
PO Box 1150
Johnston, IA 50131
Mark.jeschke@pioneer.com

Sample ID: S149
Field ID: C0
Date Sampled: 08/01/2018
Given Soil Type: Nevin
Crops Grown: COG/COG/COG
Tillage: 1-7 inches
Coordinates: Latitude: 41.673741000000
Longitude: -93.712101000000

Measured Soil Textural Class: **coarse**

Sand: **--%** - Silt: **--%** - Clay: **--%**

Group	Indicator	Value	Rating	Constraints
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	19.5	18	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
biological	Organic Matter	4.1	99	
biological	Soil Respiration	0.4	30	
chemical	Soil pH	7.1	100	
chemical	Extractable Phosphorus	39.4	12	High Phosphorus, Environmental Impact Risk
chemical	Extractable Potassium	423.3	100	
chemical	Minor Elements Mg: 124.2 / Fe: 0.8 / Mn: 6.0 / Zn: 3.9		100	

Overall Quality Score: **66** / Excellent

Figure 2. A test report from the Cornell Comprehensive Assessment of Soil Health.

University Soil Health Assessments

University extension soil health evaluations and other in-field assessments are another option that rely on observations in lieu of laboratory testing. Many states have their own soil health evaluation cards, such as the Iowa Soil Health Assessment Card or the Northeastern Illinois Soil Quality Card (Figure 3). A scorecard outlines the indicators and describes the increments for a rating. Using sensory analysis

Field ID ______________ Date ______________

Indicator	Descriptions			Ratings		
	Excellent (8–10)	Fair (4–7)	Poor (1–3)	1st Year	2nd Year	3rd Year
Surface cover	Year-round surface cover from living crop or dead mulch; cover 50–100% after planting	Surface cover from living crop or dead mulch only part of the year; cover 30–50% after planting	Surface cover from living crop or dead mulch absent part of the year; cover <30% after planting			
Soil structure (0–3 inches)	Soil aggregates crumb, don't disintegrate in water; soil tilth excellent; good weight-bearing capacity; no crusting and sealing	Soil aggregates cloddy, disintegrate somewhat in water; soil tilth moderate; weight not supported well; some crusting and sealing	Soil aggregates pulverized, disintegrate completely in water; soil tilth poor; weight poorly supported; severe crusting and sealing			
Organic matter (0–3 inches)	Soil dark color; visible organic matter at surface; organic matter content high (>4% in top 2 inches); approaching level under native vegetation	Soil somewhat dark color; little visible organic matter at surface; organic matter content moderate (3–4% in top 2 inches); lower than under native vegetation	Soil brightly/dull colored; no visible organic matter at surface; organic matter content low (<3% in top 2 inches); much lower than under native vegetation			
Soil erosion	No visual evidence of rills or soil movement and deposition in the field; few to no rock fragments visible at surface	Some visual evidence of small rills and soil movement and deposition in parts of the field; possibly some rocks visible at surface	Much visual evidence of rills and some gullies; possibly significant evidence of soil movement and deposition in parts of the field			
Soil compaction	Soil not very resistant to penetration with soil compaction tester; no evidence of plow pan; low penetration resistance in subsoil	Soil somewhat resistant to penetration with soil compaction tester; no evidence of plow pan; moderate penetration resistance in subsoil	Soil highly resistant to penetration with soil compaction tester; high penetration resistance at bottom of plow layer; high penetration resistance in subsoil			
Water infiltration	Water drains well after heavy rain; ponding largely absent; low runoff	Water drains slowly with some ponding; moderate runoff	Water drains slowly; ponding evident after rain; high runoff			
Soil biodiversity	Much evidence of earthworm activity; many nightcrawler mounds; spiders and ground beetles visible under residue	Some evidence of earthworm activity; some nightcrawler mounds; spiders and ground beetles scarce	No or little evidence of earthworm activity; no nightcrawler mounds; spiders and ground beetles absent			
Plant and root growth	Seedling emergence even and fast; plant growth vigorous and even; plants resist drought stress; root growth vigorous; roots fibrous; roots explore soil profile	Seedlings emerge somewhat even and a little slow; plant growth not exceptional; plants don't resist drought well; root growth moderate	Seedlings emergence uneven and problematic; plant growth poor and uneven; drought stress is quick; roots grow poorly; roots not fibrous; roots follow seed trench or take abrupt 90-degree turns			

ANYTIME · AFTER RAIN · WITH ADEQUATE MOISTURE · DURING GROWING SEASON

Figure 3. An example of a university extension soil health evaluation card (Penn State University).

of sight, smell, feel, and background field information, an individual can assign a rating in various categories. These assessments are the most accessible from a time and expense perspective but are based upon subjective interpretation. This system works when the same person is comparing management areas or soil improvement, but the subjective nature of the evaluations means that results completed by different people cannot necessarily be accurately compared.

Field Decomposition Tests

Just as the Haney test and Solvita CO_2 respiration test rely on biological activity for a soil health score, decomposition rates can provide an assessment of soil microbial activity. An evaluation of decomposition that is currently popular involves a common household item —100% cotton underwear— which is buried in the soil with the elastic exposed and then retrieved later (typically after 2 months) to determine the degree of decomposition. This test can be used to compare zones with differing management practices and can be evaluated by visual differences or by measuring the weight before and after the two months of decomposition.

In 2010, a more standardized method was proposed using two types of Lipton® tea bags and precise protocol to evaluate soil decomposition. Tea bags offer the advantage of being standard, mass-produced packets of plant material, more directly analogous to the crop residue decomposing in a field. One type of tea used in this test has a low C:N ratio, causing it to decompose at a similar rate under different soil conditions, while the other type of tea has a high C:N ratio, leading to different rates of decomposition based upon the soil microbial activity. The difference in the amount of decomposition between the types of teas is the indication of soil health with a narrow gap being a "healthy soil" and a wide gap indicating an "unhealthy soil" in relative terms (Figure 4).

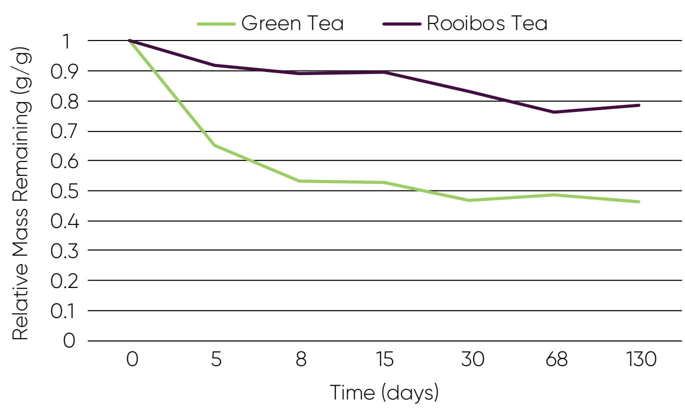


Figure 4. Decomposition of two types of tea used in a tea bag soil health test conducted at the Pioneer research farm in Johnston, IA, in 2018.

Challenges

Getting a Comprehensive Picture of Soil Health

A commonality among these soil health tests is the difficulty of taking multiple, representative samples and testing many different indicators in a timely and efficient manner. To gather information from all three health areas and discover potential yield-limiting factors, several indicators should be tested. Although a greater number of tests can provide a more complete picture of overall soil health, this must be balanced against the increase in cost that comes with testing more factors. A strong soil health assessment should include six to eight different laboratory and field tests to balance these challenges (Bünemann et al., 2018).

Inherent Soil Variation

Another challenge in developing a robust soil health evaluation is accounting for the variation in inherent characteristics of soils. For example, a healthy sandy soil may not produce as much as an unhealthy silt loam but that does not mean the silt loam should be rated higher on a scale system since the silt loam has greater room for improvement. It has been proposed that benchmarks for different climate and soil regions would help avoid rating soil health predominantly on properties that cannot be controlled or improved. These calibrated health ranges for soil types and climates would be beneficial for comparisons and recommendations but would lack indication of outputs, such as yield and water quality.

Cost and Complexity

The next challenge is creating a test that is easy and inexpensive enough that can be used on a large scale by growers. The cost of currently available tests has limited their implementation primarily to research and education. The cost of taking multiple samples to account for field variability quickly adds up with a cost of over $50 per sample for a standardized soil health test. The tests that are less cost prohibitive require more time commitment for providing ratings or labor of conducting the experiment independently. This scalability limitation could be overcome if a soil health test could be carried out with a fertility soil sample, but maintaining physical characteristics is difficult using a soil core.

Consistent, Comparable Results

Currently, soil health evaluations are often used to measure a site's improvement over time, or the evaluation is used to examine various sites with differing management practices in the same year. Creating a universal scoring system would allow different variables to be compared in different years, but the soil moisture, soil temperature, time of year, and timing of treatments would have to be considered for accurate comparisons.

Biological attributes have the potential to serve as a proxy indicator for the overall soil health, which is one reason this has been a specific area of focus in recent soil health work. A community of organisms is likely to be more diverse and numerous in an area with favorable conditions; therefore, a healthy soil would tend to contain a higher population of microorganisms than an unhealthy soil. However, populations and species are highly variable even in a small area, so the knowledge and the ability to correlate populations to outcomes is still under development. In addition, environmental conditions, such as moisture and temperature; highly influence the biological indicators, making comparisons between different environments difficult.

Soil Health Outcomes:

- Increase resilience to extreme weather
- Reduce erosion
- Enhance water quality
- Enhance productivity, yield stability, and profitability
- Increase nutrient availability
- Increase available water-holding capacity
- Increase water infiltration
- Soil rehabilitation
- Improve human health
- Reduce greenhouse gas

– Soil Health Institute

Implementation and Improvements

Even if these challenges are overcome with a new test or equation, the critical step is turning the diagnoses into a plan of action. Currently, soil health scores often have little correlation to crop productivity. The score may also not specifically identify the yield-limiting factor or factors, limiting its usefulness for management decisions. Most importantly, changes in soil management may not result in a significant change in a soil health score for several years. This can make it difficult to measure the impact of a specific method or application.

Management practices, including conservation tillage, cover crops, rotations, and input variations, do not work in the same way on every farm. Results vary across regions and soil types, so even with a soil health measurement, a challenge arises in writing a comprehensive prescription to help achieve the landowner's goals. Not every practice is quantitative or yield-correlated through a soil health test, but management changes in pursuit of these four overall goals will generally be steps in the right direction:

- Increase organic carbon
- Prevent erosion
- Balance fertility
- Promote plant growth vegetation

No matter the soil health rating or test result, the recommendation will revolve around applying the fundamental soil conservation practices to control what can be controlled – practices like monitoring and balancing fertility levels; preventing erosion through contour planting and maintaining residue; and reducing compaction through traffic management.

The value of a soil health assessment is in creating benchmarks or quantifying a change in land management. It would allow researchers to compare different sites at different time periods while minimizing the variables caused by other soil properties since they would be accounted for in the assessment score. A better understanding of soil health would benefit the producer in improved yields, the environment in improved water and air quality, and the consumer through human health.

The current effort to understand and quantify soil health faces numerous challenges that make it difficult to develop a simple, inexpensive, universally applicable measurement. However, it has initiated a valuable conversation around improving management practices and better understanding the biological elements below the soil surface.

Soil Your Undies – Evaluation of Soil Microbial Activity

*by **Samantha Reicks,** Agronomy Sciences Intern, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Soil health is a topic of many farm conversations.
- The microbial (biological) health of a soil is just one of several parameters (others include chemical and physical) being studied to describe soil health.
- The "Soil Your Undies" challenge has been developed to provide a simple visual demonstration of the soil microbial community's capacity for decomposing organic material.
    - It involves burying cotton underwear early in the growing season and digging them up later in the season to evaluate the degree of decomposition.
    - Men's cotton briefs are made up of mostly refined cotton, which is about 99% cellulose.
    - Cellulose is a long chain of glucose (sugar) molecules that soil microbes consume.

Objectives

- Determine the microbial health of three soil environments.
- See how dyes impact the behavior of soil microbe digestion.
- Provide an education tool for agronomists and farmers to visually see microbial soil activity.

Study Description

- Six men's briefs were buried about four inches deep into three cropping systems on the Pioneer farm in Johnston, Iowa.
    - Corn after corn (10 years)
    - Corn after soybeans (continuous rotation)
    - Long-term sod, mowed on a weekly basis
- One white brief and one dark blue brief were buried in each cropping system on May 30, 2017 (Figure 1).
- All six briefs were carefully dug up on August 22, 2017, and pinned to boards to be evaluated (Figures 2, 3, and 4).
- Weather for the summer of 2017 consisted of a relatively dry May, over 8 inches of rain in June, close to 6 inches of rain in early July, and then nearly no rain until the day of the dig (Figure 5).
- Temperatures were warm throughout the summer with temperature accumulation ahead of normal the entire growing season (Figure 6).

Figure 1. Cotton briefs buried on May 30, 2017.

Figure 2. Cotton briefs carefully removed from the soil on August 22, 2017.

Figure 3. Cotton briefs carefully pinned to display boards on August 22, 2017.

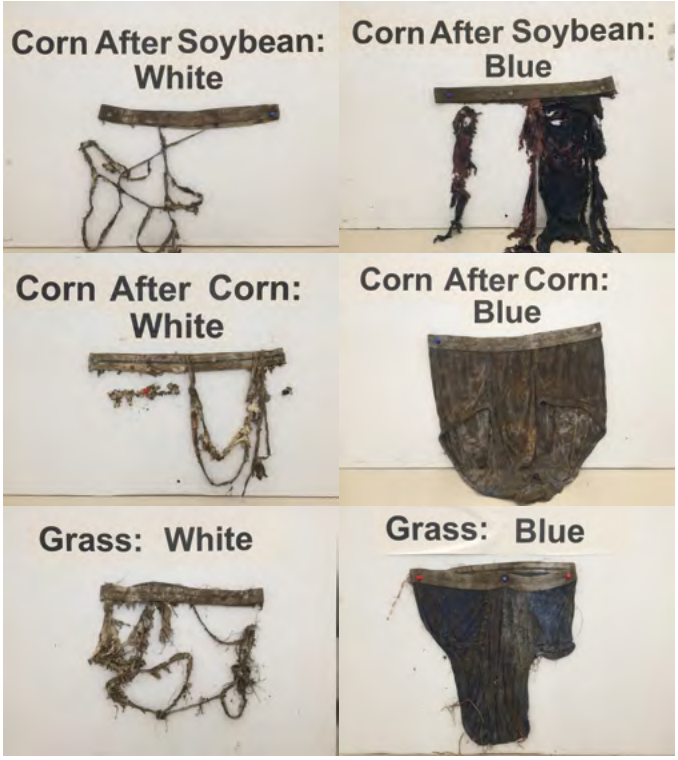


Figure 4. Cotton briefs carefully removed from the soil on August 22, 2017.

Results

- Blue dye significantly slowed the consumption rate of the cotton briefs by the microbial population as compared to the non-dyed briefs.
- Cotton briefs buried in the corn-soybean rotation underwent the most decomposition (clearly visible by observing the blue briefs), followed by the corn-on-corn system (comparing the white briefs), and the briefs buried in the grass sod had the slowest consumption rate.

Conclusions

- The ideal length of time to leave in the soil is around two months; these were in for nearly three months, hence the high level of decomposition and minimal differences in the white cotton results.
- Long-term sod that is mowed weekly is put under a lot of stress. As the plants are continuously "mowed" off, they are constantly in a regrowth state, pulling water and nutrients from the soil, and as a result, reducing microbial activity.
- Corn-soybean crop rotations offer diversity to soil in the way the root systems develop as well as the rate of residue decomposition and alters the soil microbial health in a positive way relative to continuous corn.

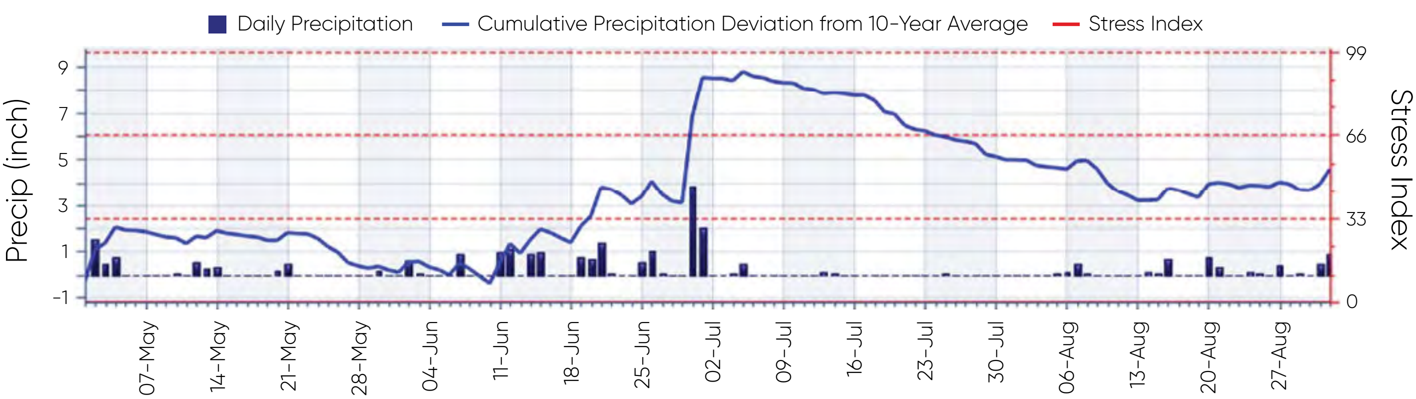


Figure 5. Precipitation for summer of 2017 in Polk County, Iowa.

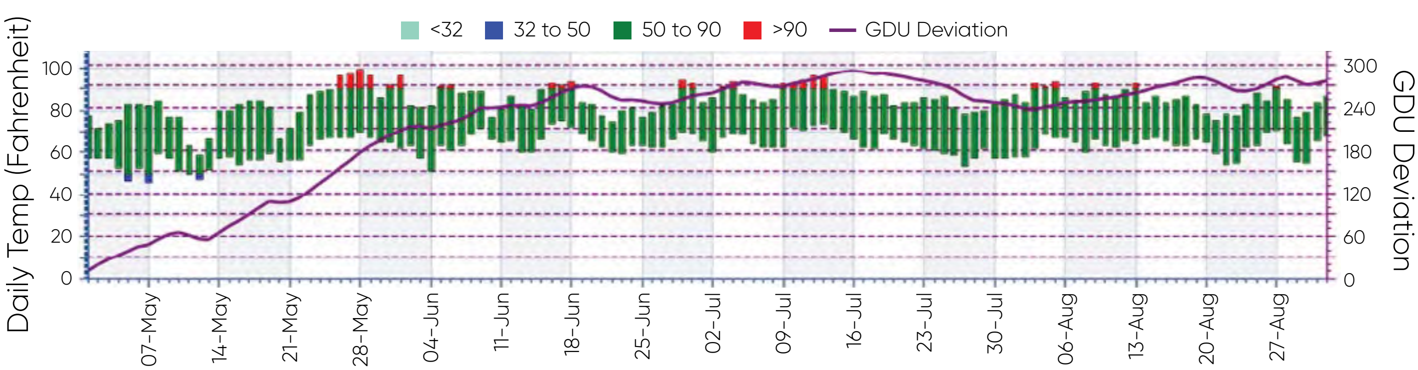


Figure 6. Temperatures and heat unit accumulation for summer of 2017 in Polk County, Iowa.

Managing Corn for Greater Yield

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Summary

- Improved hybrids and production practices are helping corn growers increase yields. Over the past 20 years, U.S. yields have increased by an average of 1.9 bu/acre/year.
- The NCGA National Corn Yield Contest provides a benchmark for yields that are attainable when conditions and management are optimized.
- The 2017 contest had 224 entries that exceeded 300 bu/acre, far more than in any previous year.
- Selecting the right hybrid can affect yield by over 30 bu/acre, making this decision among the most critical of all controllable factors.
- High-yielding contest plots are usually planted as early as practical for their geography. Early planting lengthens the growing season and more importantly, moves pollination earlier.
- Rotating crops is an important practice to help keep yields consistently high. Rotation can break damaging insect and disease cycles that reduce crop yields.
- Maintaining adequate nitrogen fertility levels throughout key corn development stages is critical in achieving highest yields. Split applications can help reduce losses by supplying nitrogen when plant uptake is high.

Introduction

Improvements in corn productivity that began with the introduction of hybrid corn nearly a century ago have continued through the present day. Over the last 20 years, U.S. corn yield has increased by an average of 1.9 bu/acre per year. These gains have resulted from breeding for increased yield potential, introducing transgenic traits to help protect yield, and agronomic management that has allowed yield potential to be more fully realized.

As growers strive for greater corn yields, the National Corn Growers Association (NCGA) National Corn Yield Contest provides a benchmark for yields that are attainable when environmental conditions and agronomic management are optimized. The average yields of NCGA winners are about double the average U.S. yields. This difference can be attributed to favorable environmental conditions, highly productive contest fields, and high-yield management practices used by contest winners.

2017 NCGA National Corn Yield Contest

The NCGA National Corn Yield Contest has achieved some notable milestones during the past few seasons, and 2017 was no exception. One of the most noteworthy aspects of the 2017 contest was that it had far more entries over 300 bu/acre than in any previous year – 224 compared to the previous high of 136 in 2014 (Table 1). Most of the surge in high-yield entries came from the Central Corn Belt. Illinois, Indiana, Iowa, Kentucky, and Nebraska all had at least 2 times the number of >300 bu/acre entries than in any previous year. Nebraska alone accounted for 41 of the 224 entries over 300 bu/acre. Average corn yields were high in each of these states in 2017 – all five recorded their highest or second-highest yield according to USDA – but none had a dramatic increase in average yield over previous seasons that would correspond with the dramatic increase in extremely high yields observed in the NCGA contest.

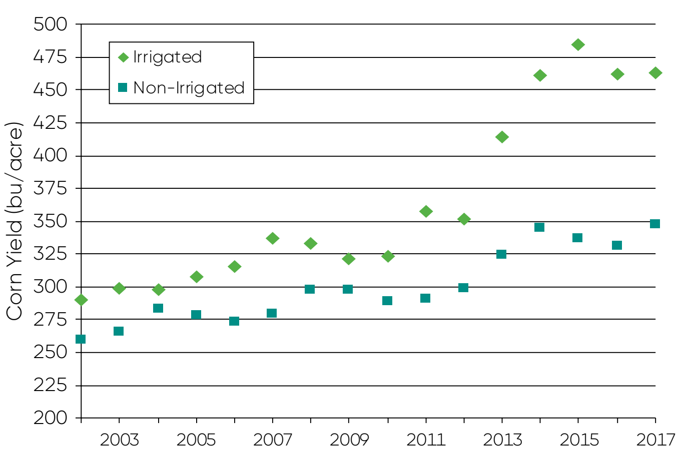


Figure 1. Average corn grain yield of NCGA National Corn Yield Contest national winners in irrigated and non-irrigated classes, 2002-2017.

A new corn yield world record of 542.27 bu/acre was set in 2017. This is the fourth time in the last five years that a new record has been set, following records of 454.98 bu/acre in 2013, 503.72 bu/acre in 2014, and 532.03 bu/acre in 2015. Both the 2015 and 2017 record yields were set with Pioneer® P1197AM™ brand corn.

A total of 31 entries exceeded 400 bu/acre over the past four years. 2017 marked the first time a yield over 400 bu/acre was achieved outside of the Southern U.S. with the top yield of 407.22 bu/acre in the irrigated class coming from an entry in Michigan planted with Pioneer® P0574AM™ brand corn.

Table 1. Number of NCGA National Corn Yield Contest entries over 300 bu/acre by state, 2013-2017

State	2013	2014	2015	2016	2017
	number of entries				
AL	0	2	2	1	3
AR	2	4	1	1	2
CA	3	1	0	2	0
CO	1	2	3	2	4
DE	0	6	3	2	0
FL	2	2	3	0	0
GA	5	6	7	4	7
IA	2	2	5	7	16
ID	0	3	1	1	0
IL	3	11	9	5	25
IN	7	4	3	1	26
KS	4	7	4	1	2
KY	1	4	1	0	17
MA	0	1	2	1	1
MD	1	9	5	4	4
MI	2	1	4	1	7
MN	0	0	0	0	1
MO	4	16	2	1	12
NC	0	1	0	1	0
NE	5	5	7	1	41
NJ	0	4	7	0	1
NM	1	1	0	2	2
NY	1	0	1	0	4
OH	6	0	0	0	1
OK	1	1	2	3	2
OR	0	1	1	1	3
PA	0	2	3	0	0
SC	0	8	3	5	9
SD	0	1	0	0	2
TN	1	12	0	3	9
TX	7	10	6	4	3
UT	1	2	6	3	7
VA	3	4	4	3	5
WA	0	0	2	2	2
WI	0	0	1	1	6
WV	7	3	0	2	0
Total	**70**	**136**	**101**	**66**	**224**

The average yields of national winners in the non-irrigated classes reached a record high of 347.6 bu/acre in 2017 (Figure 1). The average yield of national winners in the irrigated classes in 2017 was 463.1 bu/acre, which was second only to the record high of 484.4 bu/acre set in 2015.

The average yields among national winners tend to be skewed by a small number of very high yields, particularly in the irrigated classes. Therefore, as a yield performance benchmark, it can be more useful to look at a larger set of contest entries. Table 2 shows the median yield of the top 100 yielding entries in the irrigated and non-irrigated classes.

Table 2. Median yields of the top 100 irrigated and non-irrigated NCGA National Corn Yield Contest entries and the USDA average U.S. corn yields from 2013 to 2017.

Year	Non-Irrigated	Irrigated	U.S. Average
	bu/acre		
2013	293	299	158
2014	299	306	171
2015	292	288	168
2016	283	294	175
2017	312	317	177
Average	**296**	**301**	**170**

Median yields of top entries in both the irrigated and non-irrigated classes were around 300 bu/acre, which is about 75% greater than the current U.S. average. All three metrics hit record highs in 2017.

The top national yields in the NCGA contest tend to grab the headlines, but studying a larger group of high-performing entries can provide more insight on management practices that can be applied to improve yields in normal corn production. This article summarizes basic management practices employed in NCGA National Corn Yield Contest entries that exceeded 300 bu/acre over the past five years and discusses how these practices can contribute to higher yield potential for all corn growers.

Hybrid Selection

Hybrids tested against each other in a single environment (e.g., a university or seed company test plot) routinely vary in yield by at least 30 bu/acre. At contest yield levels, hybrid differences can be even higher. That is why selecting the right hybrid is likely the most important management decision of all those made by contest winners.

The yield potential of many hybrids now exceeds 300 bu/acre. Realizing this yield potential requires matching hybrid characteristics with field attributes, such as moisture supplying capacity; insect and disease spectrum as well as intensity; maturity zone; residue cover; and even seedbed temperature. To achieve highest possible yields, growers should select a hybrid with:

- Top-end yield potential. Examine yield data from multiple, diverse environments to identify hybrids with highest yield potential.
- Full maturity for the field. Using all of the available growing season is a good strategy for maximizing yield.
- Good emergence under stress. This helps ensure full stands and allows earlier planting, which moves pollination earlier to minimize stress during this critical period.
- Above-average drought tolerance. This will provide insurance against periods of drought that most non-irrigated fields experience.
- Resistance to local diseases. Leaf, stalk, and ear diseases disrupt normal plant function, divert plant energy, and reduce standability and yield.
- Traits that provide resistance to major insects, such as corn borer, corn rootworm, black cutworm, and western bean cutworm. Insect pests reduce yield by decreasing stands, disrupting plant functions, feeding on kernels, and increasing lodging as well as dropped ears.
- Good standability to minimize harvest losses.

The brands of seed corn used in the highest yielding contest entries in 2013 through 2017 are shown in Figure 2. Pioneer® brand products were used in the majority of entries exceeding 300 bu/acre and a plurality of entries over 350 bu/acre as well as 400 bu/acre.

Table 3. 2017 NCGA National Corn Yield Contest national winners using Pioneer® brand products.

Entrant Name Category	State	Hybrid/ Brand[1]	Yield (bu/acre)
Dan Gause A Non-Irrigated	SC	P2089YHR (YGCB, HX1, LL, RR2)	357.06
William Thomas A Non-Irrigated	SC	P1775YHR (YGCB, HX1, LL, RR2)	339.10
Jeannie Linneweber AA Non-Irrigated	IN	P1479AM™ (AM, LL, RR2)	347.50
John Gause A NT/ST Non-Irrigated	SC	P2160YHR (YGCB, HX1, LL, RR2)	353.58
Daniel Gause NT/ST Non-Irrigated	SC	P2160YHR (YGCB, HX1, LL, RR2)	336.24
Robert Little AA NT/ST Non-Irrigated	IN	P1366AM™ (AM, LL, RR2)	338.61
Faith Little AA NT/ST Non-Irrigated	IN	P1197AM™ (AM, LL, RR2)	322.72
David Hula NT/ST Irrigated	VA	P1197AM™ (AM, LL, RR2)	542.27
Don Stall Irrigated	MI	P0574AM™ (AM, LL, RR2)	407.22

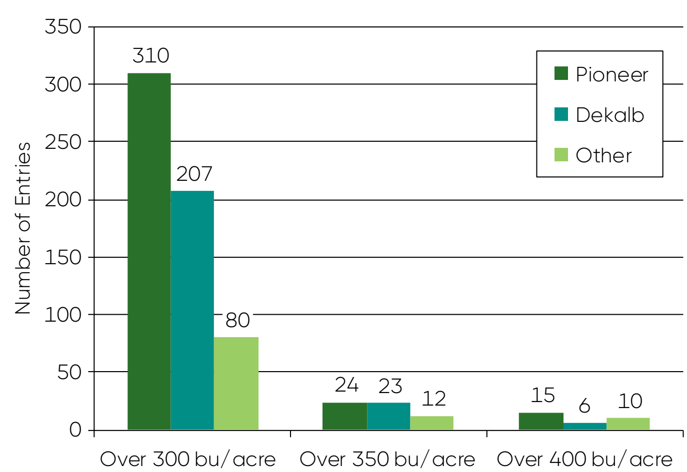


Figure 2. Seed brand planted in National Corn Yield Contest entries exceeding 300, 350, and 400 bu/acre, 2013-2017.

Planting Practices

Plant Population

One of the most critical factors in achieving high corn yields is establishing a sufficient population density to allow a hybrid to maximize its yield potential. Historically, population density has been the main driver of yield gain in corn; improvement of corn hybrid genetics for superior stress tolerance has allowed hybrids to be planted at higher plant populations and produce greater yields.

Harvest populations in irrigated and non-irrigated national corn yield contest entries over 300 bu/acre from 2013 through 2017 are shown in Figure 3. The average harvest population of irrigated entries (37,500 plants/acre) was slightly greater than that of non-irrigated entries (36,300 plants/acre) over five years. However, yields over 300 bu/acre were achieved over a wide range of populations from 25,000 to 55,000 plants/acre, demonstrating that exceptionally high populations are not necessarily a prerequisite for high yields. Although population density is important in establishing the yield potential of a corn crop, it is just one of many factors that determine final yield.

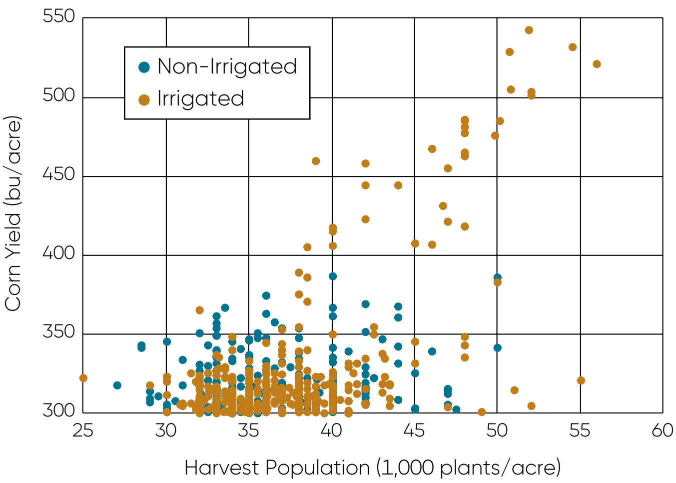


Figure 3. Harvest populations and corn yield of irrigated and non-irrigated NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

One of the most interesting aspects of the relationship between yield and plant population of high yield entries in the National Corn Yield Contest is the emergence of two distinct patterns when data from the last five years are combined. For entries between 300 and 400 bu/acre, there is no consistent relationship between harvest population and yield; populations cover a wide range with the majority between 32,000 and 42,000 plants/acre. For entries above 400 bu/acre, however, there emerges a roughly linear relationship between population and yield with each 5,000 plants/acre increase in population corresponding to a 30 bu/acre increase in yield (Figure 3).

When harvest population and yield per acre are used to calculate yield per plant, the resulting data show a decline in grain weight per plant as population increases, as would be expected (Figure 4). However, for exceptionally high yielding entries, the rate of this decline was not as steep. These results show that the key to success for top performing entries over the last few years has been to maintain greater yield per plant at high population densities. The fact that yields over 400 bu/acre have only been achieved under irrigation suggests that optimal water management is critical to maintaining high individual plant yield at high population density.

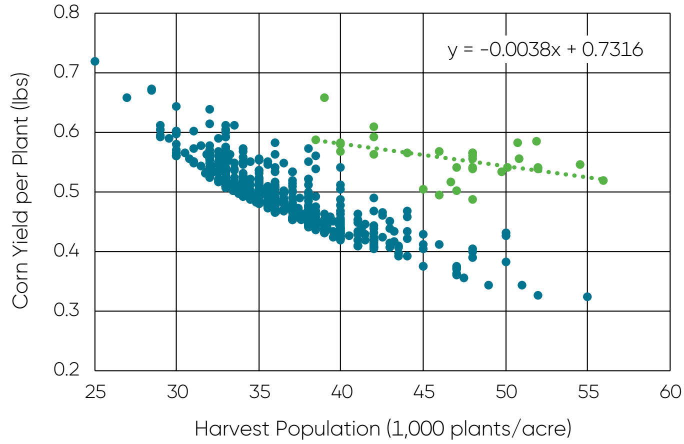


Figure 4. Harvest populations and yield per plant of NCGA National Corn Yield Contest entries yielding between 300 and 400 bu/acre and above 400 bu/acre, 2013-2017.

Harvest population and yield per plant data over a larger yield range (150 to 350 bu/acre), which encompasses most of the entries in the contest, show tremendous variation in the relative contribution of yield components to final yield (Figure 5). For example, entries yielding between 250 and 300 bu/acre ranged from harvest populations below 25,000 plants/acre with yield per plant over 0.60 lbs/plant to harvest populations over 45,000 plants/acre with plant yield less than 0.35 lbs/plant. However, average values for harvest population and yield per plant both increase for each successively higher yield range. These results suggest that greater plant density and greater yield per plant are both critical to driving higher yields.

Optimizing plant population is important for maximizing profitability, particularly when commodity prices are low. The Pioneer Planting Rate Estimator, available on www.pioneer.com and as a free mobile app, allows users to generate estimated economically optimum seeding rates for Pioneer® brand corn products based on data from Pioneer research and Pioneer® GrowingPoint® agronomy trials.

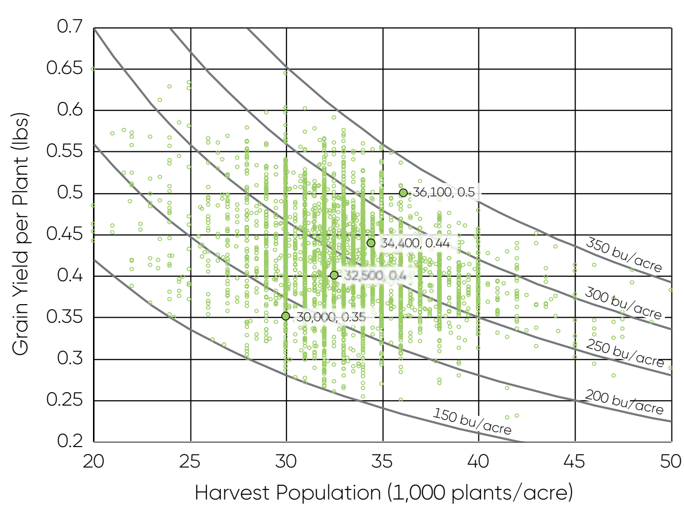


Figure 5. Harvest population and yield per plant for NCGA National Corn Yield Contest entries between 150 and 350 bu/acre, 2016-2017. Large dots indicate average values for harvest population and yield/plant for each yield range.

Row Width

The vast majority of corn acres in the U.S. are currently planted in 30-inch rows, accounting for over 85% of corn production. A majority of 300 bu/acre contest entries over the past five years have been planted in 30-inch rows (Figure 6). This proportion has increased in recent years, reaching a high of 90% in 2017 as wider row configurations (most commonly 36-inch or 38-inch) have declined in frequency and narrower row configurations (15-inch, 20-inch, 22-inch, or 30-inch twin) have largely remained steady with a slight decline in 2017.

Row spacings narrower than the current standard of 30 inches have been a source of continuing interest as a way to achieve greater yields, particularly with continually increasing seeding rates. However, research has generally not shown a consistent yield benefit to narrower rows outside of the Northern Corn Belt (Jeschke, 2013).

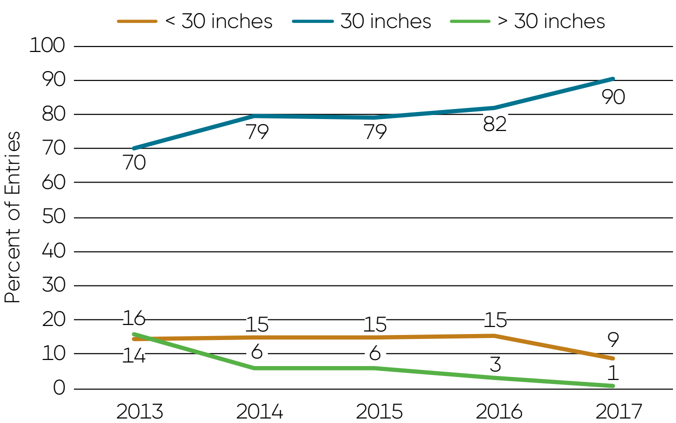


Figure 6. Row width used in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

Planting Date

High-yielding contest plots are usually planted as early as practical for their geography. Early planting lengthens the growing season and more importantly, moves pollination earlier. When silking, pollination, and early ear fill are accomplished in June or early July, heat and moisture stress effects can be reduced. Planting dates for entries exceeding 300 bu/acre ranged from March 10 to June 4, although mid-April to early-May planting dates were most common for locations in the Central Corn Belt (Figure 7).

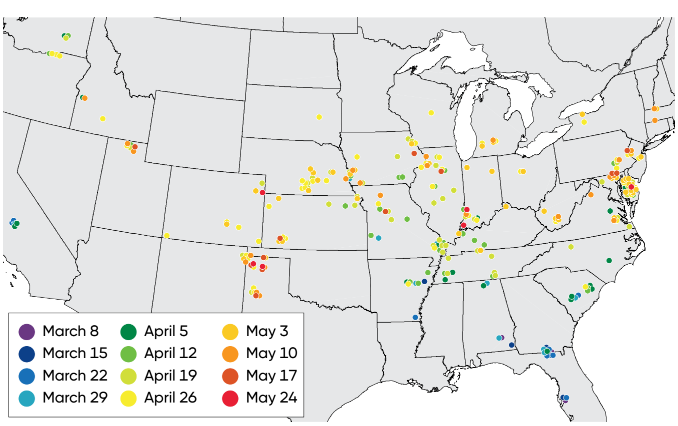


Figure 7. Planting date grouped by week of NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

Crop Rotation

Rotating crops is one of the practices most often recommended to keep yields consistently high. Rotation can break damaging insect and disease cycles that lower crop yields. Including crops like soybean or alfalfa in the rotation can reduce the amount of nitrogen required in the following corn crop. A majority of the fields in the 300 bu/acre entries (67%) were planted to a crop other than corn the previous growing season (Figure 8).

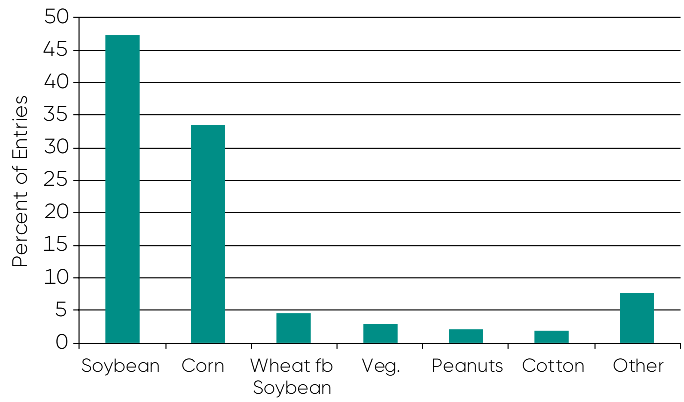


Figure 8. Previous crop in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

The so-called "rotation effect" is a yield increase associated with crop rotation compared to continuous corn even when all limiting factors appear to have been controlled or adequately supplied in the continuous corn. This yield increase has averaged about 5 to 15 percent in research studies but has generally been less under high-yield conditions (Butzen, 2012). Rotated corn is generally better able to tolerate yield-limiting stresses than continuous corn; however, yield contest results clearly show that high yields can be achieved in continuous-corn production.

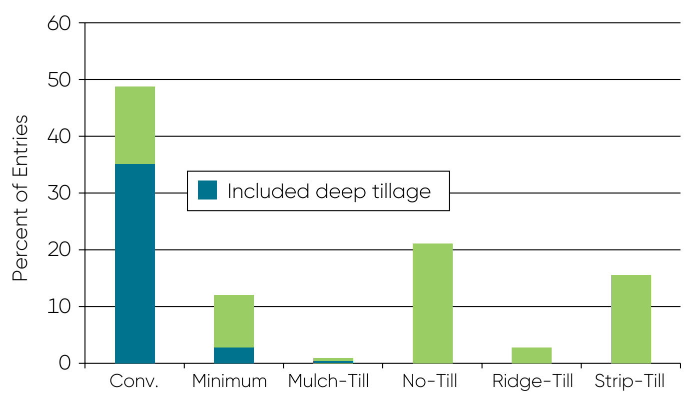


Figure 9. Tillage practices in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

Tillage

Three of the six classes in the NCGA National Corn Yield Contest specify no-till or strip-till practices; however, more than 60% of the contest entries over 300 bu/acre employed conventional, minimum, or mulch tillage (Figure 9). Of the 48% of entries employing conventional tillage, most included some form of deep tillage. Deep tillage implements included rippers, chisel plows, and sub-soilers. When fields are adequately dry, deep tillage can alleviate deep compaction and break up claypans as well as hardpans that restrict corn root growth. Deep roots are especially important as soil moisture is depleted during mid to late summer.

Soil Fertility

Achieving highest corn yields requires an excellent soil fertility program, beginning with timely application of nitrogen (N) and soil testing to determine existing levels of phosphorous (P), potassium (K), and soil pH.

Nitrogen

Corn grain removes approximately 0.67 lbs of N per bushel harvested, and stover production requires about 0.45 lbs of N for each bushel of grain produced (IPNI, 2014). This means that the total N needed for a 300 bu/acre corn crop is around 336 lbs/acre. Only a portion of this amount needs to be supplied by N fertilizer; N is also supplied by the soil through mineralization of soil organic matter. On highly productive soils, N mineralization will often supply the majority of N needed by the crop. Credits can be taken for previous legume crop, manure application, and N in irrigation water. Nitrogen application rates of entries exceeding 300 bu/acre are shown in Figure 10.

The N application rates of 300 bu/acre entries varied greatly, but a majority were in the range of 250 to 350 lbs/acre. Some entries with lower N rates were supplemented with N from manure application. As corn yield increases, more N is removed from the soil; however, N application rates do not necessarily need to increase to support high yields. Climatic conditions that favor high yield will also tend to increase the amount of N a corn crop obtains from the soil through increased mineralization of organic N and improved root growth.

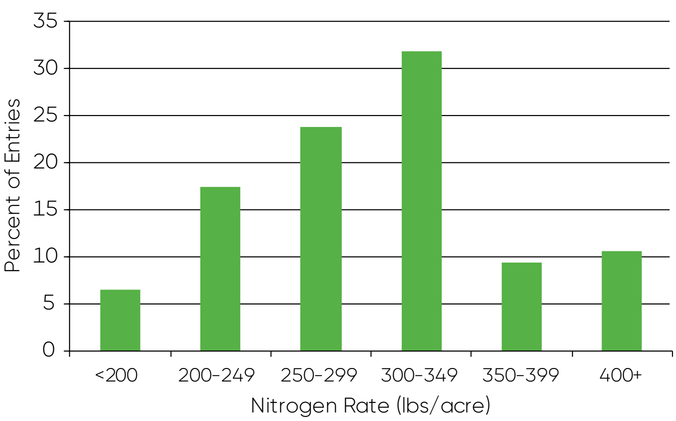


Figure 10. Nitrogen rates (total lbs/acre N applied) of NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017. (Note that N rates above 300 lb/acre are usually appropriate only for contest plots and high-yielding irrigated fields.)

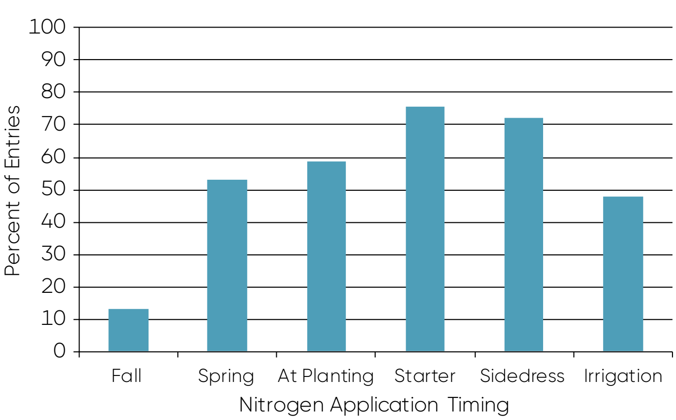


Figure 11. Nitrogen fertilizer application timing of NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

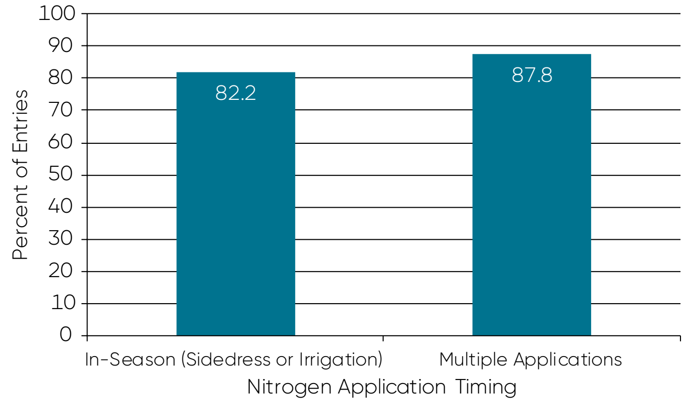


Figure 12. Nitrogen management programs of NCGA National Corn Yield Contest entries exceeding 300 bu/acre that included in-season application(s) and multiple application timings, 2013-2017.

Timing of N fertilizer applications can be just as important as application rate. The less time there is between N application and crop uptake, the less likely N loss from the soil will occur and limit crop yield. Nitrogen uptake by the corn plant peaks during the rapid growth phase of vegetative development between V12 and VT (tasseling). However, the N requirement is high beginning at V6 and extending to the R5 (early dent) stage of grain development.

Timing of N fertilizer applications in 300 bu/acre entries is shown in Figure 11. Very few included fall-applied N. Many applied N before or at planting. Over 80% of 300 bu/acre entries included some form of in-season nitrogen application, either sidedressed or applied with irrigation (Figure 12). Nearly 90% included multiple applications.

Phosphorus and Potassium

Assuming soils are maintained at adequate levels, growers should add at least the level of P and K that will be removed by the crop. In addition, these nutrients should be available in the root zone of the developing seedling. Corn grain removes about 0.35 lbs of P_2O_5 and 0.25 lbs of K_20 equivalents per bushel, according to the International Plant Nutrition Institute (IPNI, 2014). That means that a 300 bu/acre corn crop will remove about 105 lbs of P_2O_5 and 75 lbs of K_20 per acre. Recent evidence suggests that P and K fertilizer rates in some areas may not be keeping pace with increasing crop yields that are accompanied by higher nutrient removal. Pioneer agronomists and Encirca certified services agents collected soil samples from 8,925 fields in 12 Corn Belt states between fall 2015 and spring 2016 (Jeschke et al., 2017). Results of this survey showed that P and K levels below state optimum levels were common across the Corn Belt (Figure 13 and 14).

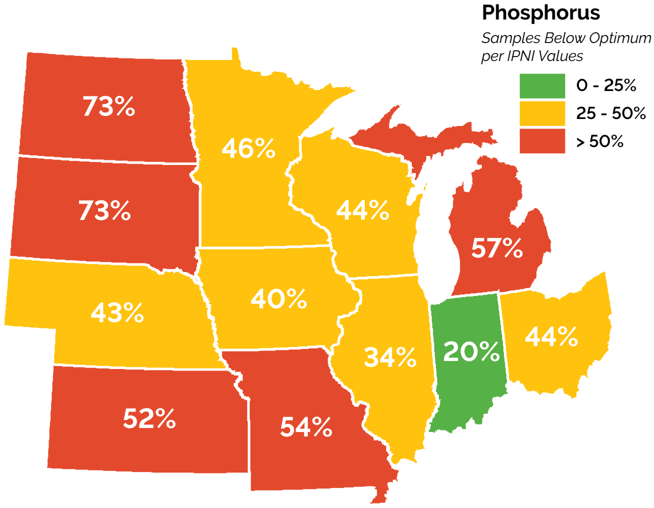


Figure 13. Percent of soil samples that fell below state optimum levels for phosphorus in the Corn Belt in 2016.

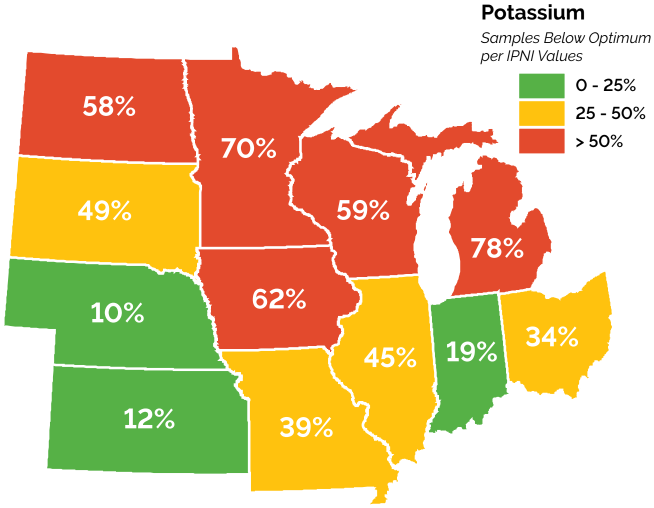


Figure 14. Percent of soil samples that fell below state optimum levels for potassium in the Corn Belt in 2016.

Micronutrients

Micronutrients were applied on approximately half of the 300 bu/acre entries (Figure 15). The nutrients most commonly applied were sulfur (S) and zinc (Zn) with some entries including boron (B), magnesium (Mg), manganese (Mn), or copper (Cu). Micronutrients are sufficient in most soils to meet crop needs.

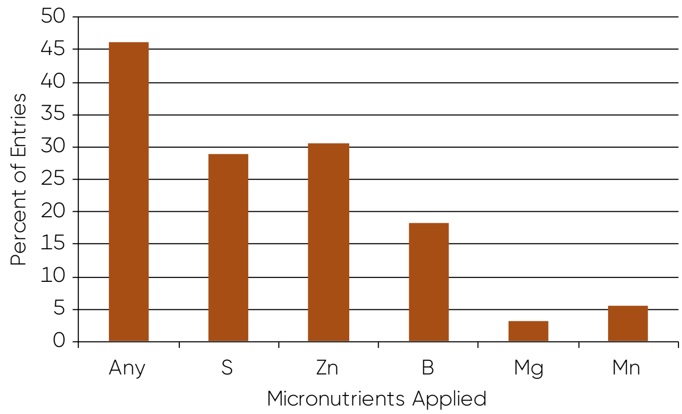


Figure 15. Micronutrients applied in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2013-2017.

However, some sandy soils and other low organic matter soils are naturally deficient in micronutrients, and high pH soils may make some micronutrients less available and therefore, deficient (Butzen, 2010). Additionally, as yields increase, micronutrient removal increases as well, potentially causing deficiencies.

Corn Hybrid Response to Plant Population: A Review for North America

by **Ignacio Ciampitti, Ph.D.,** Kansas State University

Objectives

- A meta-database (124,374 observations) of yield and plant population data points was constructed from Pioneer plant population studies conducted from 2000 through 2014 in 22 U.S. states and 2 Canadian provinces.
- This database was synthesized and analyzed as a part of the Pioneer Crop Management Research Awards (CMRA) Program with Dr. Ignacio Ciampitti at Kansas State University.
- The main objectives of this review study were to investigate corn hybrid response to plant population across North America and identify typical response models under different yield environments, ranging from less than 100 bu/acre up to nearly 300 bu/acre.

Study Description

- Pioneer corn plant population research trials were conducted from 2000 through 2014 across corn-producing areas of North America (22 U.S. States and 3 Canadian provinces) (Figure 1).
- The trials were conducted in a randomized complete block design with a split-plot arrangement with two to three replications at each site.
- Plant population tested across all sites ranged from less than 20,000 to more than 40,000 plants/acre.
- Between 30 and 50 current commercial hybrids were tested each year.
- Not all hybrids were included at each location, and not all locations were included every year.

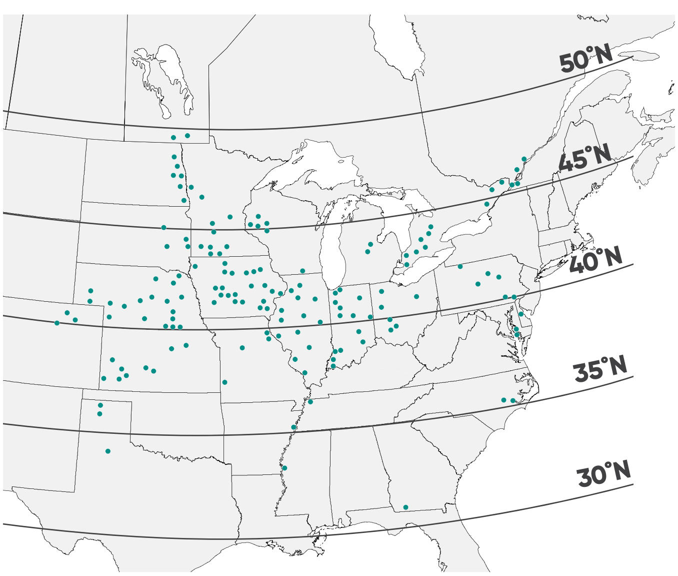


Figure 1. Locations of plant population studies conducted by Pioneer, 2000-2014. Not all locations were included every year.

Figure 2. A Pioneer plant population research experiment in 2012. A low population plot is visible in the foreground.

Results

- In general, corn hybrid response to plant population followed a quadratic response model in which yield increased with greater plant population up to an optimum point, beyond which yield declined.
- A strong interaction between hybrid and environment (soil and weather) was observed.
- Maximum attainable yield was impacted by latitude:
  - Overall maximum yield was approximately 200 bu/acre for 30 to 35° N latitude compared to 150 bu/acre for 45 to 50° N latitude.
  - Nonetheless, corn hybrid response to plant population was very similar with optimal plant population ranging from 34,000 to 38,000 plants/acre.
- Corn yield was generally lower and optimum population was greater with hybrids of shorter comparative relative maturity (CRM).
  - Long (106 to 115 CRM) and very long (>115 CRM) maturity hybrids generally reached their maximum yield within a very narrow plant population range of 34,000 to 35,000 plants/acre.
  - On the opposite CRM range, very early to medium (<78 CRM to 105 CRM) maturity hybrids typically achieved maximum yield at plant populations ranging from 36,000 to 39,000 plants/acre.
- Averaged over all hybrids, yield response to plant population depended on the yield environment (Figure 3).

Results (Continued)

- For **low-yielding environments** (below 100 bu/acre), a maximum yield of 93 bu/acre was attained at a plant population level of 24,000 plants/acre.
  - » As plant population increased in yield environments below 100 bu/acre, yield response was flat to slightly negative.
  - » For the lowest yield environments, productivity was limited primarily by water supply.
- For **medium-yield environments** (100 to 150 bu/acre), a maximum yield of about 135 bu/acre was attained at a plant population level of 24,000 plants/acre.
  - » Further increases in plant population produced a flat to slightly declining yield response (Figure 3).
- For **high-yield environments** (150 to 200 bu/acre), yield increased sharply for plant density increases from 18,000 to 30,000 plants/acre, followed by a relatively lower yield gain as plant population surpassed 30,000 plants/acre.
  - » Maximum yield (~170 bu/acre) was achieved at a plant population of 40,000 plants/acre; however, yield response was relatively flat at plant populations above 30,000 plants/acre (Figure 3).
- For **very high-yield environments** (above 200 bu/acre), yield response to plant population continued to increase even at 40,000 plants/acre (Figure 3).
- It is important to note that plant population for highest possible yield does not necessarily coincide with the "economic" optimum plant population.

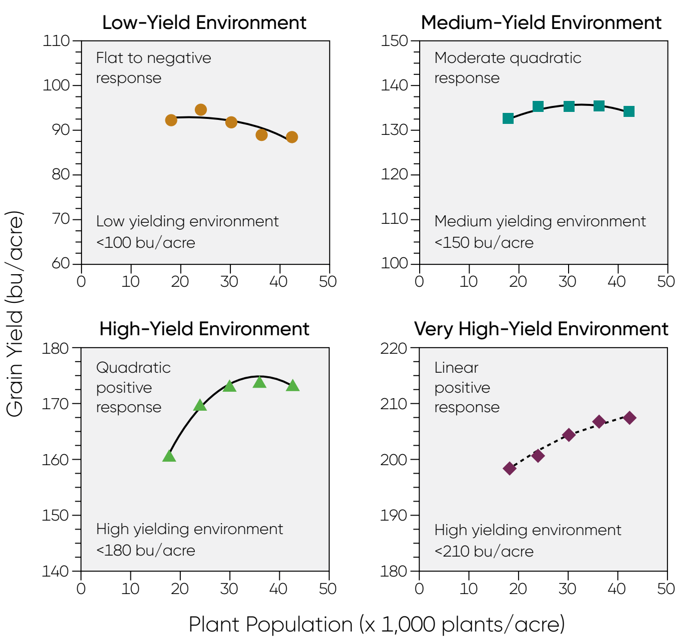


Figure 3. Corn hybrid response to plant population under 4 yield environments: a) low yielding <100 bu/acre; b) medium yielding 100-150 bu/acre; c) high yielding 150-180 bu/acre; and d) very high yielding 190-210 bu/acre. (Assefa et al., 2016).

  - » Corn hybrid agronomic factors, such as lodging and seed costs, should also be taken into account when deciding the seeding rate for corn.
  - » In addition, as previously mentioned, optimum seeding rate can vary based on hybrid maturity and production practices, such as planting date, row spacing, seedbed condition, and residue cover.
- When selecting a hybrid, keep in mind not only the response to seeding rate but also the degree of tolerance to drought and/or other stresses, and also consider traits like specific herbicide tolerance; disease and insect resistance; maturity; lodging; and overall hybrid performance.
- Consult your Pioneer sales representative to determine if seeding rates for specific hybrids should be at the lower or upper end of the recommended ranges for a given environment.
- Producers should consider experience and performance in previous growing seasons to determine if the seeding rate previously employed in their different fields was adequate for their respective yield environments.

Conclusions

- The optimal seeding rate and final plant population depends on the environment, hybrid, and cultural practices. Producers can look back at previous corn-growing seasons to evaluate if the seeding rate utilized was adequate for their yield environments.
- Optimal plant density to maximize yield is not the same as the economically optimal density. The Pioneer Planting Rate Estimator, available on www.pioneer.com and as a free mobile app, allows users to generate estimated economically optimum seeding rates for Pioneer® brand corn products based on data from Pioneer research and Pioneer® GrowingPoint® agronomy trials.

In Summary:

- » Maximum attainable yield was impacted by latitude, but corn hybrid response to plant population was very similar across latitudes with optimal plant population ranging from 34,000 to 38,000 plants/acre.
- » Long- and very long-maturity hybrids reached their maximum yield within a very narrow plant population range of 34,000 to 35,000 plants/acre. On the opposite end of the CRM range, very early- to medium-maturing hybrids typically reached maximum yield at plant populations between 36,000 to 39,000 plants/acre.
- » Optimal plant population varies with yield environment. Low yielding environments (<100 bu/acre) required about 20,000 plants/acre when yield limitations were caused by water supply. High yielding (>200 bu/acre) environments generally needed at least 30,000 plants/acre, but yield gain was still observed for very high yielding environments even at 40,000 plants/acre.

Corn Historical Yield Trends from 1987 Through 2015 for North America

*by **Ignacio Ciampitti, Ph.D.,** Kansas State University*

Objectives

- A meta-database (181,395 observations) of yield and plant population data points was constructed from Pioneer plant population studies conducted from 1987 through 2015 in 23 U.S. states and 3 Canadian provinces.
- This database was synthesized and analyzed as a part of the Pioneer Crop Management Research Awards (CMRA) Program with Dr. Ignacio Ciampitti at Kansas State University.
- The main objectives of this review study were to investigate corn hybrid response to plant population across North America and examine yield trends across different yield environments for the 1987 to 2015 period.

Study Description

- Pioneer corn plant population research trials were conducted from 1987 through 2015 across corn-producing areas of North America (23 U.S. States and 3 Canadian provinces) (Figure 1).
- The trials were conducted in a randomized complete-block design with a split-plot arrangement with two to five replications at each site.
- Plant population tested across all sites ranged from 15,000 to close to 50,000 plants/acre. About 30 to 50 important commercially-available Pioneer® brand hybrids were tested each year.
- Not all hybrids were included at each location, and not all locations were included every year.

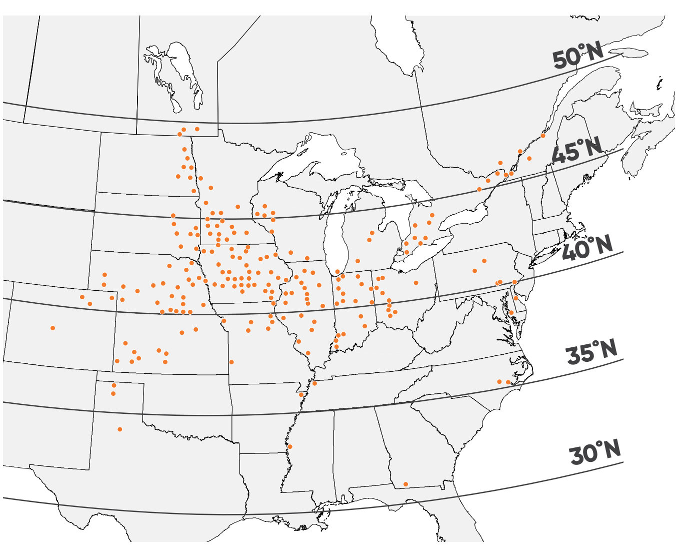


Figure 1. Locations of plant population studies conducted by Pioneer, 1987-2015. Not all locations were included every year.

Results

- Average corn yield over the duration of the study was 162 bu/acre, increasing from 135 bu/acre in 1987 to 188 bu/acre in 2015, representing an overall yield gain of 53 bu/acre.
- Maximum attained yields also increased over the 1987 to 2015 period with yields increasing from 240 bu/acre to 320 bu/acre, representing a yield gain of 60 bu/acre.

Latitude

- Latitude groups were evaluated and considered as a main factor for studying corn yield trends over time.
- Average corn yield was lower at higher latitudes ranges: 30 to 35° = 184 bu/acre; 35 to 40° = 172 bu/acre; 40 to 45° = 162 bu/acre; and 45 to 50° N = 142 bu/acre.
- Corn yield increased across all three latitude groups included in the analysis over the 1987 to 2015 period (Figure 2).
  - » Corn yield gain for the 35 to 40° latitude group was 1.7 bu/acre per year.
  - » Corn yield gain for the 40 to 45° latitude group was 1.5 bu/acre per year.
  - » Corn yield gain for the 45 to 50° latitude group was 1.86 bu/acre per year.
- Yield gain observed at all latitudes was a result of yield improvement across all the respective comparative relative maturity (CRM) groups.

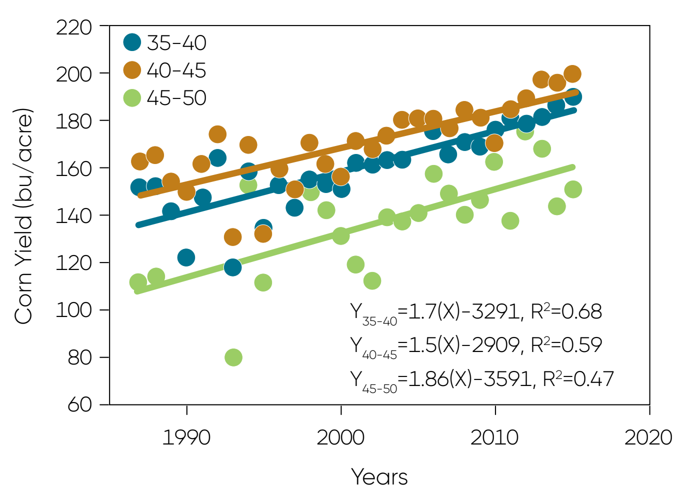


Figure 2. Corn yield trends for the 35 to 40°, 40 to 45°, and 45 to 50° N latitude ranges for the study years, 1987-2015 (Assefa et al., 2017).

Results (Continued)

Yield Environment

- The meta-database was divided into four yield environments to evaluate the average yield trend for each environment over the study period: low-yielding, LY (<110 bu/acre); medium-yielding, MY (110–160 bu/acre); high-yielding, HY (160–210 bu/acre); and very high-yielding, VHY (>210 bu/acre).
- Corn yield trends for each yield environment for the 1987 to 2015 period (Figure 3):
    - » 0.9 bu/acre per year in VHY environments
    - » 0.3 bu/acre per year in HY environments
    - » 0.15 bu/acre per year in MY environments
    - » no significant historical yield change in LY environments
- Overall, VHY and HY environments presented a greater yield improvement over time relative to the MY and LY environments (Figure 3).
- In addition to corn yield gain within yield environments, the proportion of sites falling within each yield environment category, expressed as a frequency relative to the total, was investigated for three segments of the study period: 1987-1996, 1997-2006, and 2007-2015 (Figure 4).
    - » The proportions of LY and MY environments decreased from the earliest decade (1987–1996) compared to the most recent historical period (2007–2015).
    - » The proportion of HY and VHY environments increased from the earliest to the most recent decade.
    - » In addition, the proportion of the LY and MY environments shrunk from ~50% to 25% for the 35 to 40° and 40 to 45° N latitude groups and from ~75% to 40% for 45 to 50° N latitude group.

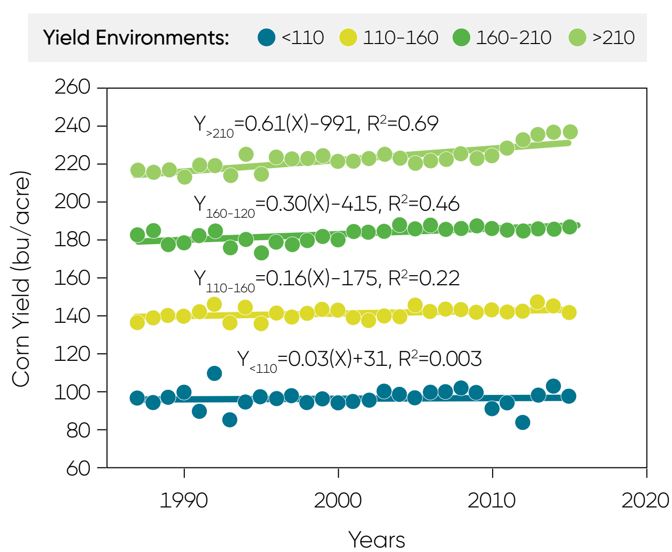


Figure 3. Corn yield trend under 4 yield environments, low yielding (<110 bu/acre), medium yielding (110-160 bu/acre), high yielding (160-210 bu/acre), and very high yielding (>210 bu/acre), 1987-2015 (Assefa et al., 2017).

- » Lastly, changes over time in yield gain and the frequency of yield environments are one of the major reasons for the consistent yield gain trends recorded for the North America during the last three decades.
- Over the entire study area, using data from the dominant CRM hybrids for each latitude and optimal plant population for each yield environment, an overall annual yield gain of 2.2 bu/acre per year was documented.

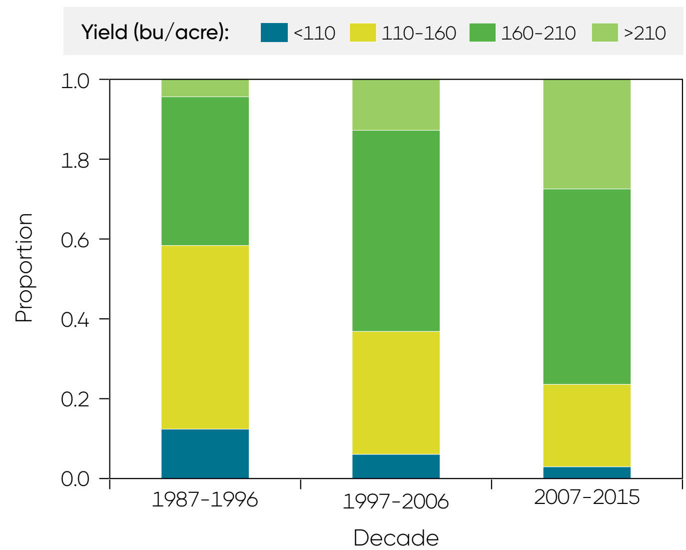


Figure 4. Proportion of corn yield environments by decade (1987-1996; 1997-2006; 2007-2015): low yielding (<110 bu/acre), medium yielding (110-160 bu/acre), high yielding (160-210 bu/acre), and very high yielding (>210 bu/acre) (Assefa et al., 2017).

Conclusions

- This historical corn yield study documented yield changes from 135 bu/acre in 1987 to 188 bu/acre in 2015 – an overall yield gain of 53 bu/acre.
- Similarly, maximum attained yield also increased over the 1987 to 2015 period from 240 bu/acre to 320 bu/acre, representing a yield gain of 60 bu/acre.

In Summary:

- Corn yield increased across all latitudes. Yield gain was similar among latitude ranges from 1.5 to 1.8 bu/acre per year.
- Yield increase per latitude was similar across all the corn CRM hybrid groups.
- Corn yield gain over the study period was greater in higher-yielding environments.
- The proportion of low- and medium-yielding environments decreased over time, while high- and very high-yielding environments increased.
- The proportion of low- and medium-yielding environments decreased more for the northern latitudes, 45 to 50° N, compared to 35 to 40° and 40 to 45° N latitude groups.
- Overall average annual yield gain for the study area from 1987 to 2015 was 2.2 bu/acre per year.

Trends in Optimum Plant Density and Yield Gains for Corn in North America

by ***Ignacio Ciampitti, Ph.D.,*** *Kansas State University*

Objectives

- Pioneer scientists have collected data on corn plant population responses and yield gains to provide better information on hybrid performance. From 1987 to 2016, nearly 200,000 yield and plant population data points were collected from more than 40 locations throughout North America (23 U.S. states and 3 Canadian provinces).
- This database was synthesized and analyzed as a part of the Pioneer Crop Management Research Awards (CMRA) Program with Dr. Ignacio Ciampitti, Associate Professor in Crop Production and Cropping Systems at Kansas State University.
- The main objectives of this long-term study were to examine the trend in the agronomic optimum plant density (AOPD) and its relationship to corn yield as well as to quantify the contribution of plant density to yield gain during the 1987 to 2016 time period.

Study Description

- Pioneer corn plant population research trials were conducted from 1987 through 2016 across corn-producing areas of North America (23 U.S. States and 3 Canadian provinces) (Figure 1).
- The trials were conducted in a randomized complete block design with a split-plot arrangement with two to five replications at each site.
- Plant population tested across all sites ranged from 15,000 to 50,000 plants/acre. 30 to 50 commercially available Pioneer® brand hybrids were included per year.
- Not all hybrids were included at each location, and not all locations were included every year.

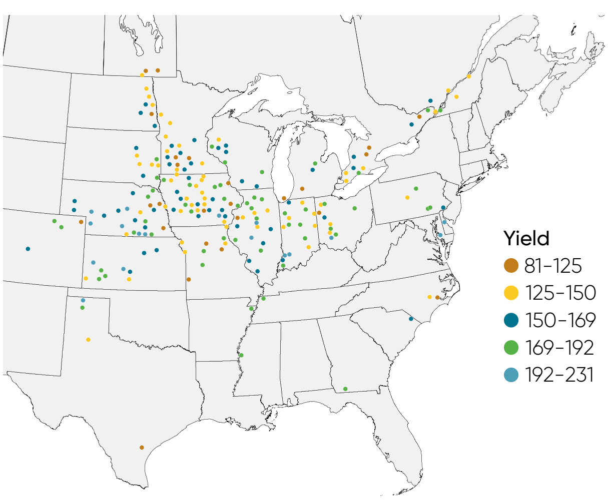


Figure 1. Locations and yield levels (bu/acre) of plant population studies conducted by Pioneer, 1987-2016.

Figure 2. A Pioneer plant population research experiment.

Results

- Across all environments and hybrids, average agronomic optimum plant density increased from 30,500 plants/acre from 1987 to 1991 to 37,900 plants/acre from 2012 to 2016 - a rate of increase of 285 plants/acre/year (Figure 3).

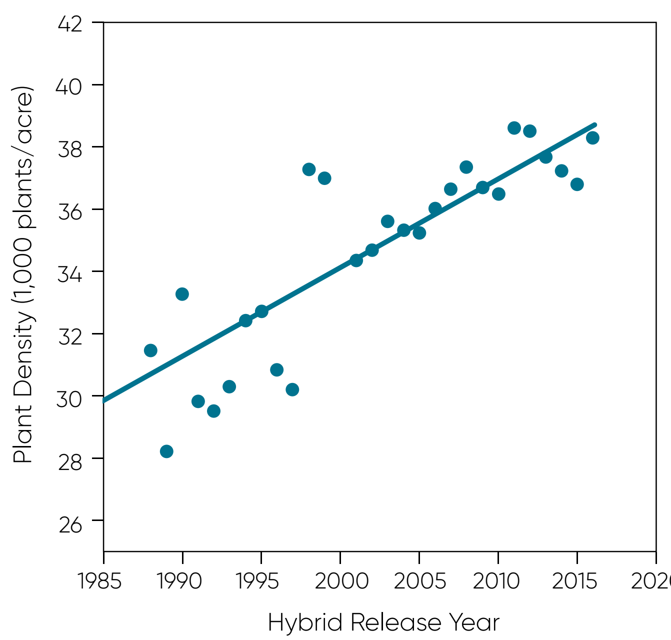


Figure 3. Historical changes in average agronomic optimum plant density over hybrid release year for corn for the entire North America, 1987-2016 (Assefa et al., 2018).

Results (Continued)

- The increase in agronomic optimum plant density varied across latitudes from 35 to 50° N latitude but without showing a consistent trend.
- Agronomic optimum plant density increased to a greater degree over time in higher-yielding environments (Table 1).

Table 1. Increases in agronomic optimum plant density by yield level, 1987-2016.

Yield Category	Yield Range bu/acre	Increase in Agronomic Optimum Plant Density plants/acre/year
Very High	>195	249
High	150-195	564
Medium	105-150	162
Low	<105	NS*

* No significant increase in optimum plant density.

- Maximum yield at the agronomic optimum plant density increased from 140 bu/acre from 1987 to 1991 to over 190 bu/acre from 2012 to 2016 - a rate of increase of 2.23 bu/acre/year (Figure 4).

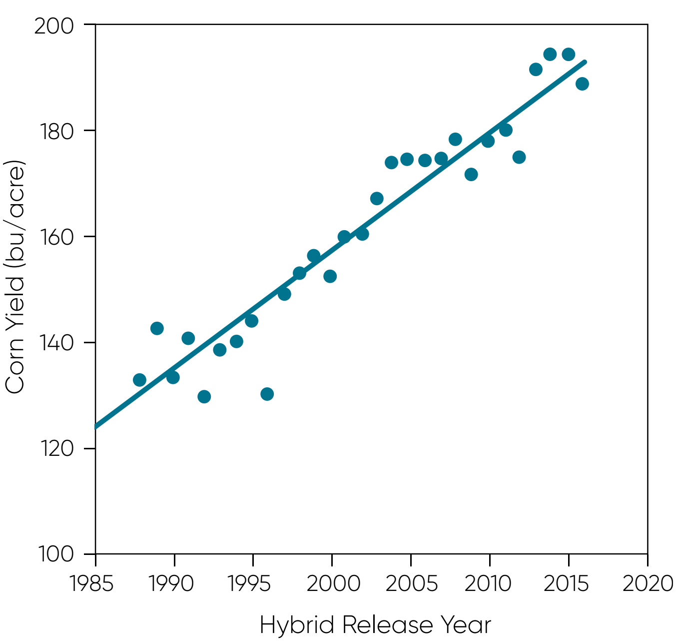


Figure 4. Maximum corn grain yield at the agronomic optimum plant density by hybrid release year, 1987-2016. (Assefa et al., 2018).

- The range of the agronomic optimum plant density increased over time from the 1987 to 1991 period to the 2012 to 2016 period. This new finding shows that modern hybrids not only need more plants in order to attain higher yields but also that the stability of modern hybrids has increased relative to older hybrids (Figure 5).
- Evaluating the six 5-year periods from 1987 to 2016, the increase in yield at the agronomic optimum plant density over time exceeded that which can be attributable solely to the increased plant density, indicating that yield per plant became less sensitive to the increases in plant density.
- Further studies should be focused on improving the understanding of the changes overtime in yield components at varying crowding stress levels.
- Overall, plant density contributed to 9 to 18% of the corn yield gain during the last 30 years of crop improvement.
- To the extent of our knowledge, this is the first time that corn yield gain is reported at a regional-scale (multi-year and -location). Overall, average corn yield gain at the agronomic optimum plant density was primarily driven by an increase in the frequency of high-yielding environments (150 to 195 bu/acre) with exception of the low-yielding sites.

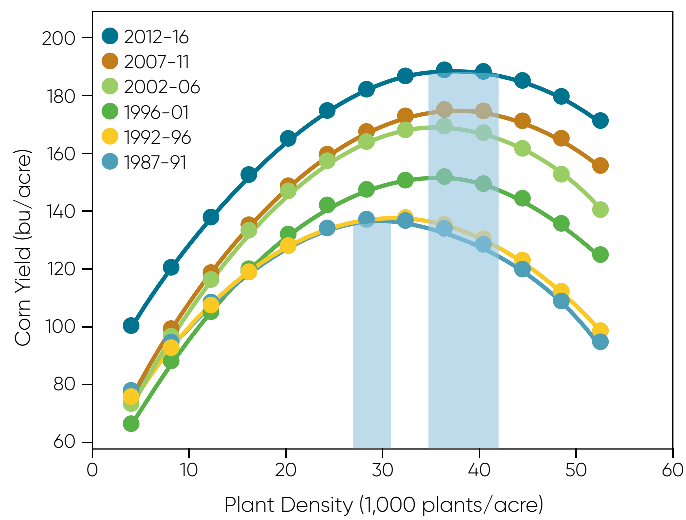


Figure 5. Agronomic optimum plant density (averaged over all Pioneer® brand hybrids) over the six 5-year time periods from 1987 to 2016. Shaded bars show the increase in agronomic optimum plant density range from the earliest time period in the study to the most recent.

Conclusions

- Agronomic optimum plant density increased during the last 30 years by nearly 7,500 plants/acre and corn yields at agronomic optimum plant density increased by more than 50 bu/acre.
- Modern hybrids not only have a higher agronomic optimum plant density but the range around the optimum level has widened over time, indicating a greater degree of stability for modern relative to older corn hybrids.
- Corn yield gain was achieved not only via improvement in tolerance to plant density, but there is sufficient evidence that confirms changes in per-plant yield, reflected in a more favorable kernel number/weight ratio.

Corn Response to Planting Date and Hybrid Maturity in the Upper Midwest

*by **Jeff Coulter, Ph.D.,** University of Minnesota*

Background and Objectives

- Timely planting is critical for high corn yield. However, delayed planting is common when rainfall occurs near the intended planting time. This is especially problematic in the Upper Midwest due to the relatively short growing season and abundance of fine-textured soils.
- When corn planting is delayed, it is essential to know whether the hybrids intended for planting are of appropriate comparative relative maturity (CRM) for economically viable grain production or whether they should be replaced with earlier-maturity hybrids to ensure corn reaches physiological maturity within the remaining growing season and has adequate time for drying prior to harvest.
- Advances in corn breeding and genetics have resulted in widespread release of hybrids with more rapid late-season dry down of grain, creating a need to reassess corn response to planting date. The objective of this study was to conduct an analysis of recent corn planting date trials conducted by researchers at the University of Minnesota.

Study Description

- Grain yield and grain moisture content at harvest were obtained from corn planting date trials conducted over 26 site-years:

  Sites: Crookston, Lamberton, Morris, and Waseca, MN

  Years: 2009 to 2016

  Planting dates: April 8 to June 16

  Hybrid CRMs: 74 to 109

  Grain yield: 87 to 251 bushels/acre

  Grain moisture at harvest: 11 to 35%

- Each trial had at least three hybrids of differing CRM planted on at least three dates in four replications. Hybrids were categorized as early-, mid-, or late-maturity based on the CRM and trial location (Table 1).

Table 1. Comparative relative maturity (CRM) of early-, mid-, and late-maturity hybrids included in planting date studies, 2009-2016.

	Hybrid Maturity (CRM) Range		
Locations	Early	Mid	Late
Crookston	74	80	86
Morris	85-93	94-96	98-109
Lamberton	85-94	96-100	102-109
Waseca	85-94	96-100	102-109
Combined	**74-94**	**80-100**	**86-109**

- Relative grain yield was calculated as a percentage compared to the planting date and hybrid with maximum grain yield in the same site-year.
- Partial economic net return was calculated as gross return (grain yield × $3.50/bu) minus drying cost ($0.045/bu for each point of grain moisture above 15%).
- Data were analyzed by hybrid maturity group across all 26 site-years.

Results

- The site-years and the hybrids included in this study represent a wide range of possible growing environments and hybrids for the Upper Midwest.
- Relative grain yield produced regression equations with better fit compared to grain yield, and it allows results to be easily applied to growing environments with differing yield potential.
- Relative grain yield was greatest when planting occurred between April 16 and May 16 for mid- and late-maturity hybrids, and between April 28 and May 23 for early-maturity hybrids (Figure 1).
- For all hybrid maturity groups, relative grain yield declined rapidly when planting was delayed beyond May 25 (Figure 1). Late-maturity hybrids produced greater relative grain yield than mid-maturity hybrids when planting occurred prior to June 4.
- Early-maturity hybrids produced less relative grain yield than mid-maturity hybrids at all planting dates (Figure 1). Relative grain yield with early-maturity hybrids was also most negatively impacted by early planting (before April 23).

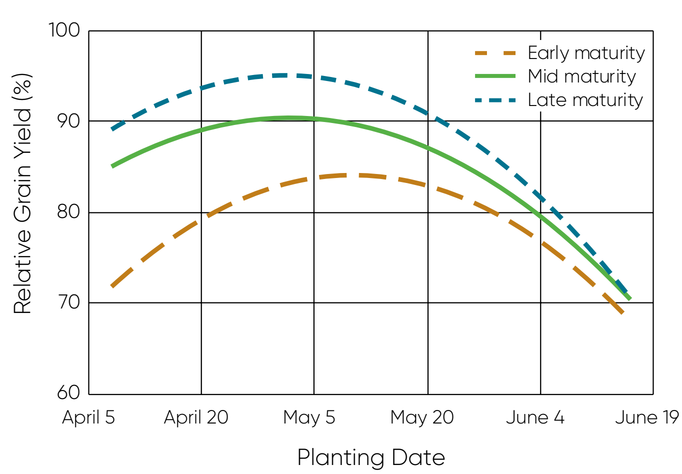


Figure 1. Relationship between relative corn grain yield and planting date by hybrid maturity group across 26 site-years, 2009-2016.

- Grain moisture at harvest was greatest for late-maturity hybrids and least for early-maturity hybrids (Figure 2). Grain moisture at harvest was least when planting occurred on May 20 or earlier, and it increased by 3 to 6 percentage points when planting was delayed until June 13.
- When planting was delayed beyond May 20, grain moisture at harvest increased more rapidly for late- and mid-maturity hybrids compared to early-maturity hybrids (Figure 2).

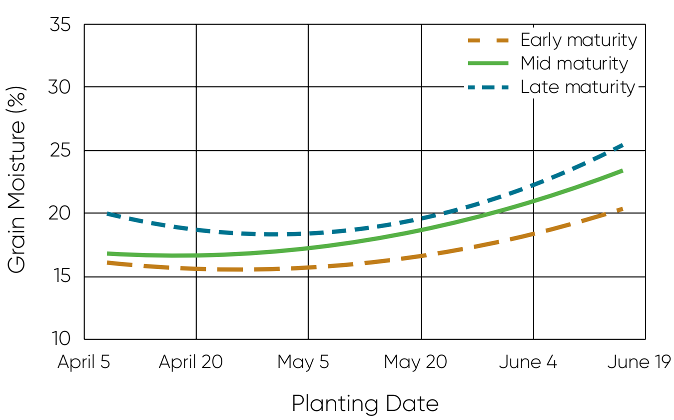


Figure 2. Relationship between corn grain moisture at harvest and planting date by hybrid maturity group across 26 site-years, 2009-2016.

- Greatest partial net return occurred with late-maturity hybrids planted on May 10 or earlier and with mid-maturity hybrids planted on April 21 or earlier (Figure 3). From April 24 to May 29, late-maturity hybrids produced greater partial net return than mid-maturity hybrids.
- Early-maturity hybrids produced the least partial net return when planting occurred prior to May 17 (Figure 3). From May 17 to June 2, partial net return did not differ significantly between early- and mid-maturity hybrids.
- When planting was delayed beyond June 9, early-maturity hybrids produced greater partial net return than late- and mid-maturity hybrids (Figure 3).

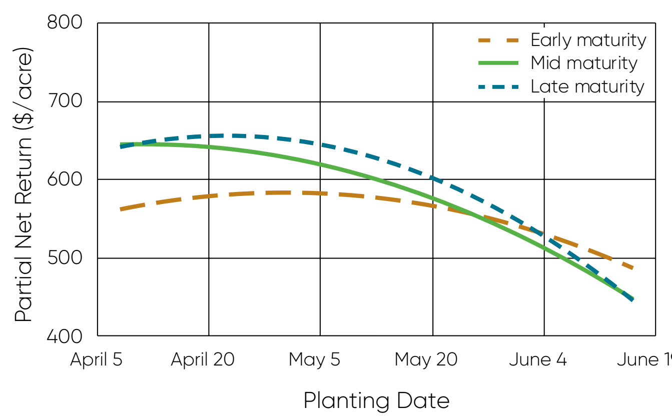


Figure 3. Relationship between partial net return to corn grain production and planting date by hybrid maturity group across 26 site-years, 2009-2016.

Conclusions

- This study confirms the importance of timely planting and appropriate hybrid CRM selection for corn grain production.
- Greatest economic net return after drying occurred with late-maturity hybrids planted on May 10 or earlier and with mid-maturity hybrids planted on April 21 or earlier. Late-maturity hybrids produced greater net return than mid-maturity hybrids when planting occurred between April 24 and May 29.
- When planting was delayed beyond June 9, early-maturity hybrids produced greater net return than late- and mid-maturity hybrids. However, corn planted in June in the Upper Midwest is at high risk of freezing in the fall before reaching physiological maturity and having high grain moisture at harvest.

Row Width in Corn Grain Production

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

- The vast majority of corn acres in the U.S. and Canada are currently planted in 30-inch rows with row spacings less than 30-inches used on less than 7% of corn acres.
- The primary rationale for narrow row spacings in corn is that by reducing the crowding of plants within a row, the crop will be able to better utilize available light, water, and nutrients by decreasing competition among individual plants.
- Yield benefits with narrow row corn have been observed most frequently in the northern portion of the Corn Belt.
- Research has shown a correlation in narrow row corn between improved yields and increased light interception; however, light interception is typically not yield-limiting in 30-inch rows outside of the northern Corn Belt.
- University and Pioneer research has shown that optimum plant population is generally not greater in narrow or twin rows than in 30-inch rows.
- Many university row spacing studies have included multiple hybrids but generally have found no difference in their response to narrow rows.

Introduction

Optimum row width has long been a topic of interest among corn producers. Ever since the replacement of horse-drawn machinery allowed corn rows to be less than 40 inches apart, growers and researchers have looked to narrower row spacings to increase corn yield. Narrower row configurations increase the distance between plants in a row, potentially increasing yields by allowing more efficient use of available space and resources. Narrow row corn is generally (and for the purposes of this review) defined as any row spacing less than 30 inches. Yield benefits of narrow row corn have not been large or consistent enough thus far to motivate a large shift away from 30-inch rows in most areas of North America. However, interest persists, largely due to the belief that continuing increases in corn yield and changing agronomic practices may eventually favor narrow rows.

Corn production in 30-inch rows.

Current Practices

The vast majority of corn acres in the U.S. and Canada are currently planted in 30-inch rows (Figure 1). This percentage has increased over recent years from 80% in 2007 to 86% in 2015, while the percent of corn acres in wider row spacings (36- and 38-inch) has declined (data not shown). Adoption of narrow row corn has been very limited with row spacings less than 30 inches currently used on less than 7% of corn acres in the U.S. and Canada. The most common narrow row spacing is 20-inch, which was used on 3.0% of corn acres in 2015, followed by 22-inch (2.6%) and 15-inch (0.7%).

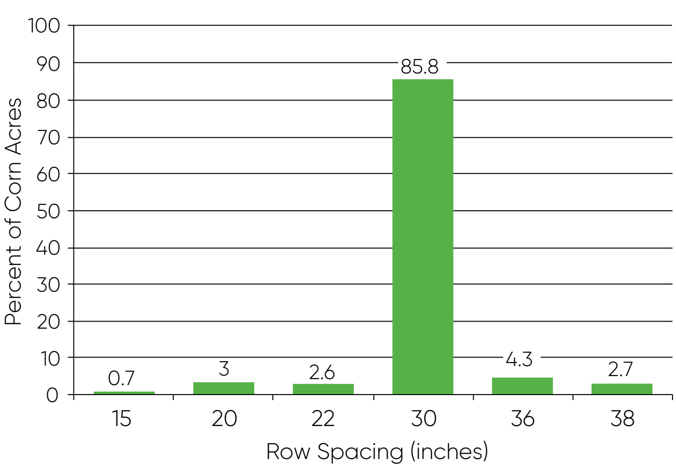


Figure 1. Corn row spacings (in inches) in North America as a percentage of total acres, 2015 (source: Pioneer survey).

Table 1. Corn acreage planted to the most common narrow row spacings from 2010-2015 in North America (source: Pioneer survey).

Row Width	2010	2011	2012	2013	2014	2015
inches			*acres (%)*			
15	0.4	0.4	0.6	0.8	0.5	0.7
20	2.7	2.5	2.5	3.3	3.3	3.0
22	1.2	1.4	1.5	1.6	2.3	2.6
All Narrow	**4.2**	**4.3**	**4.6**	**5.7**	**6.1**	**6.3**

Corn acreage planted in narrow rows has increased slightly over the past several years, comprising a combined 4.2% of corn acres in 2010 and 6.3% in 2015 (Table 1). Regional adoption of narrow rows varies widely with the highest adoption rate in the northern Corn Belt states of Minnesota and South Dakota (Figure 2). Narrow row implementation remains less than 5% in most of the central Corn Belt states.

Recent Row Spacing Research

University Research

Over the years, research on narrow row corn has produced variable results, which suggests that multiple factors likely influence corn yield response to row spacing. 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 (line running roughly through Mason City, IA; Madison, WI; and Grand Rapids, MI) (Lee, 2006). In a survey of several recent university corn row studies comparing 15-, 20-, or 22-inch rows to 30-inch rows, the greatest yield benefits with narrow rows were observed in experiments conducted in Minnesota and Michigan (Table 2). 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%) for narrow rows in Iowa, Indiana, and Nebraska (Figure 3).

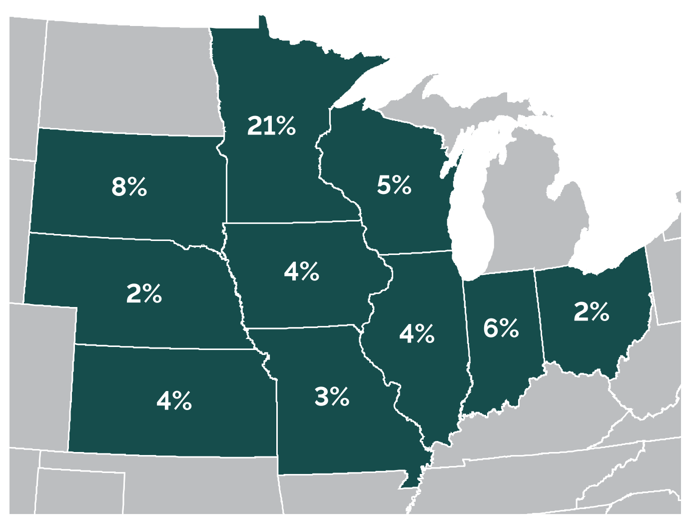


Figure 2. Narrow row corn adoption (15-, 20-, and 22-inch) in the U.S. Corn Belt (source: USDA-NASS farmer-reported row widths, 2013-2017).

Table 2. Yield advantage (%) of 15-inch; 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.

Study	Location	Years	Sites	Hybrids	Yield Level bu/acre	Populations 1,000 plants/acre	Yield Increase vs. 30-inch 15 (%)	Yield Increase vs. 30-inch 20 or 22 (%)	Yield Increase vs. 30-inch Twin (%)
1	Minnesota	92-94	3	6	100-150	25, 30, 35, 40		7.7	
2	Minnesota	97-99	1	1	100-150	33		6.2	
3	Minnesota	98-99	1	2	150-175	30	5.9	2.8	
4	Minnesota	09-11	6	3	175-200	16.5, 22, 27.5, 33, 38.5, 44		4.5*	
5	Michigan	98-99	6	6	175-200	23, 26, 30, 33, 36	3.8	2.0	
6	Nebraska	09-11	1	3	200-225	28, 33, 38, 42			1.4
7	Iowa	00-02	1	3	150-175	20, 28, 36, 44	1.2		
8	N. Dakota	06-08	1	2	>225	25, 30, 35	0.0		2.0
9	Michigan	98-99	1	1	150-175	24, 30, 34	0.5	0.8	
10	Wisconsin	98-01	1	1	175-200	34.5**	0.0		
11	Iowa	97-99	1	3	150-175	20, 28, 36	0.0		
12	Iowa	95-96	1	3	150-175	20, 28, 36	-0.6		
13	Minnesota	09-10	2	3	150-175	16.5, 22, 27.5, 33, 38.5, 44		-1.0	
14	Indiana	09-11	1	3	>225	28, 33, 38, 42			-1.0
15	Iowa	97-99	6	6	150-175	24, 28, 32, 36	-1.9		

1: Porter et al., 1997; 2: Johnson and Hoverstad, 2002; 3: Sharratt and McWilliams, 2005; 4: Coulter and Shanahan, 2012; 5: Widdecombe and Thelen, 2002; 6: Novacek et al., 2013; 7: Pecinovsky et al., 2002; 8: Albus et al., 2008; 9: Tharp and Kells, 2001; 10: Pedersen and Lauer, 2003; 11,12: Pecinovsky et al., 2002; 13: Van Roekel and Coulter, 2012; 14: Robles et al., 2012; 15: Farnham, 2001.

*Average yield increase at 38,500 and 44,000 plants/acre. A significant row spacing by population interaction was observed. **Approximate final stand, which differed from target populations.

Even among northern locations, however, yield benefits to narrow rows were inconsistent. For example, Van Roekel and Coulter (2012) found no yield advantage to narrow rows in research conducted during 2009 and 2010 at two southern Minnesota locations. Research at these same two locations in the early 1990s found an average 7.3% yield advantage for 20-inch rows over 30-inch rows (Porter et al., 1997).

Pioneer Research

Similar results were observed in Pioneer research. Results from 76 research studies conducted between 1991 and 2010 showed an average yield advantage of 2.7% with narrow or twin rows in the northern Corn Belt states of Minnesota, North Dakota, South Dakota, Wisconsin, and Michigan, compared to a 1.0% advantage across studies in Illinois, Iowa, Indiana, Missouri, Nebraska, Ohio, and the southern tip of Ontario (Figure 3).

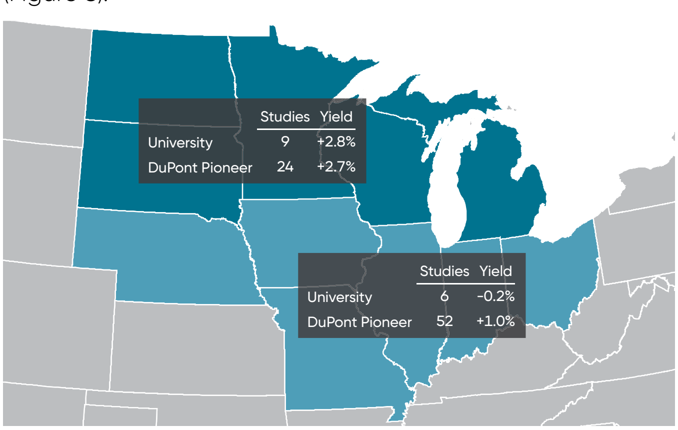


Figure 3. Average corn yield response to narrow rows in northern and central Corn Belt states observed in 20 years of university and Pioneer studies.

Pioneer also conducted numerous on-farm research studies from 2010 to 2012 comparing yield in twin and 30-inch rows. Most of the studies were conducted in Illinois, Iowa, and Minnesota, although side-by-side comparisons were also done in Colorado, Indiana, Kansas, Missouri, and Ohio. A total of 192 paired comparisons across 44 locations showed no overall yield advantage to twin rows over 30-inch rows (Figure 4).

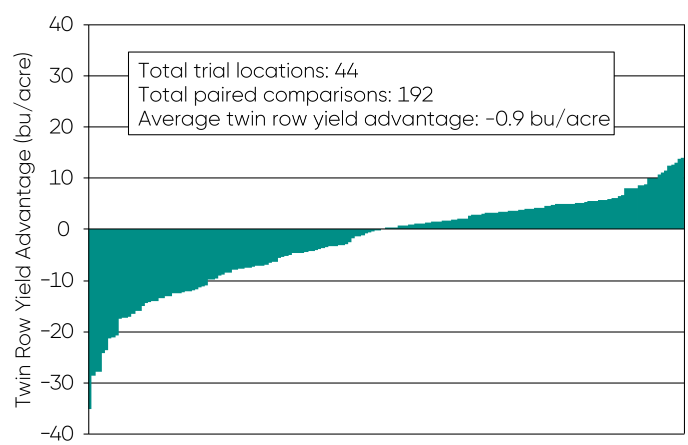


Figure 4. Yield advantage of twin rows compared to 30-inch rows in Pioneer on-farm research studies.

Rationale of Narrow Row Corn

The primary rationale for narrow row spacings in corn is that by reducing the crowding of plants within a row, the crop will be able to better utilize available light, water, and nutrients by decreasing competition among individual plants. However, the variability of corn yield response to narrow rows observed in research studies poses the question of why corn yield increases in narrow rows in some cases but not in others and particularly why narrow rows seem to provide a more consistent benefit in the northern Corn Belt. Identifying environmental and agronomic factors that tend to favor narrower rows can help determine the best fit for this practice in current and future corn production systems.

Light Interception

Research has shown a strong relationship between improved yields in narrow row corn and increased light interception (Andrade et al., 2002). In the absence of major water or nutrient limitations, corn yield is largely driven by the amount of solar radiation intercepted by the crop during the critical period for yield determination immediately before and after silking. In order to maximize yield, the crop canopy needs to capture 95% or more of photosynthetically active radiation (PAR) during this period. Corn at a constant 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).

Despite the ability of narrow rows to increase interception of solar radiation, research has shown that corn in 30-inch rows can routinely capture over 95% of PAR in Midwestern production. Studies conducted in Illinois (Nafziger, 2006), Nebraska (Novacek et al., 2013), Indiana (Robles et al., 2012), Minnesota (Sharratt and McWilliams, 2005), and Michigan (Tharp and Kells, 2001) found that narrow and twin rows tended to increase light interception during vegetative growth stages, but this advantage diminished as the plants approached flowering. By the time the plants reached silking, there was little or no difference in light interception between 30-inch and narrow rows (Table 3).

Table 3. Light interception at V10 and R2 as well as yield of corn grown at 34,500 plants/acre in twin row, 30-inch and 15-inch rows in a University of Illinois study (Nafziger, 2006).

Row Type	Light Interception (%) V10	Light Interception (%) R2	Yield (bu/acre)
Twin	79.5	98.9	187.4
30-inch	70.3	98.8	209.6
15-inch	83.3	98.5	199.3
LSD 0.10	6.2	0.8	8.5

Increased light interception is generally thought to be the reason that yield increases with narrow rows tend to be more frequent in the northern Corn Belt (Thelen, 2006). A research study conducted in Michigan in which narrow rows significantly increased yields found that differences in light interception between 30-inch and narrow rows were similar to those observed in other studies. Narrow rows intercepted more light during vegetative growth, but by flowering, there was no difference. However, the researcher hypothesized that the timing of the disparity in light interception may be the basis for the yield increase in narrow rows. The increased light interception in narrow rows coincided with the period of maximum day length for northern latitudes whereas light interception of corn further south in the Corn Belt would tend to be less affected by row spacing during this period due to its more advanced growth stage.

This is illustrated in Figure 5, which shows projected growth timelines relative to day length for an 89 CRM hybrid planted May 5 at Moorhead, MN, compared to a 113 CRM hybrid planted April 15 at Champaign, IL. Day length reaches its maximum at the summer solstice on June 21. At this point, the Moorhead crop is at a growth stage where narrow rows will increase light interception, whereas the Champaign crop is closer to silking and the light interception advantage with narrow rows has likely begun to diminish.

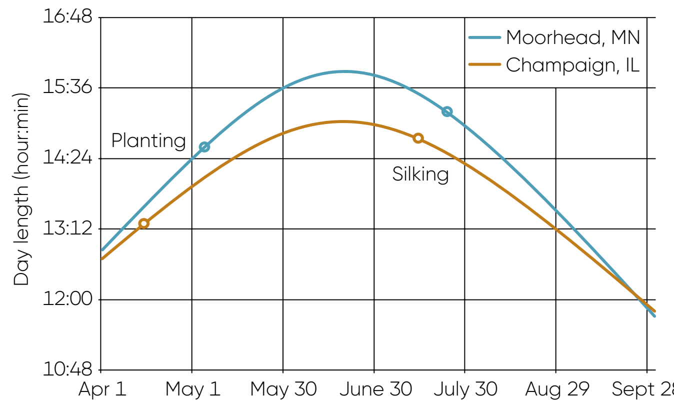


Figure 5. Projected silking date relative to day length for corn at Moorhead, MN, and Champaign, IL.

Water and Nutrient Recovery

In addition to improving capture of solar radiation, narrow rows can also improve uptake of resources from the soil. The more equidistant plant spacing in narrow rows creates a more uniform distribution of roots within the soil profile, which reduces competition among individual plants within a row for water and nutrients (Sharratt and McWilliams, 2005).

Research has shown that narrow rows can 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. Narrow rows have the added benefit of improving light interception when canopy development is limited by nitrogen deficiency. However, both of these advantages are 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).

Pioneer nitrogen rate study showing nitrogen deficient corn in the foreground. Narrow rows may increase yield under nitrogen deficiency by improving uptake from the soil and increasing light interception.

The potential of narrow rows to increase yields by improving water uptake is less clear. Barbieri et al. (2012) found that narrow rows increased water uptake during the early stages of crop growth, likely due to deeper and more uniform distribution of roots in the soil profile, but this advantage diminished as the season progressed. Total seasonal crop evapotranspiration ultimately did not differ between row spacings. Conversely, Sharratt and McWilliams (2005) found that narrow-row corn did have greater total soil water extraction in one year of a two-year study.

The effect of corn row spacing on water use likely depends on moisture availability patterns during the growing season. In cases where drought stress persists during the growing season, increased early water extraction may reduce water that is available later in the season. Increased early water uptake may have the added effect of creating greater demand for water later in the season due to improved early crop growth. If water is not limited later in the season, the greater early uptake may be advantageous for the crop. However, research does not indicate any broad advantage to narrow-row corn under drought stress conditions.

Potential Interacting Factors

Plant Population

In examining the potential value of narrow-row corn production, it is important to consider not just current crop management systems but also factors that are likely to change in the future. One such factor is plant population density. Historic yield gains in corn have largely been driven by the continual improvements in stress tolerance, which have allowed corn to be planted at ever-increasing densities.

Average corn seeding rates in the U.S. and Canada have increased linearly over the last 20 years from approximately 25,000 seeds/acre in 1992 to over 31,000 seeds/acre in 2017 (Figure 6). Extending this trend line 20 years into the future yields a predicted average seeding rate of over 37,000 seeds/acre in 2035. Whether or not the increases in optimum seeding rates over the last 20 years will continue at the same rate over the next 20 years remains to be seen; however, it raises the question of how agronomic practices may need to adapt to maximize production in the future.

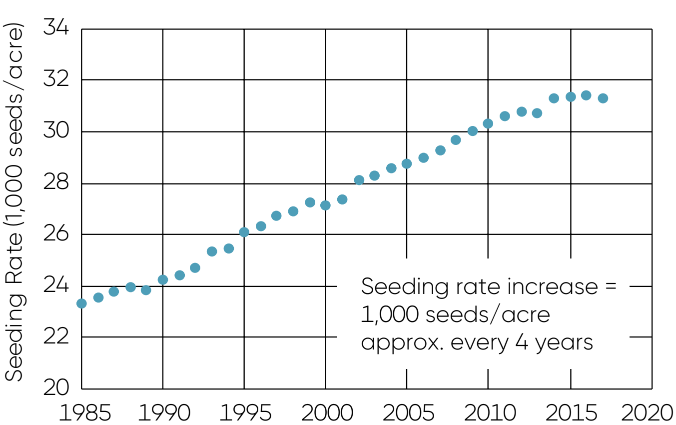


Figure 6. Average corn seeding rates reported by growers in North America, 1985-2017 (source: Pioneer survey).

As corn population density increases, plants are crowded closer together within the row. At a density of 30,000 plants/acre, corn plants are spaced 7 inches apart within a row when planted in 30-inch rows. This spacing drops to 5.8 inches at 36,000 plants/acre and 5.0 inches at 42,000 plants/acre. There has been some speculation that crowding within the row can be yield-limiting at higher populations, in which case narrow rows could serve to alleviate this effect by increasing space between plants (Figure 7).

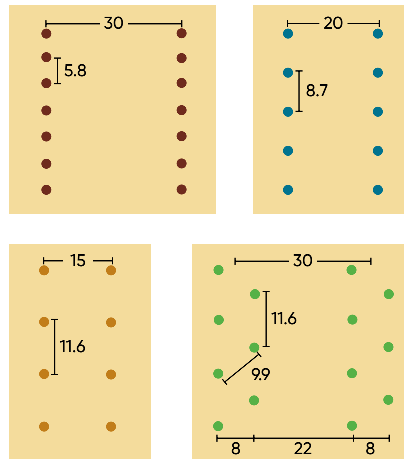


Figure 7. Across- and within-row spacing (in inches) in various row configurations at 36,000 plants/acre.

Row spacing studies in corn have routinely tested for interactions with plant population and specifically, whether or not narrow rows have a higher optimum density than 30-inch rows. Several university studies have included plant populations in excess of 40,000 plants/acre and have found little evidence that narrow rows have a higher optimum population (Table 2). Pioneer research on twin-row corn also found no difference between row spacings at high populations (Figure 8).

One notable exception was a University of Minnesota/Pioneer research study in northwestern Minnesota that found significantly greater yield with 22-inch rows than 30-inch rows at the two highest plant populations tested (38,500 and 44,000 plants/acre) (Coulter and Shanahan, 2012). However, for growers outside of the northern Corn Belt, current research does not indicate that yields at higher plant populations will increase with narrow rows.

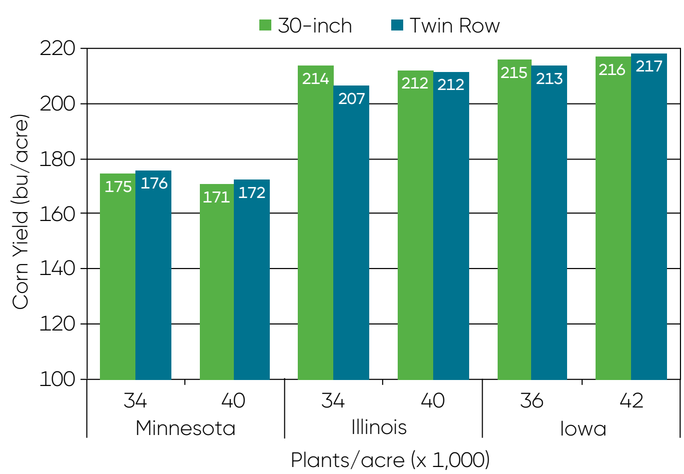


Figure 8. Corn yield in 30-inch rows and twin rows among plant populations included in Pioneer studies conducted in Minnesota, Illinois, and Iowa in 2010.

Hybrids

A common question regarding narrow row corn is whether certain hybrids are more suited to this system than others and also if future improvements in corn genetics may eventually produce hybrids specifically optimized for narrow rows.

Many university row spacing studies have included multiple hybrids but generally have found no difference in response to narrow rows. Of the twelve studies summarized in Table 2 that included more than one hybrid, only one (Study 15) reported a significant hybrid by row spacing interaction (Farnham, 2001). Out of six hybrids tested in this study, one yielded better in 15-inch rows, one yielded better in 30-inch rows, and four did not differ.

Pioneer on-farm twin row studies conducted in 2010 included several locations with multiple hybrids, some locations with as many as 10 hybrids. Among 14 hybrids that were tested at three or more locations, no significant differences in yield between twin rows and 30-inch rows were observed nor were any hybrid by row spacing interactions observed among hybrids compared at multiple locations (data not shown). Yield response to row configuration often appeared to differ among hybrids at individual locations; however, these differences diminished as the number of testing locations increased.

It has been suggested that improvements to stress tolerance in high population environments may yield new hybrids particularly suited to a high-density narrow row or twin row configuration. Decades of breeding corn for higher yield has resulted in modern hybrids with very different leaf architecture than those of 50 years ago, so it is not unreasonable to suppose that future breeding efforts could further alter the morphology of corn plants.

The idea of optimizing hybrids for narrow row production has typically focused on leaf architecture, specifically that plants with narrower and more upright leaves may be more suited to narrow rows. Research thus far, however, has not shown a relationship between leaf architecture and yield response to row spacing among contemporary hybrids.

Research conducted in Michigan compared performance of six hybrids with differing leaf architecture 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).

There is some indication that modern hybrids may actually be more suited to maximize yield in 30-inch rows than those of the past. Van Roekel and Coulter (2012), in noting the lack of yield response to narrow rows at two Minnesota locations where similar research had found a significant yield response in the early 1990s, hypothesized that selection by plant breeders for increased tolerance to stress associated with high plant densities may have also resulted in improved performance in 30-inch rows relative to older genetics. Analysis by Hammer et al. (2009) tends to support this hypothesis. Their modeling studies indicated that historic improvements in corn yield were likely more related to changes in root architecture than leaf architecture, specifically roots systems that grow deeper in the soil at a steeper angle. Plants with more vertical, downward-growing root systems would seem less likely to be affected by competition with neighboring plants and therefore, less sensitive to differences in row spacing.

Conclusions

The extensive history of research on corn row spacing has repeatedly shown that it is a very complex issue with many interacting factors. Yield results have often been inconsistent and highly variable across environments, making it difficult for growers to determine the best solution for their individual farms. However, the accumulated body of Pioneer and university research conducted over the past 20 years does not indicate that the current standard 30-inch row spacing is limiting to corn productivity for most of the Corn Belt. This research also provides little evidence to suggest that narrow rows will consistently increase yield relative to 30-inch rows on productive soils under current agronomic practices. Yield results in the northern Corn Belt have tended to be more positive for narrow rows but still have shown a high degree of variability.

Many Pioneer and university corn row spacing studies have included multiple hybrids and have generally found no difference in hybrid performance among row-spacings, indicating that growers currently in narrow row systems are not limited in their choice of corn products for maximum performance. Consult your local Pioneer sales professional for information on the best products for your specific management system and growing environments.

Deriving Value from Multi-Hybrid Planting

*by **Mark Jeschke, Ph.D.,***
Agronomy Manager

Summary

- Three conditions are necessary for a multi-hybrid planting strategy to provide a yield advantage:
    - Within-field variation in yield due to environmental or management factors
    - Difference between hybrids in yield response to within-field environmental variation
    - Spatial predictability of within-field environmental variation so that the right hybrids can be placed in the right areas of the field
- The most common strategy for variable hybrid placement involves pairing a hybrid with high yield potential and a hybrid with high tolerance to a yield-limiting stress factor.
- The environmental factor most likely to provide the basis for a successful multi-hybrid management strategy is soil moisture.
- Pioneer on-farm trials conducted in 2015 did not show a benefit to multi-hybrid planting, largely due to favorable growing conditions and lack of drought stress during the season.
- Four years of studies by South Dakota State University showed a yield benefit with multi-hybrid planting in some site years, but most often there was no yield difference.
- It is important for growers to understand the methods used in multi-hybrid research trials and the manner in which the data are interpreted in order to draw meaningful inferences from the results.

Introduction

Advances in farming technology over the past 20 years have provided the opportunity to fine-tune crop management by varying inputs across the landscape within a field. Precision farming pioneers long envisioned that corn hybrids could be an important input for variable management (Dudding et al., 1995), considering that 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; Thomson McClure, 2014). Pioneer and university scientists began initial explorations into the potential value of variable hybrid placement across a field in the mid-1990s (Jeschke and Shanahan, 2015).

Today, the technology to vary hybrid placement is readily available, making the potential value of this technology for improving yields an important consideration. In addition to potential benefits, growers must also consider potential risks as well as the cost of deploying multi-hybrid planting. Costs include the initial investment in equipment and the increased effort as well as complexity associated with developing multi-hybrid prescriptions and managing a greater number of seed products during planting season.

Deriving Value from Multi-Hybrid Planting

Three 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. And finally, the within-field environmental variation must have some degree of spatial predictability so that the right hybrids can be placed in the right areas of the field.

The final condition is the most challenging of the three to meet because of the effects that weather can have in shaping the growing environment in any given season. Placing a drought-tolerant hybrid, for example, would require having a reasonably good idea at the outset of the growing season where in the field drought stress is likely to be yield limiting. In general, environments with a high degree of yield variability across the landscape where yield-limiting stress does not vary greatly year-to-year due to weather are most likely to benefit from variable hybrid placement.

The most common strategy for variable hybrid placement typically involves pairing a hybrid with high-yield potential and a hybrid with lower yield potential but a higher level of tolerance to a yield-limiting stress factor expected to be present within the field. In practice, these designations are often colloquially referred to as "offensive" and "defensive" hybrids, or "race-horse" and "work-horse" hybrids. The offensive hybrid is assigned to areas of the field expected to be relatively free of a yield-limiting stress factor where it can help maximize yield, and the defensive hybrid is placed in areas where yield-limiting stress is expected in order to help minimize yield reduction associated with it.

This approach assumes an implicit tradeoff between yield potential and stress tolerance, which may or may not be the case depending on the individual hybrid(s). A given hybrid may be high yielding and also have a high degree of tolerance to a particular yield-limiting factor, in which case the optimal strategy would be to plant the entire field to that hybrid. In general, advancements in plant breeding have helped to reduce the prevalence of this tradeoff by developing hybrids with greater yield stability across environments. Hybrid yield stability is discussed in greater detail in a *Crop Insights* article, "Strategies and Considerations for Multi-Hybrid Planting" (Jeschke and Shanahan, 2015).

Weighing the benefits and risks of deploying a multi-hybrid strategy depends, in part, upon the default scenario against which it is being compared: i.e., what a grower would likely do if he/she were not varying hybrid placement.

For example, consider a field that is generally very high yielding but has a few drought-prone spots within it. The default scenario in this instance would likely be to plant a high yield potential hybrid across the whole field with the understanding that it will perform poorly in some areas. A multi-hybrid strategy in this case would involve placing a drought-tolerant hybrid in the drought-prone spots, thereby exchanging top-end yield potential for resilience against yield loss from drought stress in those portions of the field. The greatest risk associated with deploying a multi-hybrid strategy in this scenario is if drought stress does not manifest to the extent expected, in which case top-end yield potential will have been sacrificed for no gain.

Conversely, consider a field that is mostly drought-prone but has a few consistently productive areas in it. In this situation, the default scenario would likely be to plant a drought-tolerant hybrid across the whole field. The multi-hybrid strategy would provide the opportunity to capture additional value by placing a higher yield potential hybrid in the highly productive spots. Then, the greatest risk associated with the multi-hybrid strategy would be if the spots expected to be high yielding instead experience drought stress, in which case the attempt to achieve greater yield would actually result in lower yield than if the whole field had been planted to the drought-tolerant hybrid.

Simplified examples showing different possible yield outcomes in both of these scenarios are shown in the appendix at the end of this article.

Effects of Seasonal Variability

The greatest challenge in successfully implementing a multi-hybrid strategy is knowing which hybrid to put where. The variation in growing environments across a field can be influenced by weather conditions experienced during the season.

Since the decision of where to place a hybrid must be made at the start of the season, it requires a prediction based on knowledge of soil characteristics and field history of the nature and extent of yield-limiting stress likely to occur. The success or failure of a multi-hybrid strategy will depend in large part on the accuracy of this prediction.

Some of the initial studies conducted by Pioneer in the 1990s illustrated how challenging this can be (Figure 1). As an example, a field-scale split-planter study conducted in northern Illinois showed substantial variation in relative hybrid performance across the field, indicating potential value of variable hybrid placement. When the split-planter study was repeated in the same field with the same two products two years later, the pattern of relative hybrid performance was very different. A multi-hybrid prescription based on the results of the initial study would not have been suited to the conditions experienced during the subsequent season.

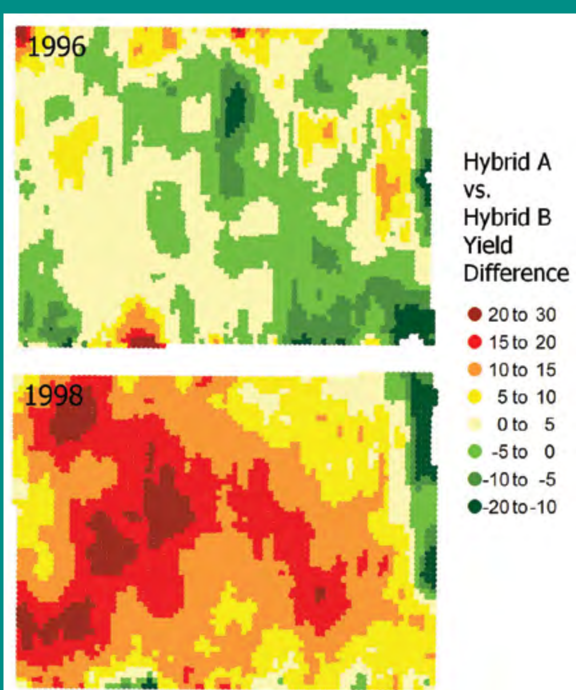


Figure 1. Yield difference maps from a Pioneer split-planter study conducted in northern Illinois in 1996 and 1998, using the same two hybrids both years. The high degree of temporal variability relative to spatial variability in this field would make effective hybrid placement a challenge.

Hybrid Placement by Soil Water Availability

A multi-hybrid strategy can potentially be used to manage any yield-limiting stress for which hybrids vary in their response. However, the environmental factor most likely to provide the basis for a successful multi-hybrid management strategy is probably soil moisture. Drought frequently causes substantial reductions in yields, and hybrids often differ in their tolerance to drought stress in ways that are well characterized. The terms *defensive* and *offensive* as applied to corn hybrids often function largely as a proxy for drought tolerance.

The primary challenge associated with successfully deploying a multi-hybrid strategy to manage drought stress is the fact that drought stress can vary greatly in severity and extent from year to year, making it difficult to satisfy the third criterion presented at the outset of this article – spatial predictability of stress that allows the right hybrids to be placed in the right areas of the field. Multi-hybrid planting will likely have a higher probability of success in places where drought stress is more predictable, such as marginal soils or drier areas of the Western Corn Belt, compared to more productive areas where rainfall is more abundant, common in the Central and Eastern Corn Belt. The remainder of this article will largely focus on multi-hybrid planting examples and research results dealing with managing drought stress.

Research Results

Pioneer On-Farm Trials

Field-scale on-farm trials were conducted in 2015 to explore the potential value of variable hybrid placement. Trials were established in southwestern Iowa and northeastern Missouri; however, the Missouri trials were lost due to excessive rainfall and flooding during the growing season. Eight trials were successfully completed, all in southwestern Iowa. The trials were planted using a Kinze 4900 multi-hybrid planter. Field size ranged from 56 to 199 acres.

Management zones for the trial fields were delineated based on soil types. A hypothetical multi-hybrid prescription was created for each field by assigning one of the two hybrids to each management zone based on which hybrid was expected to be the higher yielding of the two. In the actual prescription that was planted, blocks of both hybrids were placed within all soil types that had significant presence in the field, allowing the ability to compare yield of the hybrid assigned in the multi-hybrid prescription and the alternate hybrid in each zone as well as estimate the yield that would have been achieved with multi-hybrid planting versus solid seeding of either hybrid across the entire field.

Based on local recommendations, two corn products were selected for each field; were designated as a "defensive" product and "offensive" product; and were assigned to low and high productivity management zones, respectively. Products designated as defensive were generally more drought-tolerant, while products designated as offensive generally had higher top-end yield potential and less drought tolerance. A total of four Pioneer® brand corn products were used across the eight trials (Table 1). Offensive and defensive designations for each trial are shown in Table 2. Note that Pioneer P1197AM™ brand corn was deployed as the offensive hybrid in some trials and as the defensive hybrid in others.

Table 1. Pioneer® brand corn products used in 2015 on-farm multi-hybrid planting trials.

Hybrid/Brand[1]	Year*	CRM	Drought Tolerance**
P0937AM™ (AM,LL,RR2)	2014	109	6
P1142AMX™ (AMX,LL,RR2)	2013	111	7
P1151AM™ (AM,LL,RR2)	2012	111	9
P1197AM™ (AM,LL,RR2)	2014	111	7

* Commercial year.

** Drought tolerance is a complex trait, determined by a platform's ability to maintain yield in limited-moisture environments. A higher score indicates the potential for higher yields vs. other platforms of similar maturity in limited-moisture environments.

Table 2. Corn product designations for each multi-hybrid planting trial location in Pioneer on-farm trials.

Location	Defensive Product (Hybrid/Brand[1])	Offensive Product (Hybrid/Brand[1])
1	P1151AM™	P1197AM™
2	P1151AM™	P0937AM™
3	P1151AM™	P0937AM™
4	P1142AMX™	P1197AM™
5	P1197AM™	P0937AM™
6	P1197AM™	P0937AM™
7	P1151AM™	P0937AM™
8	P1151AM™	P1197AM™

Pioneer On-Farm Trial Results

Results showed that at all eight trial locations, the best outcome would have been achieved by planting one hybrid across the entire field (Table 3). In most cases, this was the offensive hybrid. At five of the eight locations, the offensive hybrid was the best yielding across all management zones. At the two locations where Pioneer® P1197AM™ brand corn was designated as the defensive hybrid, it was higher yielding than the offensive hybrid. The predicted whole-field average yield for the multi-hybrid prescription was usually intermediate between the predicted whole-field average yields for the two individual hybrids. Estimated yield for multi-hybrid planting was 10.8 bu/acre less on average than if the whole field had been planted to the higher yielding hybrid.

Table 3. Predicted whole-field average yield in Pioneer on-farm trials for both individual hybrids and the multi-hybrid prescription as well as the difference between multi-hybrid and the better of the two hybrids.

	Predicted Whole-Field Avg. Yield			MH vs. Best
Location	Defensive	Offensive	MH	
	bu/acre			
1	233	239	236	-3
2	191	220	195	-26
3	212	232	225	-7
4	200	232	214	-18
5	267	257	258	-9
6	257	253	252	-5
7	216	231	221	-10
8	213	226	217	-10

At the three locations where the defensive hybrid had greater yield in portions of the field, the potential benefit of multi-hybrid planting was limited in part by imperfect hybrid placement, i.e., there was not perfect alignment between the zones where the defensive hybrid was assigned and zones where it actually performed better. Had hybrid placement been optimal in these three locations, multi-hybrid planting would have resulted in a whole-field average yield between 0.6 and 2.6 bu/acre better than planting the entire field to the best of the two hybrids (Table 4). Lost yield potential due to imperfect hybrid placement at these locations ranged from 2.6 to 8.7 bu/acre.

Table 4. Potential yield advantage with multi-hybrid planting at select locations if hybrid placement had been optimal.

	Multi-Hybrid			
Location	Assigned placement	Perfect placement	Best Hybrid	MH Adv.
	bu/acre			
1	236.3	240.3	238.9	+1.4
5	258.3	267.6	267.1	+0.6
6	252.1	260.1	257.5	+2.6

The outcome of the multi-hybrid trials in 2015 was largely driven by the weather conditions experienced during the growing season. Moisture was generally ample, in some cases excessive, in the study area in 2015, which minimized the number and extent of environments in which a more drought-tolerant hybrid would provide a yield advantage. This is an example of the first risk/benefit scenario described at the beginning of this article in which multi-hybrid planting can have a downside risk if the stress factor that it is intended to manage is not present. Given that these trials were all conducted in one growing season under similar conditions, the results do not provide much insight on the potential value of multi-hybrid planting across a wider diversity of environments. However, they do provide a very good illustration of a set of conditions under which multi-hybrid planting is unlikely to provide value and could, in fact, carry significant downside risk.

South Dakota State University Research

Researchers at South Dakota State University conducted a four-year study from 2013 to 2016 comparing conventional and variable hybrid planting at several locations in South Dakota (Sexton et al., 2013; 2014; 2015; 2016). 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. Corn products suited to these environments were selected with the input of Pioneer agronomists (Table 5).

Table 5. Pioneer® brand corn products selected for upland and lowland environments in multi-hybrid research conducted by South Dakota State University.

	Hybrid/Brand[1]	
Year	Upland	Lowland
2013	P0533AM1™ (AM1,LL,RR2)	P0987AM1™ (AM1,LL,RR2)
	P0876AM™ (AM,LL,RR2)	P1151AM™ (AM,LL,RR2)
2014	P0533AM1™ (AM1,LL,RR2)	P0987AM1™ (AM1,LL,RR2)
	P0876AM™ (AM,LL,RR2)	P1151AM™ (AM,LL,RR2)
2015	P0533AM1™ (AM1,LL,RR2)	P0636AM™ (AM,LL,RR2)
	P0297AMX™ (AMX,LL,RR2)	P0157AMX™ (AMX,LL,RR2)

For the first two years of the study, research locations were planted using a modified Monosem twin-row planter capable of switching between two hybrids. The latter two years of the study used a Kinze 4900 multi-hybrid planter. The plots were set up as field-length strips and laid out so that each strip included both upland and lowland landscape positions.

Research trials were successfully completed at three locations in 2013 with multi-hybrid planting providing a significant yield benefit at two of the three. At one location, two of the multi-hybrid pairs (Pioneer® P0876AM™ and P1151AM™ brand corn; Pioneer® P0876AM™ and P0987AM1™ brand corn) yielded better than the best individual hybrid, producing overall average yields of 198 bu/acre and 197 bu/acre compared to 190 bu/acre with the whole field planted to Pioneer® P0876AM™ brand corn. This represents an ideal scenario for multi-hybrid planting since it allowed yields greater than those achieved with any individual hybrid planted across the entire field. Results at this location also demonstrated the importance of optimal hybrid selection as one of the multi-hybrid pairs (Pioneer® P0533AM1™ and P1151AM™ brand corn) was among the lowest yielding entries in the study. At the second location, the multi-hybrid entries were higher yielding on average, but the highest yielding pair of hybrids did not yield any more than the best individual hybrid. At the third location, multi-hybrid planting did not show a yield benefit.

Research trials were completed at two locations in 2014. Multi-hybrid planting with Pioneer® brand products provided a 6 bu/acre yield advantage at one location but no advantage at the other location. Multi-hybrid planting did not show a yield benefit at any of the four study locations in 2015. This outcome was attributed to the generally favorable growing conditions and lack of drought stress experienced during the 2015 season. Research was only conducted at one location in 2016 and did not show any yield benefit for multi-hybrid planting.

Results of the four-year study showed that multi-hybrid planting can be an effective tool to improve corn yield, but that success is dependent upon hybrid selection, hybrid placement, and weather conditions experienced during the growing season. Results of trials conducted in 2015 mirrored those of the Pioneer trials in Iowa in which the yield-limiting stress the multi-hybrid prescription was designed to manage did not manifest. Unlike the Pioneer trials, the SDSU study showed little downside risk associated with multi-hybrid planting. It provided a yield benefit in some site-years and no yield difference in the majority of site-years but no instances where the outcome of a multi-hybrid pair was substantially worse than the better of the two hybrids. The risk associated with multi-hybrid planting is likely to be greatly dependent on the profiles of the individual hybrids; the greater the divergence between the two hybrids in top-end yield potential or tolerance to a key yield-limiting stress, the greater the potential to lose yield if conditions during the growing season do not play out as anticipated.

Evaluating Potential Multi-Hybrid Applications

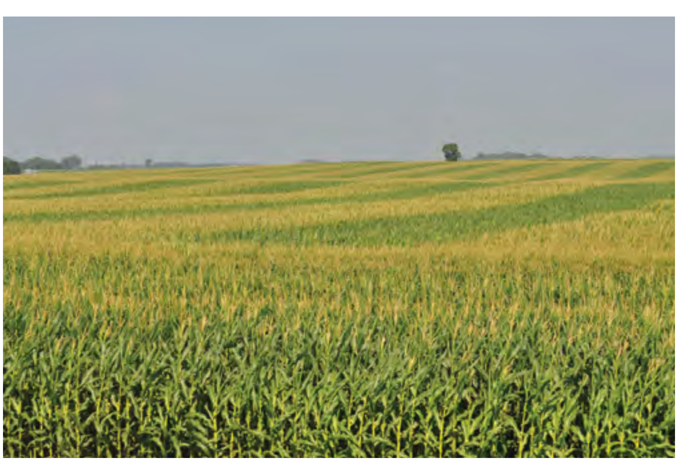
The yield benefit of variable hybrid placement in a field can be tested in on-farm trials in much the same manner as variable rate seeding prescriptions are often tested – by placing check blocks within management zones. In the case of a multi-hybrid prescription, a zone where Hybrid A is prescribed would contain a check block planted to Hybrid B nested within it. This allows an assessment of the yield advantage of the prescribed hybrid versus the alternative. This is the method used to test the value of multi-hybrid planting in Pioneer on-farm trials conducted in 2015.

These yield comparisons within management zones can then be used to estimate the field-level average yield of the multi-hybrid prescription compared to one or each of the hybrids planted across the whole field. The most meaningful comparison would be to compare the multi-hybrid yield versus the yield of the hybrid a grower would have been likely to choose to plant over the whole field. Since management zones are likely to vary in size, management zone yields should be weighted by acreage in estimating a whole-field average yield.

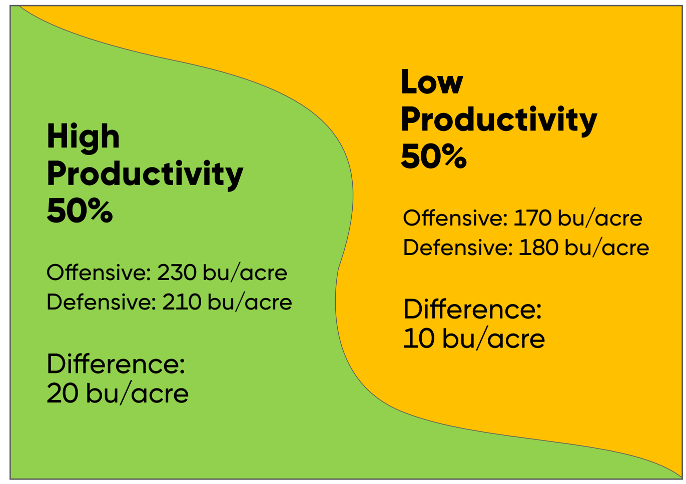
Split-planter trials provide an excellent means to explore the potential value of variable hybrid placement without the need for a multi-hybrid planter. Much of the initial research exploring the potential value of variable hybrid placement involved split-planter trials. Comparing performance of two hybrids across the landscape of a field can provide insight into the potential benefit of multi-hybrid planting. This information coupled with the multi-year yield history of the field can provide an idea as to how stable the differences in yield performance may be from year to year.

Interpretation of Research Results

It is important to understand the methods used in multi-hybrid research trials and the manner in which the data are interpreted in order to draw meaningful inferences from the results. Several industry reports of multi-hybrid planting research results have focused solely on the difference in hybrid yield performance based on soil productivity level. (For example: Hybrid A outyielded Hybrid B by 8 bu/acre on high productivity soils while Hybrid B outyielded Hybrid A by 5 bu/acre on low productivity soils.) This sort of information can give an idea of the yield benefit variable placement of two hybrids might potentially provide, but it does not provide a valid estimate of the actual field-scale yield benefit a grower is likely to realize from multi-hybrid planting for two major reasons. First, it fails to account for other factors like differences in management zone size within a field, accuracy of hybrid placement, and spatial consistency in productivity levels year-over-year. Secondly, and more importantly, simply taking an average of the yield differences between two hybrids across management zones in a field effectively compares the multi-hybrid prescription and its inverse, which is not a useful comparison.



This point is illustrated using a highly-simplified example in Figure 2. In this example, the field is evenly split between soils characterized as high productivity and low productivity. The offensive hybrid yields 20 bu/acre more on the high-productivity soils and the defensive hybrids yields 10 bu/acre more on low-productivity soils for an average difference of 15 bu/acre. However, the whole-field average yield with multi-hybrid planting would be 205 bu/acre compared to a whole-field average of 200 bu/acre using the better of the two hybrids, which means that the actual yield benefit of multi-hybrid planting is 5 bu/acre, not 15 bu/acre.



Single Hybrid: (.5 x 230 bu/acre) + (.5 x 170 bu/acre) = 200 bu/acre whole field average

Multi-Hybrid: (.5 x 230 bu/acre) + (.5 x 180 bu/acre) = 205 bu/acre whole field average

Figure 2. Simplified example showing whole-field average yields with a single hybrid and multi-hybrid planting in a field evenly split between high- and low-productivity zones.

Conclusions

The commercial availability of equipment capable of variable hybrid placement has provided growers with a powerful new tool for managing yield-limiting stress in corn production. However, successfully deriving value from this technology is not without its challenges, and it will not necessarily provide a benefit to all operations. Research results presented in this summary represent a relatively small portion of the vast diversity of environments in which corn is grown. Continued on-farm experimentation across a wider range of environments will help direct multi-hybrid technology to the places where it will provide the greatest benefit.

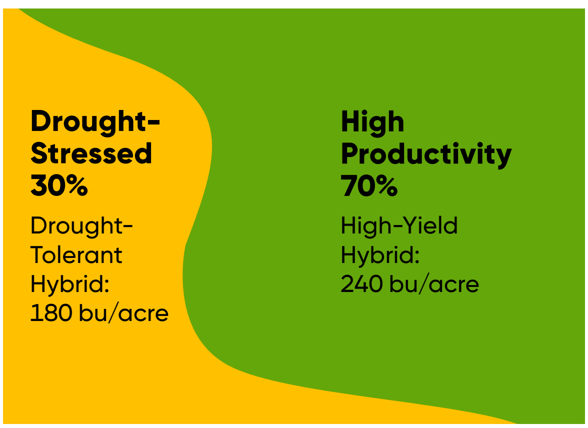
In general, environments with a high degree of yield variability across the landscape where yield-limiting stress does not vary greatly year-to-year due to weather are most likely to benefit from variable hybrid placement. The potential benefit or risk associated with multi-hybrid planting will depend greatly on the profiles of the individual hybrids; the greater the divergence between the two hybrids in top-end yield potential or tolerance to a key yield-limiting stress, the greater the potential to capture additional yield but also the greater the potential to lose yield if conditions during the growing season do not play out as anticipated.

Appendix: Multi-Hybrid Yield Scenarios

Example 1: High Productivity Field

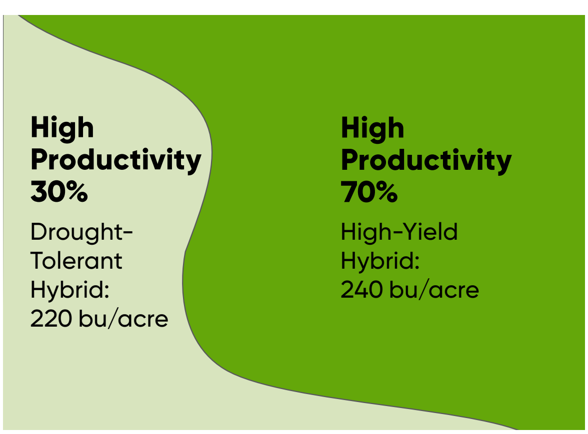
(.3 x 160 bu/acre) + (.7 x 240 bu/acre) = 216 bu/acre

Figure 1A. Primarily high-productivity field planted entirely to a high-yield potential hybrid, producing a whole-field average yield of 216 bu/acre.



(.3 x 180 bu/acre) + (.7 x 240 bu/acre) = 222 bu/acre

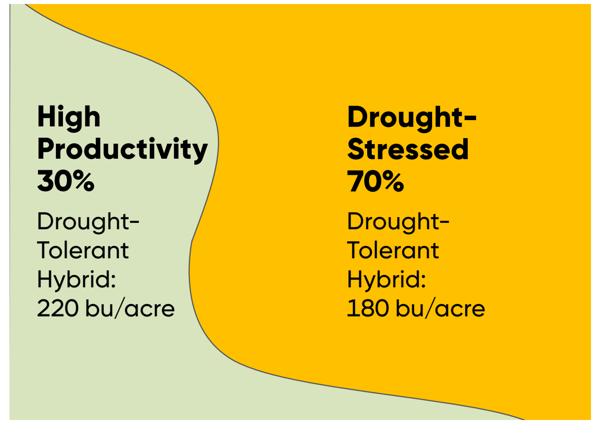
Figure 1B. Primarily high-productivity field with variable hybrid placement. Placing a drought-tolerant hybrid in the drought-stressed zone improves the whole-field average yield to 222 bu/acre, a 6 bu/acre advantage compared to planting the high-yield hybrid across the whole field.



(.3 x 220 bu/acre) + (.7 x 240 bu/acre) = 234 bu/acre

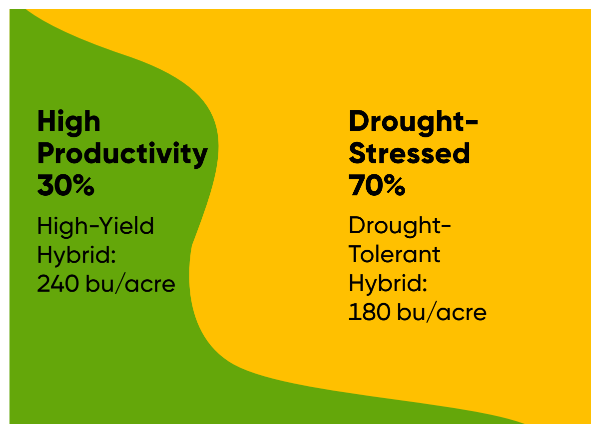
Figure 1C. Scenario in which variable hybrid placement does not match field conditions. Placement of the drought-tolerant hybrid in a zone that ends up being highly productive results in a 6 bu/acre disadvantage compared to planting the high-yield hybrid across the whole field.

Example 2: Drought-Stressed Field



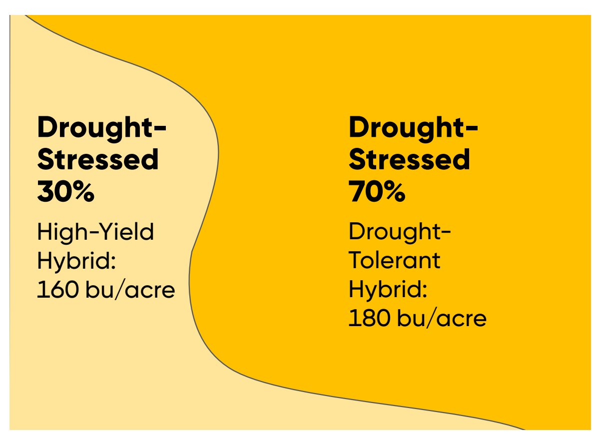
(.3 x 220 bu/acre) + (.7 x 180 bu/acre) = 192 bu/acre

Figure 2A. Primarily drought-stressed field planted entirely to a drought-tolerant hybrid, producing a whole-field average yield of 192 bu/acre.



(.3 x 240 bu/acre) + (.7 x 180 bu/acre) = 198 bu/acre

Figure 2B. Primarily drought-stressed field with variable hybrid placement. Placing a high-yield potential hybrid in the high-productivity zone improves the whole-field average yield to 198 bu/acre, a 6 bu/acre advantage compared to planting the drought-tolerant hybrid across the whole field.



(.3 x 160 bu/acre) + (.7 x 180 bu/acre) = 174 bu/acre

Figure 2C. Scenario in which variable hybrid placement does not match field conditions. Placement of the high-yield hybrid in a zone that ends up being drought stressed results in a 6 bu/acre disadvantage compared to planting the drought-tolerant hybrid across the whole field.

Yield Variation Across Planter Width

*by **Troy Deutmeyer,** Field Agronomist, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Previous research has shown that corn yield can vary across the planter pass due to interrow compaction caused by the tractor and planter wheels tracks during planting (Ahlers, 2012).
  - » A study of 12 on-farm locations in Minnesota found an average yield reduction of 11 bu/acre in the center segment of the planter pass.
  - » Trials in this study were all planted in narrow rows (20 or 22 inches) and included both center-fill and row-unit box planters, although no difference between them was observed.
- Continuing trends toward larger, heavier planters and larger, heavier tractors to pull them coupled with higher frequency of wet conditions during planting make this a persistent concern for corn production.

Objective

- Trials were conducted at three locations in northeast Iowa in 2018 to quantify stand count, ear count, and corn yield variation across planter width.

Study Description

- Trials were conducted at locations in Delaware, Buchanan, and Clayton counties in northeast Iowa.
- Data were collected from two planter passes at each location, consisting of field-length strips.
- Each planter pass was subdivided into three segments – the center segment encompassing the planter as well as tractor wheel tracks and the two wing segments.
- Harvest population and harvestable ear counts were sampled for each planter segment, and each planter segment was harvested separately for moisture and yield. Results are presented as the average of the two wing segments compared to the center segment.
- Planter configuration and soil conditions at planting varied among locations:
  - » Buchanan county: 24-row center-fill planter, 30-inch rows, favorable conditions at planting
  - » Clayton county: 16-row center-fill planter, 30-inch rows, wet soil conditions at planting
  - » Delaware county: 12-row row-unit box planter, 30-inch rows, favorable soil conditions at planting

Results

- All three locations showed a reduction in corn yield in the center planter segment relative to the wing segments (Figure 1).
- Yield reduction at the wet location was greater than that at the more favorable locations, indicating that planting into wet soils may increase yield loss associated with wheel-track compaction.
- Yield reduction appeared to be largely attributable to reduction in harvest stand and harvestable ears at two of the three locations (Figure 2).
- Stand and ear count reductions in the center section at two locations suggest that these rows may benefit from an increased seeding rate in an attempt to reduce yield loss.
- Given the limited number of locations and variation in planter configurations, results from this study should be considered provisional, suggesting areas of interest for further research.

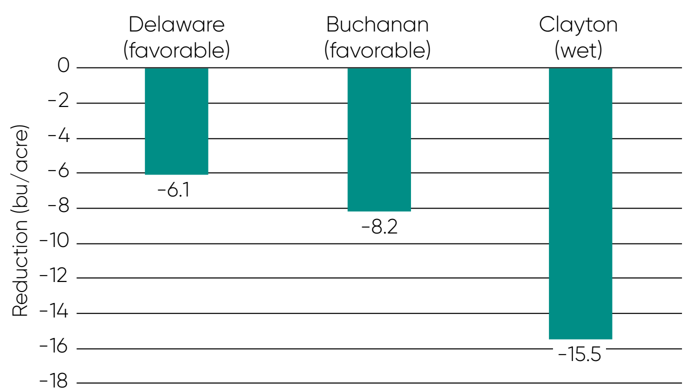


Figure 1. Yield reduction in the center segment relative to wing segments of the planter pass at three northeast Iowa trial locations.

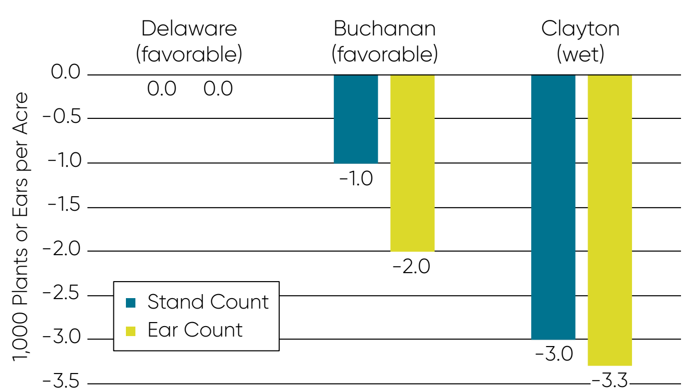


Figure 2. Harvest stand and harvestable ear reduction in the center segment relative to wing segments of the planter pass by location.

Corn Stand Evaluation and Replant Considerations

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Many different stress factors are capable of reducing corn stands, such as:

- Cold or wet soils
- Insect feeding
- Unfavorable weather conditions

Start by assessing the density and health of the current stand.

Stand Counts

- Take several sample counts to represent the field.
- Sample a length of row equal to 1/1,000th of an acre.
- Measure off the distance appropriate for your row width, count the number of live plants, and multiply by 1,000 to obtain an estimate of plants/acre.

Row Width	Length of Rows
38 in	13 ft 9 in
36 in	14 ft 6 in
30 in	17 ft 5 in
22 in	23 ft 9 in
20 in	26 ft 2 in
15 in	34 ft 10 in

- In situations like flooding damage, only a portion of the field may need to be considered for replant.
- Frost or hail can damage a wide area. In this case, plant density and health should be assessed across the entire field.
- When an injury event, such as frost or hail, occurs, it is best to wait a few days to perform a stand assessment as it will allow a better determination of whether or not plants will recover.

Growth of green tissue near the growing point indicates that this plant would have recovered.

Soft, translucent tissue near the growing point indicates that this plant will not recover.

Stand counts should be taken randomly across the entire area of a field being considered for replant; this may include the entire field or a limited area where damage occurred.

After a plant stand has been assessed, it is important to consider other factors:

- Is the stand consistent; are large gaps present?
- Will the stand have adequate crop canopy to assist with weed control and irrigation efficiencies?
- Will replanting provide an economic gain?
- Are the remaining plants healthy and relatively equal in maturity?

Replant Yield Potential

- The expected yield from the current stand should be compared to expected replant yield.

Table 1. Yield potential for a range of planting dates and final plant populations (source: Emerson Nafziger, Eric Adee, and Lyle Paul, Univ. of Illinois).

Planting Date	Plant Population (1,000 plants/acre) 10	15	20	25	30	35	40
	% of maximum yield						
April 1	54	68	78	88	95	99	99
April 10	57	70	81	91	97	100	100
April 20	58	71	81	91	97	100	99
April 30	58	70	80	89	95	97	96
May 9	55	68	77	86	91	93	91
May 19	50	63	72	80	85	86	84
May 29	44	56	65	73	77	78	75
June 8	35	47	56	63	67	67	64

Other Factors to Evaluate

- Stand uniformity – An uneven stand will yield less than a relatively even stand with the same number of plants.
- Plant health – Plants that are severely injured or defoliated will have reduced photosynthetic capability and a lower yield potential.

Corn yield is influenced by stand density as well as stand uniformity:

- Variation in plant size can have a negative impact on yield.
- Plants with delayed emergence or development are at a competitive disadvantage with larger plants in the stand and will have reduced leaf area, biomass, and yield.

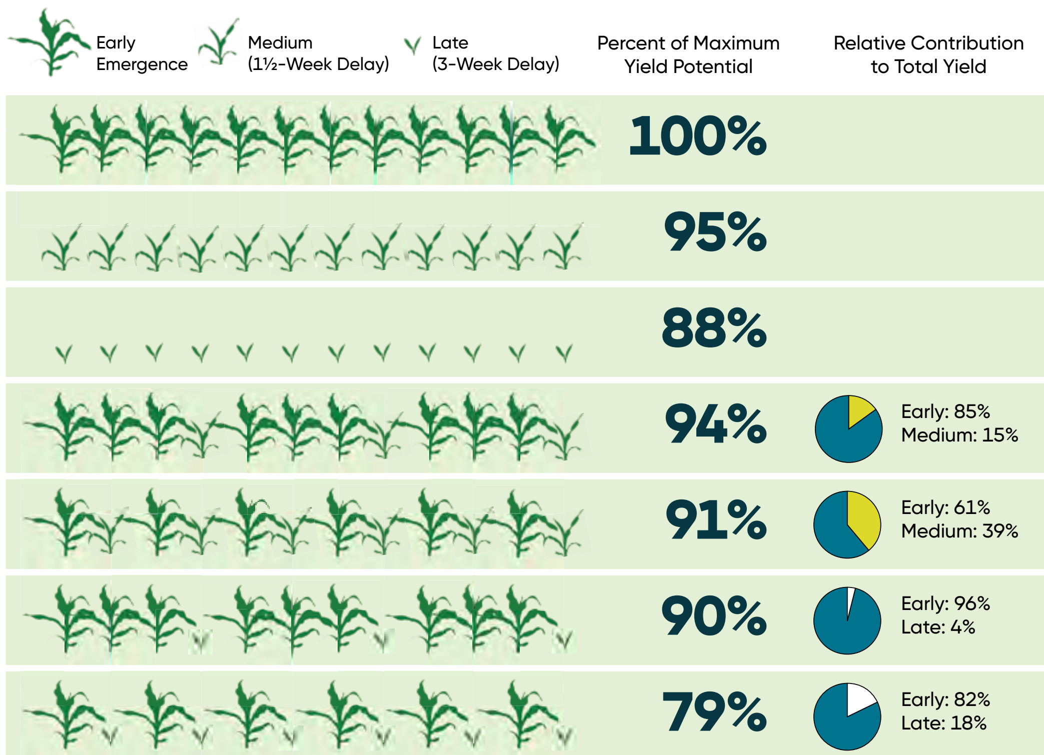


Figure 1. Yield potential of delayed and uneven corn stands.

Data from Carter, P.R., E.D. Nafziger, and J.G. Lauer. 1989. Uneven emergence in corn. North Central Regional Ext. Pub. No. 344

Profitability of Replant

- Even if replanting will increase yield, the yield increase must be sufficient to pay for all of the costs associated with replant, such as:
  - » Extra herbicide or tillage costs
  - » Planting costs
  - » Increased grain-drying costs

Also consider these factors when making a replant decision:

- Probability of an autumn freeze prior to physiological maturity of replanted corn
- Increased susceptibility of late-planted corn to summer drought or disease and insect pests, such as gray leaf spot and European corn borer

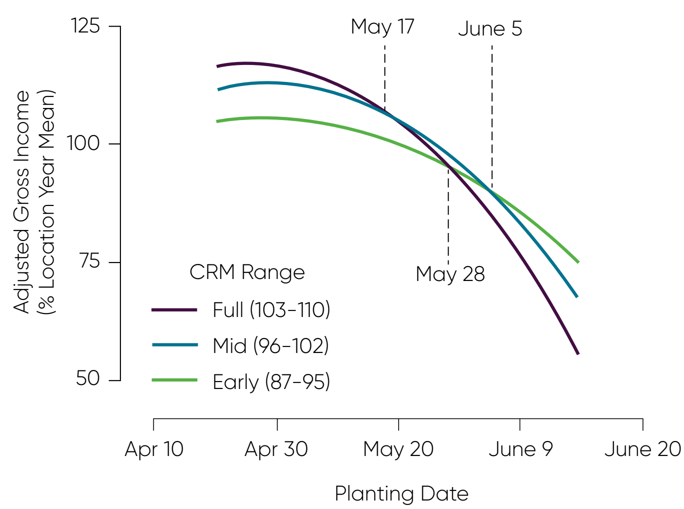


Figure 2. This chart shows the relative profitability of full-season, mid-maturity, and early-maturity hybrids in 29 north-central Corn Belt environments over 17 years of Pioneer research.

Maturity Selection for Delayed Planting

- A frequent question pertaining to replanting corn is how full season of a hybrid can be planted and still reach normal physiological maturity.
- When considering which hybrid to replant, consider growing degree unit (GDU) accumulation between the planting date and average first frost date as well as hybrid GDU requirements to reach physiological maturity.
- Research has shown that corn can adjust its growth and development, requiring fewer growing degree units GDUs to reach maturity when planted late. Late-planted corn showed a reduction in GDU requirements of about six GDUs per day of planting delay.
- Results indicate that a grower may consider switching to a mid-maturity hybrid if replanting after May 17 and an early maturity hybrid if replanting after June 5.

Uniformity of Corn Emergence in Eastern Iowa

*by **Eric Zumbach,** Field Agronomist, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Uniformity of emergence is one key to producing high corn yields. Plants that emerge later than those around them can be at a competitive disadvantage and yield less, which can reduce the overall yield of the field.
- Research has shown that if 25% of the plants come up 10 days later than the rest, overall corn yields can be reduced by as much as 6% (Carter and Nafziger, 1989).
- Many factors can lead to the uneven emergence in corn. Factors include variation in soil moisture and temperature; poor seed to soil contact; planting into wet soils; soil crusting; insect and disease pressure; and more.

Objectives

- A study was conducted in southeastern and east central Iowa in 2018 to observe plant uniformity and development from emergence through black layer.
- The objective of this study was to understand the effect of uneven emergence on growth, development, and ultimately, yield.

Study Description

- Emergence, growth, and development observations were collected from 31 locations in southeastern and east central Iowa in 2018.
- Sample areas at each location consisted of row lengths equivalent to 1/1000 of an acre for two Pioneer® brand corn products selected by Pioneer sales representatives from their product knowledge plots (Figure 1).

Figure 1. Sample area at one study location in 2018. Flags were placed daily to indicate emerged plants throughout the emergence period.

- Sample areas were monitored daily and emerged plants counted from first emergence through final emergence.
- Sample areas were hand-harvested following maturity, and kernel counts were taken for each plant.

2018 Planting Season Highlights

- Corn planting in the far southeastern corner of Iowa was the earliest in the state in 2018 due to relatively dry soil conditions.
- The majority of southeastern Iowa had an ideal planting window from late April through first part of May.
  - » Dry, sunny conditions and record low dew point temperatures in April allowed soil conditions to dry quickly.
  - » Soil temperatures in southeastern Iowa hit the critical 50 °F soil temperature between April 22 and April 25 (Figure 2).
- Warm soil temperatures following planting in late April and early May contributed to very good emergence across the majority of southeastern and east central Iowa.
- Very little soil crusting due to heavy rain was observed.

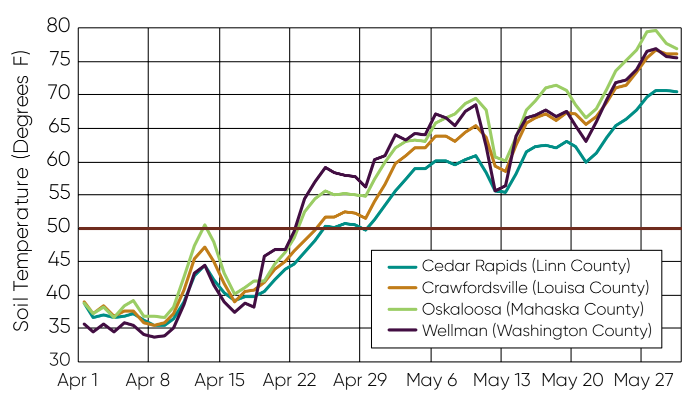


Figure 2. Daily average soil temperatures at 4-inch depth at 4 southeastern Iowa locations in 2018.

Results

- Time to first emergence following planting ranged from 7 to 18 days across the 31 locations with an average of 9.8 days (Figure 3).
- Across the 31 study locations, an average of 82% of the final stand emerged within 2 days (Figure 4), an outcome that was reflective of the highly favorable soil conditions for emergence experienced in southeastern and east central Iowa in 2018.

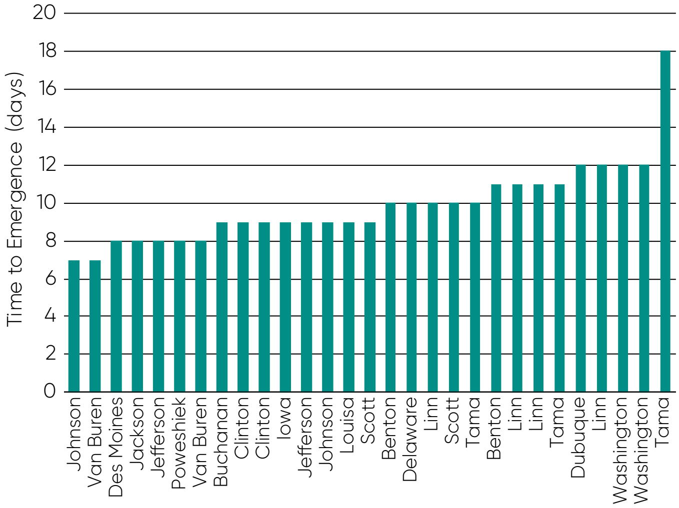


Figure 3. Days to emergence for each study location in 2018 (locations listed by county).

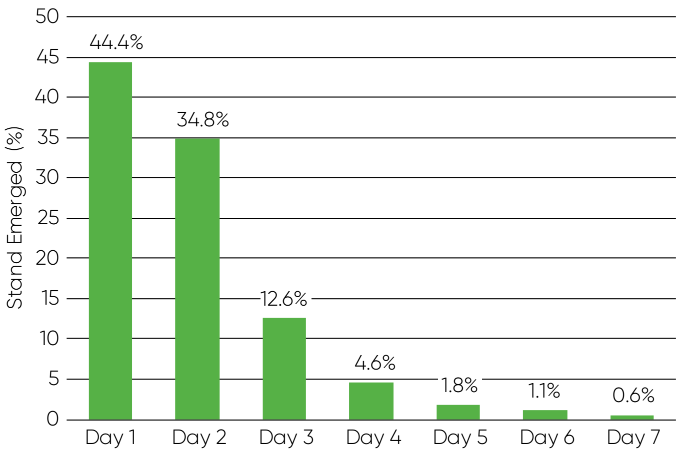


Figure 4. Percent of corn stand emerged for each day during the emergence period, averaged across locations.

- Kernel counts taken from ear following maturity illustrated the importance of achieving uniform emergence in corn. Average kernels per ear were dramatically reduced for plants that did not emerge within the first two days (Table 1).

Table 1. Average number of plants emerged per day and corresponding number of kernels per ear across study locations.

Day	Average Number of Plants Emerged per Day	Average Kernels per Ear
1	15.0	587
2	11.7	567
3	4.2	508
4	1.6	328
5	0.6	372
6	0.4	396
7	0.2	302

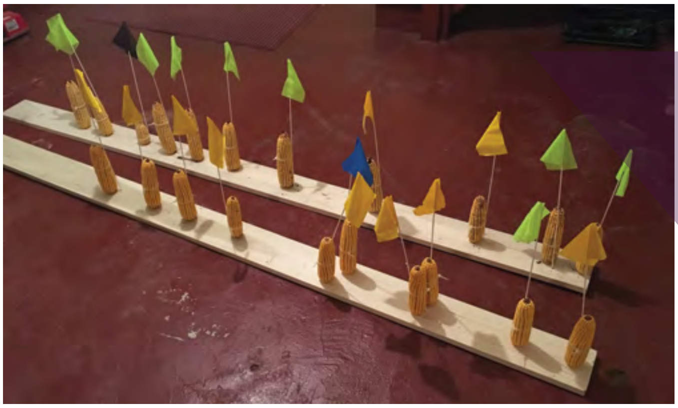


Figure 5. Ear board showing emergence differences (flags), uniformity of ears, and plant spacing.

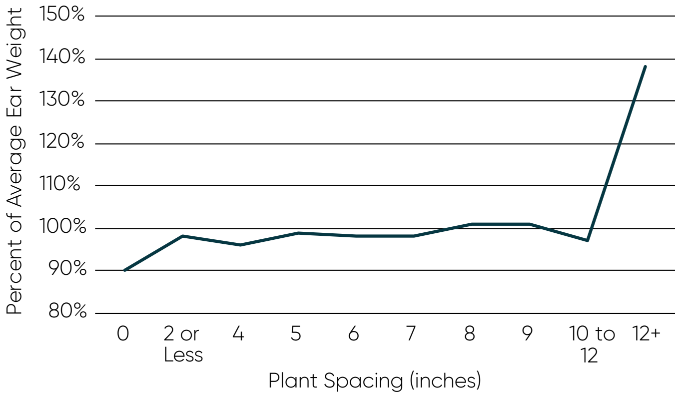


Figure 6. Ear weight as a percent of average as affected by distance to the nearest neighboring plant within the row.

- Four locations were selected to evaluate plant-to-plant spacing in relationship to yield. Results showed if plants emerge at the same time, a "double" can have almost no yield implications. However, it is important to avoid skips and recognize that even perfectly spaced plants can be runts if emergence timing is not uniform.

Conclusions

- Research has shown that plant-to-plant uniformity of emergence is important for optimum yields.
- Conditions across east central and southeastern Iowa in 2018 were very favorable for rapid and uniform emergence.
- Conditions will vary from year to year, so growers need to continue to manage factors, which can lead to uneven emergence. Factors include: non-uniform residue distribution; soil compaction; inconsistent seed spacing and depth; soil temperature and moisture variation; and poor seed to soil contact.
- To minimize the risk of uneven emergence, avoid working soils and/or planting when fields are too wet.

Chilling and Flooding Injury to Emerging Corn

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Planting Into Stressful Conditions

- Corn is a warm-season crop with tropical origins, as such it is susceptible to stresses that result from early planting under cool soil conditions.
- When corn is planted early and soil temperatures are below 50 °F (10 °C), it is likely that corn seeds will remain in the soil at least three to four weeks prior to emergence.
- During this time, corn may encounter a number of stresses, including herbicide injury as well as insect and disease pressure.
- Problems can also result from the physical properties of the seedbed, including crusting, ponding, or saturated soils. Cold temperatures resulting from cold rain or snow can severely impact the seed.

Effect of Cold Soils and Water

- Early planting often exposes seeds to hydration with cold water, which can cause direct physical damage.
- Prolonged exposure to low temperatures reduces seed as well as plant metabolism and vigor; increases sensitivity to herbicides and seedling blights; and causes oxidation damage due to the effects of free radicals in the cell.

Imbibitional Chilling Injury

- When the dry seed imbibes cold water as a result of a cold rain or melting snow, imbibitional chilling injury may result.
- The cell membranes of the seed lack fluidity at low temperatures, and under these conditions, the hydration process can result in rupture of the membranes.
- Cell contents then leak through this rupture and provide a food source for invading pathogens.
- Cold water can similarly affect seedling structures as they begin to emerge.
- Research has shown that temperatures at or below 50 °F (10 °C) are most damaging to the germination and emergence process, especially if they persist long after planting (Table 1).

Snowfall soon after planting imposes a very high level of stress on corn emergence due to seed imbibing chilled water or prolonged exposure to cold, saturated soils.

Table 1. Planting dates, soil temperatures, and final stand counts in Pioneer research plots with cold conditions after planting.

Location	Planting Date	Average Soil Temp. 4 Weeks Post-Plant	Final Stand (%)
Michigan	Apr 16	56 °F (13 °C)	90
Minnesota	Apr 23	48 °F (9 °C)	81
North Dakota	Apr 11	41 °F (5 °C)	61

Flooding Effects on Emergence

- Flooding can have an equally as devastating effect on seedling emergence and survival as cold soils.
- Most corn hybrids can only survive for 24 to 48 hours under water with smaller seedlings suffering the most damage.
- Flooding damages corn biochemically. By impairing mitochondria, it causes release of free radicals, which damage cell membranes.
- Flooding also causes oxygen starvation and shifts the plant's metabolic processes to anaerobic fermentation. Resulting acidosis (low pH) can kill the cells.
- At a minimum, flooding reduces the plant's metabolic rate, making seedlings more sensitive to disease, insects, and herbicides.
- Many pathogens, such as *Pythium*, thrive in standing water. Seedlings that are weakened by flooding or cold damage are more likely to succumb to disease if the pathogen is present in the soil.
- Flooding damage does not only occur in ponded areas of a field; if fields are completely saturated to the soil surface and remain that way due to continual rain or limited drainage, seeds and non-emerged seedlings are under water.

Genetic Tolerance to Cold Stress

- Pioneer plant breeders have selected within the natural variation expressed by corn genotypes to develop hybrids with strong emergence and vigor characteristics under cool soil conditions.
- Pioneer provides stress emergence (SE) scores for all North America hybrids to help growers manage early-season risk.
- Stress emergence refers to the genetic potential of a hybrid to germinate and emerge under stressful conditions associated with early planting, including cold, wet soils or short periods of severe weather.

Chilling/Flooding Injury Diagnosis

Table 2. Corn seedling injury symptoms and likely causes.

Symptom	Likely Cause	Result
Stubby coleoptiles Leaves emerging prematurely	Imbibitional chilling or cold damage	Death, unless unprotected leaf reaches the surface
Brown tissue behind root tip Adventitious roots	Chilling damage Flooding	Chance for survival unless shoot meristem is damaged
Leafing underground Leaves growing along soil crust	Mechanical damage Soil crusting	Usually death as seedlings lose ability to penetrate soil
Corkscrew mesocotyl or coleoptile	Temperature fluctuations Herbicide injury	Seedling death
Fused coleoptile or bursting on side	Cold damage Genetic tendency	Seedling death
Rotted seed or mesocotyl Spotty wilting	Seedling disease	Seedling death or stunting
Bleached leaves	Herbicide or cold injury	Seedlings can grow out of it unless impairment of photosynthesis is extensive
Pruned roots	Insect damage	Weak seedlings, wilting

Imbibitional Chilling and Cold Injury: Club-shaped coleoptile

Imbibitional Chilling and Cold Injury: Underground emergence

Flooding Damage: Note necrotic area of each root above root tip.

Cold Damage: Corkscrew seedling

Flooding/Chilling Damage: Note dead primary root (above seed) and adventitious roots on mesocotyl (below, left of seed).

Cold Damage: Fused coleoptile, bursting on the side

Reduction in Corn Yield Due to High Night Temperatures

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager,* ***Nanticha Lutt,*** *Agronomy Sciences Intern,*
and ***Stephen Strachan, Ph.D.,*** *Global Program Leader*

Night Temperatures and Corn Yield

- Corn producers are generally aware that high night temperatures can be detrimental to yield; however, the effects on specific plant processes and yield components are not as well understood.
- Corn originated in the Central Highlands of Mexico and adapted during its evolution to the predominant climatic conditions of this region, consisting of warm days and cool nights.
- Research has shown that above-average night temperatures during reproductive growth can reduce corn yield both through reduced kernel number and kernel weight.

Yield Reductions from Warm Nights

2010 Growing Season

- In 2009, many farmers in the Midwestern United States produced record corn grain yields. However, in 2010, even with adequate rainfall, corn grain yields were much lower.
- A notable difference between these two growing seasons was night temperatures following pollination.
- The average minimum night temperatures during July and August of 2009 were about 5 to 8 °F lower than the average minimum night temperatures in 2010 in the Corn Belt (Figures 1 and 2).

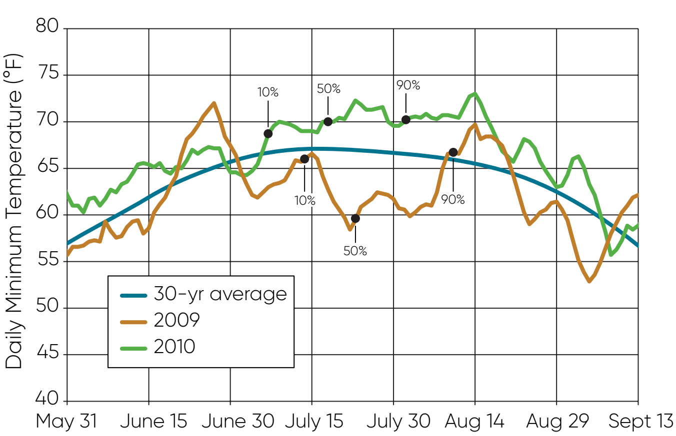
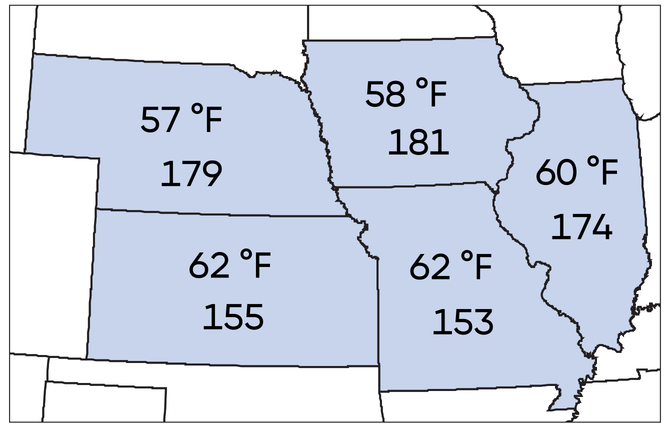


Figure 1. Daily minimum temperatures (7-day moving average) for Des Moines, IA, in 2009 and 2010 and 30-yr average minimum daily temperatures (1981-2010). Approximate dates of 10%, 50%, and 90% silking in Iowa in 2009 and 2010 based on USDA crop progress reports.

2009 Night Temperature Minimums



2010 Night Temperature Minimums

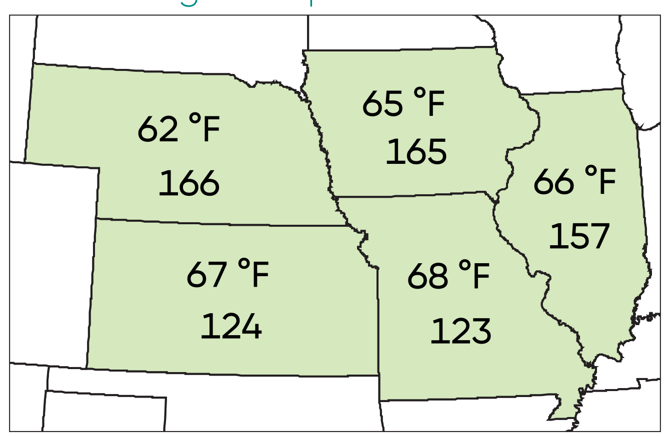


Figure 2. Average minimum temperatures experienced in July and August of 2009 and 2010 and average yields (bu/acre) in Iowa, Illinois, Missouri, Kansas, and Nebraska (data from NCEI NOAA, USDA NASS).

University of Illinois Study

- The first experimental evidence that high night temperatures can have a detrimental effect on corn yield came from an experiment performed at the University of Illinois (Peters et al., 1971).
- Corn grown with an average night temperature of 85 °F yielded 40% less grain than corn grown with an average night temperature of 62 °F (Table 1).

Table 1. Effect of night temperature from silking through physiological maturity on corn yields (Peters et al., 1971).

Treatment	Average Night Temperature	Grain Yield
	°F	*bu/acre*
Natural Air	65	168
Cooled	62	162
Heated	85	100

Further Research on Temperature Effects

- Research has shown a reduction in kernel number associated with high night temperatures (Cantarero et al., 1999).
- Results showed that kernel abortion in heated night plots was 8% higher than in the control plots. Ears in the heated plots had an average of 34 kernels per row at harvest compared to 37 kernels per row in the control plots.
- A study by Badu-Apraku et al. (1983) examined the effect of temperature on grain fill after kernel number had already been set.
- Results showed that grain yield per plant was significantly affected by temperature regime (Table 2).

Table 2. Effect of temperature on grain fill duration, grain weight per plant, and kernel number (Badu-Apraku et al., 1983).

Day / Night Temperature	Grain Fill Duration	Grain Wt Per Plant	Kernel Number
°F	days	oz	
77 / 59	39 a	4.4 a	550 a
77 / 77	31 b	3.6 b	580 a
95 / 59	24 c	2.5 c	593 a
95 / 77	21 d	2.4 c	606 a

Why Do Warm Nights Reduce Yield?

- Current research supports two hypotheses that may explain why higher temperatures during the grain filling period reduce grain yield:
  - » Higher rate of cellular respiration
  - » Accelerated phenological development

Higher Rate of Respiration

- The most commonly cited explanation for the detrimental effect of high night temperatures on corn yield is increased expenditure of energy due to a higher rate of cellular respiration at night.
  - » Cellular respiration consumes carbon assimilated through photosynthesis to maintain and increase plant biomass.
  - » Higher temperatures produce faster rates of cellular respiration in a corn plant, making less sugar available for deposition as starch in the kernels.
  - » A lower rate of respiration relative to photosynthesis has generally been viewed as favorable for maximizing agricultural productivity and grain yield.
- Although higher night temperatures undoubtedly increase the rate of respiration in corn, research generally suggests that higher rates of night respiration probably do not have a large impact on corn yield.
  - » In a study that examined the effects of elevated night temperature, night respiration in plant leaves did not significantly differ between heated and control plots (Cantarero et al., 1999).
  - » In another study, respiration rates were found to be high for newly emerged plants but declined as plants developed (Quin, 1981). Researchers concluded that increased respiration rates associated with high night temperatures likely did not have a major impact on corn yield.

Accelerated Phenological Development

- Elevated night temperatures reduce the time required for corn plants to reach physiological maturity.
- Shortening the length of time between silk emergence and maturity reduces the number of days that the corn plant is engaged in photosynthesis during grain fill, effectively reducing the amount of energy the corn plant can convert into grain yield.
- Following the 2010 growing season, Iowa State University researchers used the Hybrid-Maize model to explore the effects of night temperature on length of grain fill (Elmore, 2010).
- The model compared predicted days to maturity based on actual 2010 temperatures versus daily minimum temperatures from July 15 to Aug 15 replaced with those from the 2009 growing season (labeled as T_{min} Alt in Table 3).
- Results showed that lower night temperatures during the month-long period following silking extended grain fill by a week or more.
- Research conducted by Badu-Apraku et al. (1983) provides further evidence that shortening the days from silk emergence to physiological maturity reduces grain yield.
- Results showed that duration of the grain fill period and grain yield per plant were both significantly affected by temperature (Table 2).
- **Research generally shows that accelerated phenological development is likely the primary mechanism by which high night temperatures can negatively affect corn yield.**

Table 3. Simulations conducted with Hybrid-Maize resulting days in reproductive stages and total days to maturity at five Iowa State University Research and Demonstration Farms.

ISU Research Farm	Year	Days in Reproductive Stages	Total Days to Maturity
Sutherland	2010	61	131
Sutherland	2010 T_{min} Alt	72	144
Nashua	2010	55	122
Nashua	2010 T_{min} Alt	63	130
Ames	2010	50	115
Ames	2010 T_{min} Alt	59	124
Lewis	2010	50	115
Lewis	2010 T_{min} Alt	58	123
Crawfordsville	2010	50	114
Crawfordsville	2010 T_{min} Alt	57	120

Corn Development and Dry Down in the Far-Northern Corn Belt

by ***Jeff Coulter, Ph.D.,*** *University of Minnesota, and* ***Zach Fore,*** *Field Agronomist*

Background and Objectives

- Corn development and dry-down rates in the far-northern Corn Belt are often predicted using information from the central Corn Belt since little information is available for this region. As a result, inaccurate predictions are common due to differences in growing environments and hybrid comparative relative maturity (CRM) between regions.
- The objectives of this study were to evaluate corn development and dry-down rates across several growing environments in the far-northern Corn Belt and determine whether this was influenced by hybrid CRM.

Study Description

- Field trials were conducted in northwestern Minnesota and eastern North Dakota at six to eight locations per year from 2015 to 2017.
- Two to six Pioneer® brand corn hybrids of differing maturity (73-87 CRM) were evaluated in each trial with three replications per locations.
- Data were collected 10 to 15 times per location from corn emergence until harvest. Corn developmental stage, location of the kernel milk line, and grain moisture content were recorded. Site-specific weather data were used to calculate growing degree units (GDUs) at 86/50 °F maximum/minimum thresholds.

Results

- There was a linear relationship between cumulative GDUs from planting and corn vegetative stage (Figure 1), and this was consistent among hybrids and years. On average, 59 GDUs were required to advance each vegetative stage during the VE to V18 stages.
- The 2011 Iowa State University Extension publication titled "Corn Growth and Development" reports that 108- to 112-CRM hybrids grown in central Iowa require 84 GDUs to advance one vegetative stage during the VE to V10 stages and 56 GDUs to advance one vegetative stage beyond the V10 stage.
- These GDU requirements of 108- to 112-CRM hybrids are similar to those of the 73- to 87-CRM hybrids in this study after the V10 stage but are greater than those in this study during earlier growth stages (Table 1).
- Assuming daily high/low air temperatures of 80/55 °F, the greater GDU requirements of 108- to 112-CRM hybrids are equivalent to an additional 1.4 days per vegetative stage during the VE to V10 growth period or 14 days total.
- There was a linear relationship between cumulative GDUs from planting and progression of the kernel milk line from the crown (Figure 2), which varied by year but did not differ significantly among hybrids. On average, kernel milk line progressed downward by 1% per 4.5, 3.5, and 3.8 GDUs in 2015, 2016, and 2017, respectively.

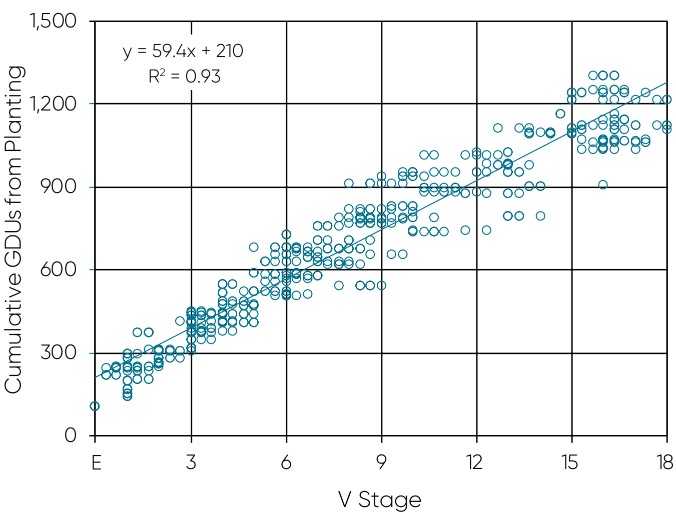


Figure 1. Relationship between corn vegetative (V) stage and cumulative GDUs from planting for 73- to 87-CRM hybrids across hybrids, locations, and years (2015–2017).

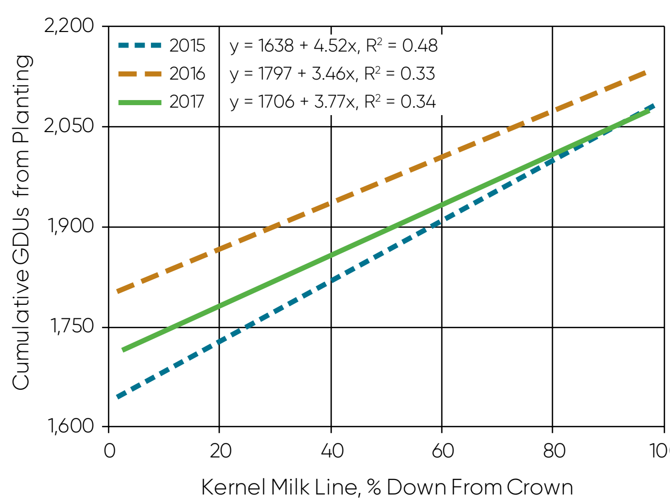


Figure 2. Relationship between kernel milk line location and cumulative GDUs from planting for 73- to 87-CRM hybrids in 2015, 2016, and 2017, across hybrids and locations.

Table 1. Relationship between cumulative GDUs from planting and corn vegetative (V) stage reported for 108- to 112-CRM hybrids in the 2011 Iowa State University Extension publication "Corn Growth and Development" compared with that for 73- to 87-CRM hybrids in this study.

Corn V Stage	Cumulative GDUs from Planting to Reach V Stage		
	108 to 112 CRM Hybrids	73 to 86 CRM Hybrids	Difference
V1	204	269	-65
V2	288	329	-41
V3	372	388	-16
V4	456	448	8
V5	540	507	33
V6	624	566	58
V7	708	626	82
V8	792	685	107
V9	876	745	131
V10	960	804	156
V11	1016	863	153
V12	1072	923	149
V13	1128	982	146
V14	1184	1042	142
V15	1240	1101	139
V16	1296	1160	136
V17	1352	1220	132
V18	1408	1279	129

- There was a linear relationship between cumulative GDUs from planting and dry down of grain in the field (Figure 3). As with kernel milk line progression, this differed among years but did not differ significantly among hybrids.
- On average, grain moisture declined by one percentage point per 14.4, 7.2, and 13.6 GDUs in 2015, 2016, and 2017, respectively (Figure 3). This is equivalent to a one percentage point decline in grain moisture with each 1.0 day in 2015, 0.5 day in 2016, and 0.9 day in 2017, assuming daily high/low temperatures of 80/50 °F during the dry-down period

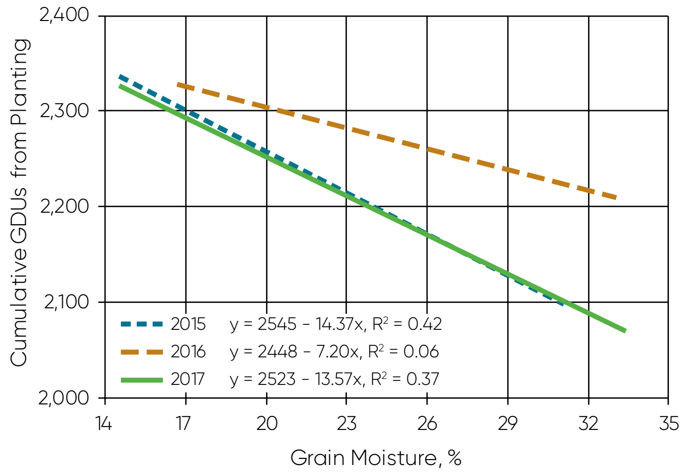


Figure 3. Relationship between grain moisture and cumulative GDUs from planting for 73- to 87-CRM hybrids in 2015, 2016, and 2017, across hybrids and locations.

Conclusions

- Results from this study confirm that corn development during the vegetative stages is more rapid until the V10 stage for early maturity hybrids grown in the far-northern Corn Belt compared to that reported for longer-season hybrids grown in the central Corn Belt.
- From the VE to V10 stages, this difference in GDU requirements between hybrid groups was equivalent to 14 days. Beyond the V10 stage, the rate of vegetative development was similar, although the hybrids in this study produced 15 to 18 leaves while hybrids adapted to the central Corn Belt typically produce 19 to 20 leaves.
- In this study, there was a linear relationship with GDU accumulation from planting for kernel milk line progression and in-field dry down of grain after physiological maturity. These relationships varied by year but did not differ significantly among the hybrids tested.
- There was also greater variability in the relationship between these variables and cumulative GDUs from planting in comparison to corn vegetative development and is attributed to differences in soil moisture content during grain fill and weather conditions during dry down.

Stalk Lodging in Corn: Causes and Management

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Stalk Lodging in Corn

- Stalk lodging is generally defined as breakage of the corn stalk below the ear following physiological maturity, which makes harvest more difficult and can reduce harvestable yield.
- There are a number of factors that can contribute to stalk lodging in corn, but it is most commonly associated with a combination of weakened stalks due to some sort of stress during grain fill and stalk rot pathogens that subsequently invade the weakened stalks.
- Severe weather during drydown can be a primary or contributing cause of stalk lodging. In many cases, stalks that are already weak will break under high winds and rain.
- Insect feeding, particularly that of second-generation European corn borer, can be a cause of stalk lodging but is far less common now due to the wide adoption of Bt corn.

Carbohydrate Demand During Grain Fill

- Stalk lodging problems often originate from stress during grain fill that increases the amount of carbohydrates remobilized from the stalks and roots.
- Upon successful pollination, ear development places a great demand on the plant for carbohydrates. When the demands of the developing kernels exceed the supply produced by the leaves, stalk and root storage reserves are utilized.
- Environmental stresses, which decrease the amount of photosynthate or energy produced by the plant, can force plants to extract even greater percentages of stalk carbohydrates, which preserves grain fill rates at the expense of stalk quality.
- High temperatures accelerate plant development, shortening the time to maturity and reducing the total amount of photosynthate production.
- Factors that reduce functional leaf area, such as disease lesions, insect feeding, or hail damage, also reduce photosynthate production.
- As carbohydrates stored in the roots and stalk are mobilized to the ear, these structures begin to decline and soon lose their resistance to soil-borne pathogens.
- High temperatures during grain fill increase the rate at which fungi invade and colonize the plant.
- Though pathogens play a key role in stalk rot development, it is primarily the inability of the plant to provide sufficient photosynthate to the developing ear that initiates the process.

Stress Factors That Can Lead to Weak Stalks

Drought Stress

- Decrease in photosynthetic rates due to drought stress has been well documented. Water relations within the plant as well as CO_2 and oxygen exchange are directly affected.
- In addition, if leaf rolling occurs during drought, the effective leaf surface for collection of sunlight is reduced.

Low Solar Radiation

- Photosynthesis is most efficient in full sunlight. The rate of photosynthesis increases directly with intensity of sunlight.
- Photosynthesis can be reduced more than 50% on an overcast day compared to a day with bright sunshine.
- Prolonged cloudy conditions during ear fill often result in severely depleted stalk reserves.

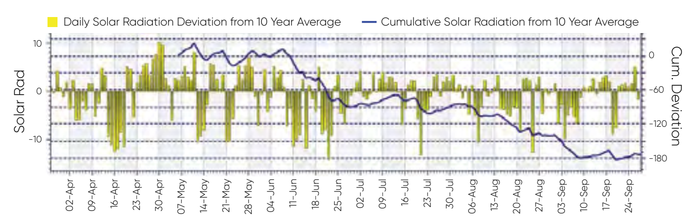


Figure 1. A Pioneer hybrid plot in 2018 in which poor stalk quality was associated with below-average solar radiation throughout the grain fill period (September 28, 2018; Stephenson County, IL).

Reduction in Leaf Area

- Any reduction in leaf area will limit total photosynthesis.
- Leaf area may be reduced due to hail, frost, disease lesions, insect feeding, or mechanical injury.
- Whenever functional leaf area is reduced prior to completion of ear fill, stalks will be weakened.

Nutrient Deficiency

- Research studies have documented that soil fertility has a profound effect on stalk quality.
- Studies show that a combination of high nitrogen and low potassium can severely reduce stalk quality.
  - High nitrogen is associated with greater kernel number, which increases the demand for carbohydrates to supply the developing ear.
  - Potassium functions in the building of leaf and stalk tissue. Sufficient plant-available potassium is important in preventing premature plant death.

Favorable Conditions Followed by Stress

- Depletion of stalk tissue can be most severe when favorable growing conditions precede stress during grain fill.
- If favorable growing conditions exist when the number of kernels per ear is being established (V10-V17), the eventual demand for photosynthate will be large.
- Each potential kernel represents an additional requirement for translocatable sugars from the plant. If stress conditions develop during ear fill that render the plant unable to produce enough sugars, stalks will suffer.

Figure 2. Pioneer hybrid advancement trial showing differences in stalk lodging among hybrids. Photo courtesy of Bob Liska, Pioneer Product Agronomist.

Genetic Differences

- Hybrid genetics are an important influence on stalk lodging potential. Some hybrids naturally partition more carbohydrates to the stalk.
- In the hybrid advancement process, researchers are careful to select hybrids with the highest harvestable yield potential across many years and environments.
- Hybrids also differ in their level of genetic resistance to stalk rot pathogens. Pioneer® brand corn products are rated for their resistance to the most common stalk rot pathogen, anthracnose.

Pre-Harvest Scouting

- Weak stalks can be detected by pinching the stalk at the first or second elongated internode above the ground. If the stalk collapses, advanced stages of stalk rot are indicated.
- Another technique is to push the plant sideways about 8 to 12 inches at ear level. If the stalk crimps near the base or fails to return to the vertical position, stalk rot is indicated.

Harvesting Lodged Corn

Lodged or Standing Fields First?

- In most situations, it is better to harvest lodged fields or field areas before the well-standing fields. This strategy must be evaluated on a case-by-case basis, however.
- If better-standing corn is ready for harvest, it may be more efficient and cost effective, in some cases, to harvest it first before lodging increases there.
- In some cases, lodged corn may have a more limited window of time during the day when it can be harvested effectively, when stalks and leaves are dry enough to feed through the head but not so dry that they shatter and pile up on the head. In these cases, alternating between harvesting lodged corn and standing corn nearby may be favorable.

Speed and Direction

- In order to pick up and save more ears from lodged plants, slower than normal ground speeds are required.
- Under severe stalk lodging conditions, harvesting against the direction of the lodging is usually an advantage.

Strategies for Flat Fields

- If the crop or ears are 8 to 10 inches or more above ground level, then it will likely dry to some extent, and the corn can be harvested with a low-profile corn head.
- If the crop or ears are 6 inches or less above ground level, then the corn will not likely dry, and a reel mounted on a corn head or a soybean platform may be needed to harvest the crop.
- Some fields may lodge worse as time progresses, especially if a stalk rotting disease, such as anthracnose, is present. Watch these fields closely.

Add-On Snouts and Reels

- Various aftermarket header attachments are available that can help with harvest of severely lodged corn.
- Plastic snouts and reels can help to pick up lodged corn and move it off the corn head and into the combine.

Informing Future Management Decisions for Corn Rootworm

*by **Clint Pilcher, Ph.D.,** Global Integrated Solutions Manager, **Michael Price,** Statistics Consultant, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

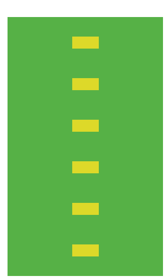
- Corn rootworm (CRW) continues to be the most economically damaging corn insect pest across the Corn Belt.
- Primary yield loss results from larvae feeding on root tissue, but under extreme conditions, adult feeding can impact ear pollination, affecting kernel set and grain quality.
- Corn rootworm continues to prove its ability to adapt and develop resistance to most management tactics available.
- Populations that have adapted to certain tactics require a multi-pronged approach to manage this critical pest.
- In 2018, resistance to the Herculex Rootworm trait (Cry34/35) was confirmed in a field in northeast Iowa.
- Knowledge of corn rootworm management history and current population levels is key to understanding risk and providing effective recommendations.
- Our goal with customers is to sustain long-term profitability through maintaining value of their available control tactics.

Objectives

- Create awareness and quantify adult corn rootworm beetle numbers under different cropping systems to inform grower management decisions.
- Review corn rootworm adult trapping data over the past three years (2016-2018) and report on observed patterns.
- Review "Best Management Practices" for corn rootworm, highlighting the decision-tree process for our growers.

Study Description and Methods

- Pherocon™ AM/NB yellow sticky traps were placed in fields around blister stage (R1) mounted on the plants as shown in the photo to the right (Metcalf, 1986).
- Between one and six sticky traps were placed in the field being sampled following a spatial pattern as shown below. Traps were placed at least 100 ft from the field edge.
- Adult beetles were counted every seven days with the average count per trap recorded.
- Where possible, northern and western corn rootworms were counted separately.
- Trapping and counting continued for four to eight consecutive weeks.
- Trapping was done in both corn-following-corn and corn-following-soybean rotations as well as other rotational schemes (Figure 1).



Yellow sticky trap pattern within a corn field.

Western corn rootworm

Northern corn rootworm

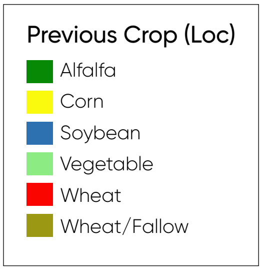
Study Description and Methods

- Dates of trap collection were recorded along with the average number of all beetles for each week.
- Where possible, cropping history and historical use of Herculex® RW (HXRW) insect protection for corn rootworm management were recorded.

Results

- Data collected are represented as follows:
  - » 2016: 773 fields in Iowa, Illinois, Minnesota, Nebraska, and South Dakota
  - » 2017: 685 fields in Iowa, Illinois, Kansas, Minnesota, Missouri, Nebraska, South Dakota, and Wisconsin
  - » 2018: 466 fields in Iowa, Illinois, Indiana, Minnesota, Nebraska, South Dakota, and Wisconsin
- Category thresholds are listed below:
  - » Low pressure = traps average <21 beetles/week
  - » Moderate pressure = traps average 21-50 beetles/week
  - » High pressure = traps average >50 beetles/week

Yellow sticky trapped mounted on a corn plant.



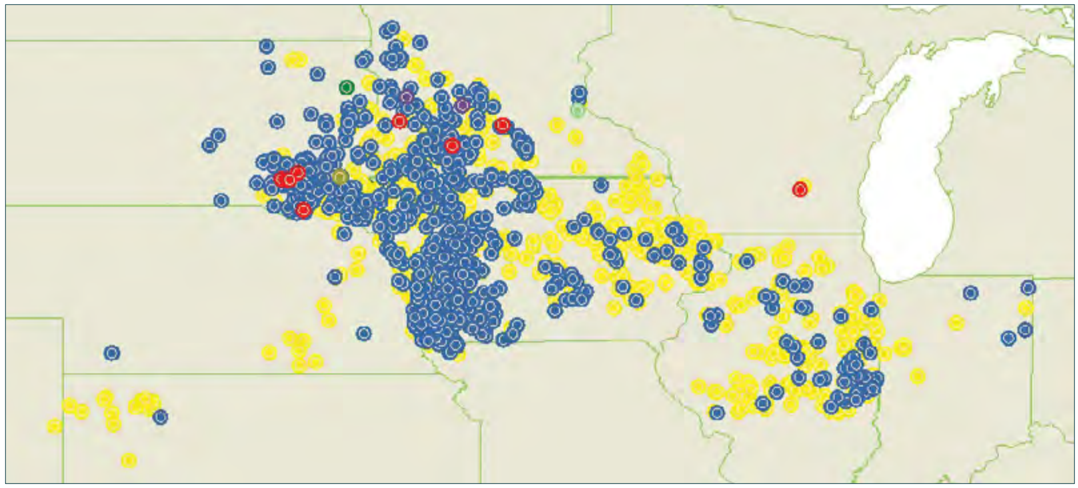


Figure 1. 2016, 2017, and 2018 trapping locations and previous crop.

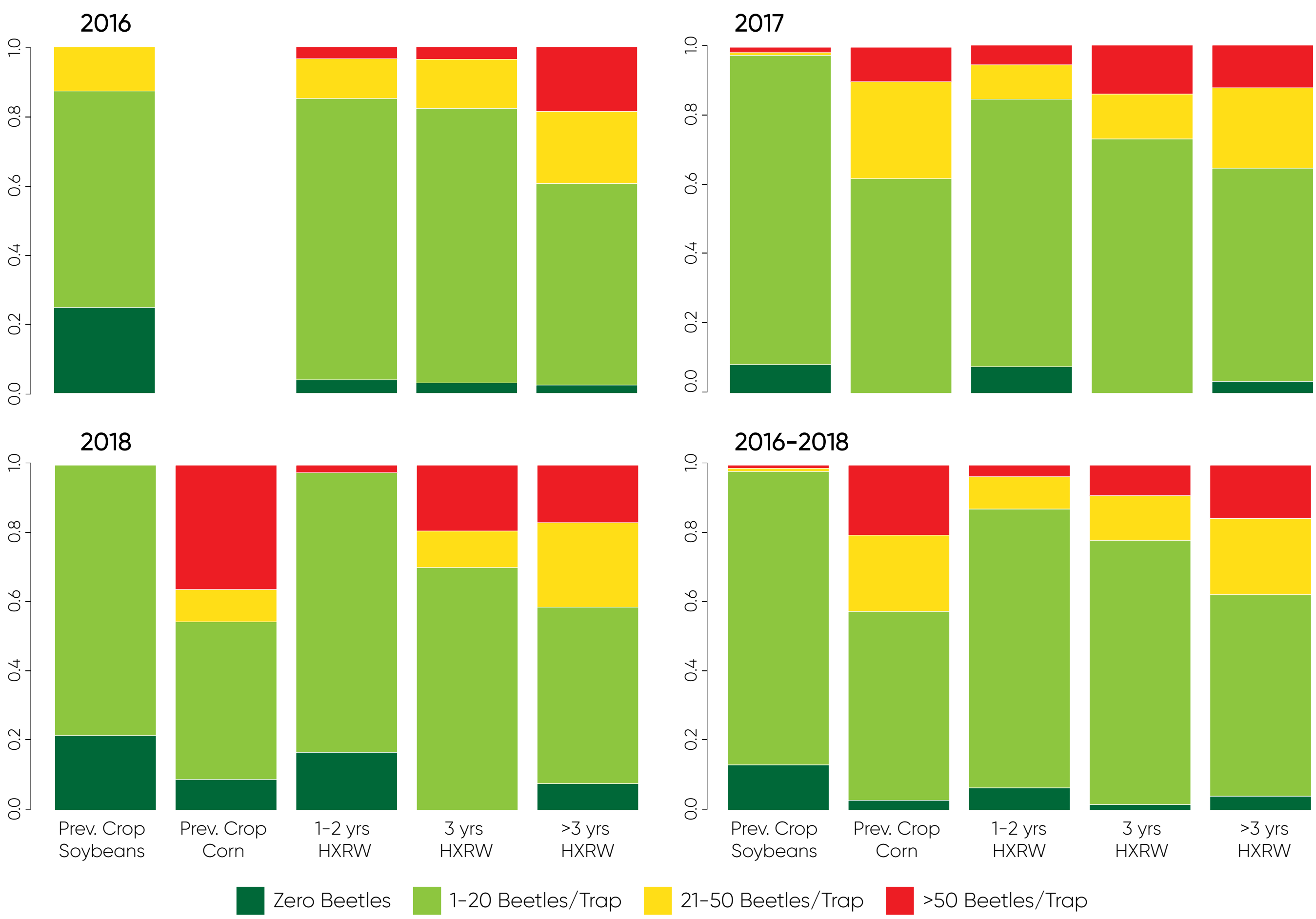
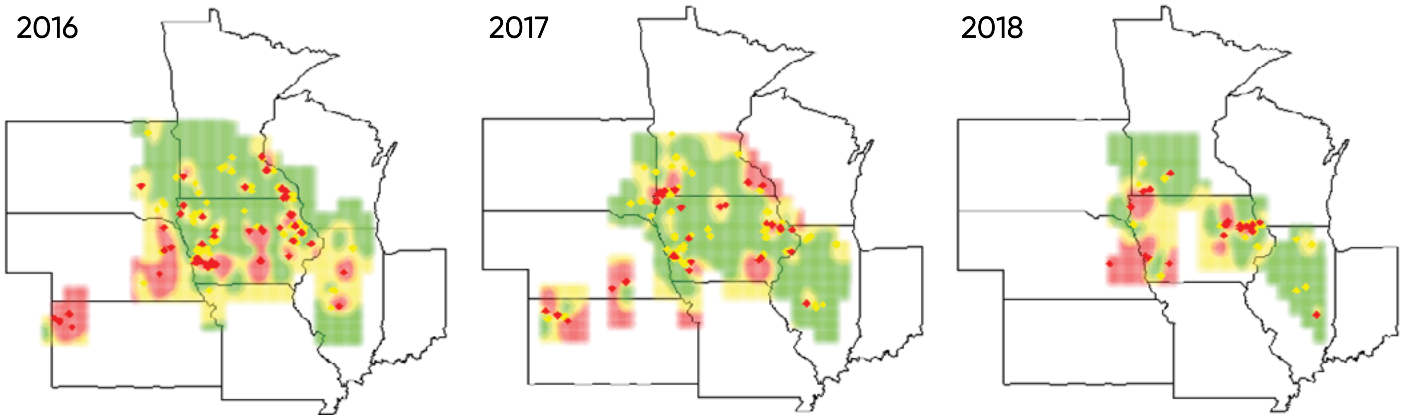


Figure 2. Percentage of beetle numbers within each threshold category by year (2016-2018), cropping history, and corn rootworm management history using HXRW insect protection.

- Figure 2 shows the percentage of beetle numbers within each threshold category by year (2016 to 2018), cropping history, and CRW management history using HXRW insect protection.
- Corn fields where soybeans were grown the previous year reported the lowest numbers of corn rootworm beetles.
- Among corn fields where non-Bt corn was the previous crop, 35 to 45% of the fields had moderate to high corn rootworm beetle counts. Note: only one location was reported in 2016, so distribution is not shown.
- Where previous corn rootworm management history with HXRW was recorded, the data were divided into 3 categories based on the number of consecutive years of HXRW use prior to the current growing season: 1–2 years of HXRW use, 3 years of HXRW use, and >3 years of HXRW use.
    - » In 2016, the first two categories had similar distributions, whereas 2017 and 2018 had greater corn rootworm pressure on the third year of HXRW use.



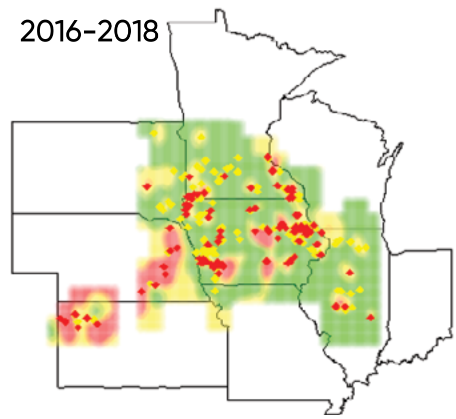
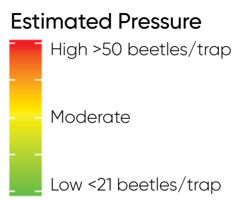


Figure 3. Estimated corn rootworm population pressure* based on current year's trap counts. Yellow and red dots indicate trap locations with moderate and high beetle counts.

**Pressure maps may not accurately describe corn rootworm abundance for specific fields. Maps can be used as a general guide to help predict abundance over a large area and locate hot spots within the region. Always scout fields to get an accurate assessment of pest pressure.*



Results (Continued)

  - » In all three years, greater CRW pressure was observed if HXRW had been used more than three consecutive years in the same field. If HXRW had been used for more than three years, the distribution of CRW pressure is similar to using non-Bt corn the previous year.
- The average maximum beetle counts per trap were as follows for each previous crop category: Soybeans (4 beetles); Non-Bt corn (27 beetles); 1-2 years HXRW (10 beetles); 3 years HXRW (23 beetles); > 3 years HXRW (27 beetles).
- Beetle counts were used to estimate areas where higher corn rootworm pressure may have been observed in the same year. Yellow and red colored areas (Figure 3) indicate higher pressure areas based on the thresholds used.
  - » The method used predicts the value at a given location by computing a weighted average of known values, in this case the sticky trap values.
  - » All estimated pressure areas are within 10 miles of a sticky trap. The numbers used are that year's maximum weekly sticky trap beetle count.
  - » The shading in these maps show the predicted pressure observed in the current year based on the current year sticky trap numbers.
- While partly dependent on where traps were placed, certain geographies tended to see an increased likelihood of corn rootworm pressure (Figure 3).
- These maps may indicate higher risk zones and areas where consistently moderate to high levels of corn rootworm beetle numbers have occurred (Figure 3).
- Corn rootworm beetle populations can be impacted by specific management activities in individual fields, so its important to monitor corn rootworm beetle populations each season.
- Of the locations that differentiated northern and western corn rootworm beetles, about 34% of those locations had northern corn rootworm beetles present.
- About 35% of the locations did not differentiate the 2 species, so the data were combined to summarize.

Table 1. Percent fields within each beetle pressure category.

Threshold	2016 (n= 773)	2017 (n = 685)	2018 (n = 466)
Low	80.7%	83.1%	88.0%
Medium	10.9%	10.5%	6.9%
High	8.4%	6.4%	5.2%

Conclusions and Discussion

- The percentage of locations with medium to high beetle populations decreased over the past three years (Table 1).
- Whether this trend is reflective of a general decline in beetle populations or simply a result of fewer sticky traps being placed in some of the higher pressure geographies like Kansas and Nebraska in 2018 is unknown.
- Predicting corn rootworm pressure is not an exact science as there are many variables that determine population size the following year.

Conclusions and Discussion (Continued)

- However, one cropping practice that consistently favored higher corn rootworm populations was corn after corn (Figure 2).
- Even when Bt corn products with corn rootworm protection were used, beetle numbers in continuous-corn scenarios exceeded numbers found in corn following soybeans (Figure 2).
- In addition to continuous corn affecting rootworm populations, continuous use of the same corn rootworm trait seems to influence populations as well.
- Growers that used HXRW for three or more years saw an increased chance for higher corn rootworm populations.
- Confirming Cry34/35 resistance in 2018 is an important reminder that corn rootworm populations can and will adapt to Bt corn traits if they are the sole rootworm management tactic.
- These data support the recommendation of not using the same Bt trait in the same field for more than three years in a row.
- Sticky traps have also been used as an indication for the potential need to spray adults to minimize pollination issues or decrease egg load the following season.
- There are many challenges with this practice, including the potential for extended adult emergence, which can limit the effectiveness of a foliar insecticide treatment.
- Figure 3 demonstrates that some areas tend to consistently have moderate to high levels of corn rootworm pressure across years; however, there were many areas where we might have expected higher corn rootworm populations the following year based on trap counts that did not experience that result.
- Even though accurately predicting corn rootworm populations the following year is difficult, the following four indicators can help estimate level of risk:
  1. Multiple years of continuous corn
  2. Lodged corn with significant root feeding
  3. Continuous use of same management tactic
  4. High corn rootworm beetle numbers

Best Management Practices

- There are several best management practices (BMPs) that should be considered for corn rootworm management. Identifying beetle population levels can inform BMP decisions.

Using ***multiple tactics over time*** to keep beetle populations down should be your **primary goal** in *managing corn rootworm!*

- Results from this study demonstrate that crop rotation is the best practice to reduce corn rootworm populations.
- Corn planting dates can also influence population levels: Planting early is preferred to planting late (more attractive to egg-laying adults)
- When rotating to a non-corn host, it is important to keep the field weed free.
  - » Corn rootworms are attracted to weeds that pollinate late in the growing season, especially ragweed and pigweeds, including waterhemp.
  - » Other weeds, including volunteer corn, can diminish the value of rotating as females will lay their eggs in the soybean fields, preparing the next generation for success in corn the following year.
- If low to moderate population levels of corn rootworm beetles were observed in your field, consider the following tactics:
  1. Rotate to another crop.
  2. Plant a non-Bt rootworm product, and use either Poncho® 1250/VOTiVO® insecticide seed treatment or a soil-applied insecticide.
  3. Consider a pyramid Bt corn product (AcreMax Xtreme or SmartStax); i.e., a product with more than one trait for corn rootworm protection.
- If high levels of corn rootworm beetles were observed in your field, consider the following tactics:
  1. Rotate to another crop.
  2. Apply foliar insecticide (potentially multiple applications) to effectively control beetles prior to egg-laying.
  3. Use a pyramid Bt corn product (AcreMax Xtreme or SmartStax).
  4. Consult with your Pioneer sales professional, university extension, crop consultant, or other local experts for recommendations if considering using a Bt corn product and a soil-applied insecticide.

For growers desiring *more corn in their rotation,* a favorable cropping sequence is **2 years of corn** followed by **1 year** of a *rotational crop.*

- The year following rotation should see little corn rootworm pressure, except in higher-risk areas, such as corn rootworm variant zones. In this case, a non-Bt hybrid should be used. Monitor corn rootworm populations in first-year corn to determine the best practice to use in second-year corn.

CRW beetles on a pickup truck next to a corn field.

Acknowledgment

Thank you to the Pioneer Field Agronomy team and Pioneer Sales Representatives for collecting most of the data utilized in this update.

Field Perspectives on Western Bean Cutworm in North America

*by **Ryan Lee, Ph.D.,** Technical Educator,*
*and **Miles Lepping, Ph.D.,** Research Entomologist*

Summary

- Western bean cutworm (WBC) has historically been a secondary pest of corn; however, in favorable environments, it can cause significant economic damage.
- For each larva per plant on average, yield loss estimates have been reported from 4 bu/acre to as much as 15 bu/acre.
- In addition to yield loss, a major consideration for areas with higher ear rot pressure is the risk of reduced grain quality resulting from a western bean cutworm infestation.
- Scouting for eggs and larvae in the crop is the best method to determine the necessity and the timing of a treatment.
- Pheromone trapping, the most common and economical adult monitoring method, provides a highly valuable resource for tracking moth flight.
- When peak moth flight appears to have started, compare this timing to the approaching stage of your corn crop to determine if your fields are likely to be attractive to egg-laying females.
- In areas where WBC is well established, utilize trusted detection methods to time treatments, and rotate insecticide modes of action to limit the risk of pesticide resistance.

"Across much of the corn-producing area of North America, **western bean cutworm** is an occasional, secondary pest of corn; however, in ***favorable environments*** it can cause **significant *economic damage."***

Introduction

The western bean cutworm (WBC) (*Striacosta albicosta*) has garnered broader interest in recent years following its range expansion towards the east (Hutchison et al., 2011) and subsequent adaptation to the Herculex® I trait (Smith et al., 2017). In this article, we provide perspectives on WBC from our colleagues in the field and review management practices for WBC in corn systems.

Across much of the corn-producing area of North America, WBC is an occasional, secondary pest of corn. However, in favorable environments, WBC is a key pest that can cause significant economic damage. Western bean cutworm was first recognized in the early 1900s as a pest of dry beans in the Western U.S. and later discovered in corn production systems. There, it has been managed as a consistent economic threat since the 1960s (Keith et al., 1970). Throughout the 2000s, WBC's range has expanded eastward where it is now a sporadic pest except in areas around the Great Lakes where economic-level damage can occur. Recent mapping of this pest's distribution identifies its range and areas of higher risk for infestation (Figure 1).

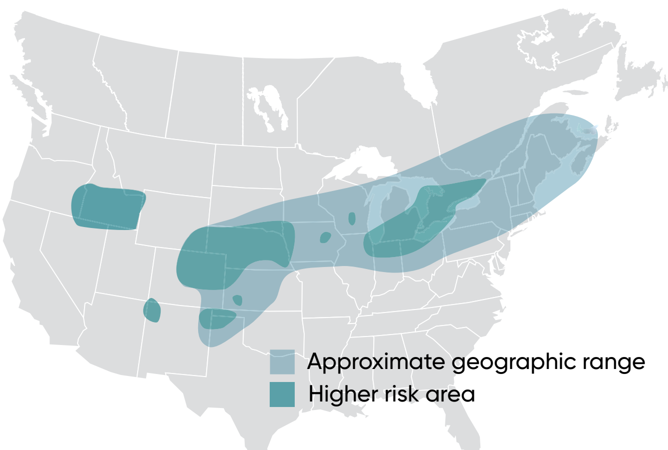


Figure 1. Geographic range of western bean cutworm.

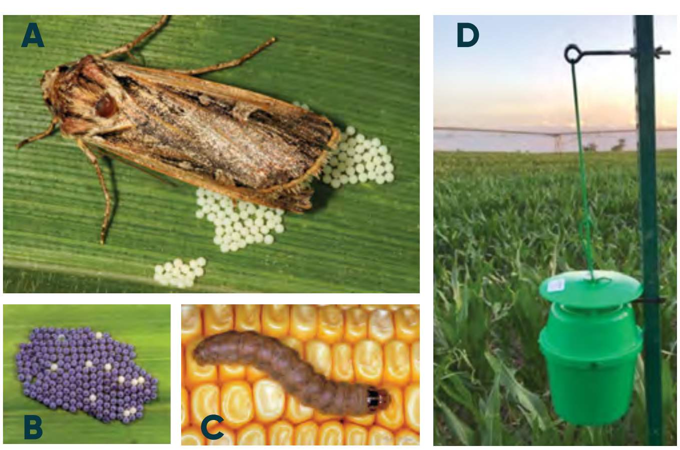


Figure 2. Western bean cutworm female depositing eggs **(A)**; purple eggs indicating imminent hatch **(B)**; mature larva **(C)**; and bucket trap set at 4 ft (1.2 m) above the ground **(D)**.

Life Cycle

Following adult emergence and mating in mid-summer, eggs are primarily laid in the top half of the canopy on the upper surfaces of new whorl leaves in corn. However, egg masses are occasionally found lower in the canopy on leaves near the ear as well as on the underside of leaves – an observation new to the literature. Over five to seven days, eggs progress from white to tan then purple/grey just before hatch (Figure 2). First instars consume the eggshells, thus making post-hatch identification of egg masses difficult (Figure 3).

Pre-tassel, first instars move up the plant to the tassel to feed on pollen before moving back down the plant where they enter the ear either through the tip or boring through the side to feed on kernels. Post-tassel, first instars may immediately bore into the ear to feed on developing kernels. Mature larvae drop off the plant and burrow into the soil where they overwinter as pre-pupae. Larvae can burrow deeper in sandy soils, and minimal tillage practices do not expose the pupae to weather. Both of these factors increase survival and have been proposed as potential drivers of their eastward expansion.

Figure 3. Hatching first instar western bean cutworm larvae consume their remaining egg shell before moving to plant tissue.

Pest Impact

Yield impact remains the primary driver for watching this pest. For each larva per plant on average, yield loss estimates have been reported to reach ~3.7 bu/acre (Appel et al., 1993) to as much as ~15.1 bu/acre (Paula-Moraes et al., 2013) or more (Rice, 2006). In addition to yield loss, a major consideration for areas with higher ear rot pressure is the risk of reduced grain quality resulting from a western bean cutworm infestation. This pest creates holes in the husk, allowing mold and other fungal spores to colonize the ear, reducing grain quality and potentially producing toxins. In areas with consistent ear mold pressure, such as Gibberella or Fusarium, secondary infections may cause greater economic damage than direct yield loss as infected grain can be a concern at the elevator. The threat of downgraded grain can be enough to justify monitoring the crop and treating with insecticides in addition to a fungicide regime.

Bt Corn Management

Pioneer® brand Optimum® Leptra® hybrids contain the Agrisure® Viptera® trait, which expresses the Vip3 protein. This trait helps limit WBC feeding activity and provides a valuable tool within an integrated pest management approach. In areas where hybrids with this trait are available, lepidopteran pest management is partially simplified, although monitoring for unexpected crop damage is recommended to steward these products. Given the limited availability of Bt hybrids for this pest, fine-tuning your approach to managing WBC is key to protecting yield potential. If you select a Bt product, continue to adhere to requirements detailed in the product use guide.

Trapping, Scouting, and Treatment Decision Making

Scouting for eggs and larvae in the crop is the best method to determine the necessity and the timing of a treatment. Naturally, scouting is time consuming, and detection success is complicated by the scattered distribution of insects in the field, when present. To make the best use of scouting resources, concentrate efforts during higher-risk periods by tracking moth flights and crop development stage. It is important to note that crop damage has not been correlated with moth flights. That is, high moth flight counts do not necessarily equate to economic levels of crop damage. Therefore, we look for rapidly increasing counts to indicate when field scouting should begin.

Depending on location, moth flight typically starts in late June, ramps up in July, and continues into August, especially for areas surrounding the Great Lakes. Peak flight tends to start around mid/late-July in most locations. Moth monitoring data for 2017 and 2018 show approximate peak flight periods (Figure 4) with earlier peaks occurring in more southern latitudes, as expected.

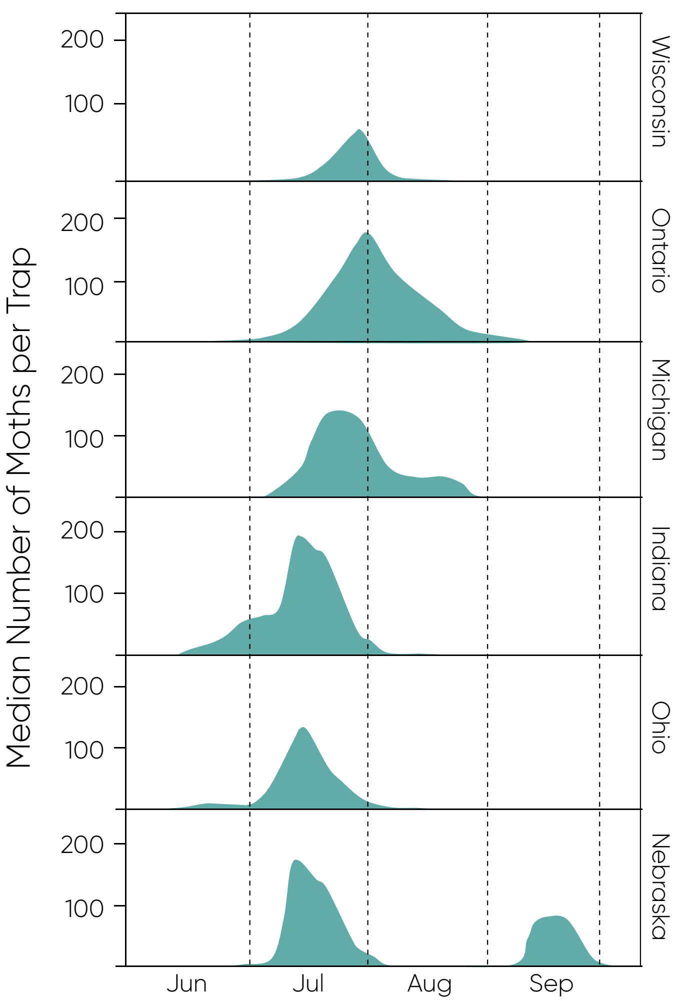


Figure 4. Western bean cutworm pheromone trapping results for 2017 and 2018. Median male moth counts are presented for each state; average counts are shown for Ontario. The second peak shown for Nebraska was observed in 2017.

These plots highlight the relatively long period over which scouting is needed to monitor for the presence of eggs and larvae. The plot for Nebraska showed an apparent second peak in September for trapping stations in the northeast and southwest parts of the state – where traps may have detected that local pest population suppression was achieved until management tactics ceased after August. Guidance from our field experts is for farmers to be aware of the sustained flight period that may translate into the potential need for rescue applications throughout August.

Figure 5. Ear mold colonies established in western bean cutworm feeding sites.

Adult emergence is linked to growing degree days (GDD); thus, the timing of the flight season can vary from year to year (Dorhout, 2007). Predictive methods based on accumulating GDDs can be used to estimate the approximate timing that scouting could begin with the caution that degree day targets may not necessarily align to actual moth flight, especially for more variable environments, such as those in the Great Lakes region (Michel et al., 2010). Variation in seasonal or local weather events can have a significant impact on the timing of moth emergence and flight timing; therefore, we continue to rely on trapping to indicate when the WBC season has begun.

Pheromone trapping, the most common and economical adult monitoring method, provides a highly valuable resource for tracking moth flight. These traps can effectively detect the presence of adult male emergence and general flight activity. While pheromone trapping captures males only, we expect female abundance to track well with male counts as females typically emerge a few days prior to males. While some females may disperse long distances before mating or laying eggs, many females may remain local to mate and then find host plants for egg deposition. If a trap count on your farm suddenly spikes upward over two consecutive trapping dates, it is definitely time to start scouting for eggs over the coming weeks.

In areas where the pest is well-established, the absolute number of moths captured is of less importance than the relative numbers; i.e., are counts increasing, sustaining, or decreasing? When peak flight appears to have started, compare this timing to the approaching stage of your corn crop to determine if your fields are likely to be attractive to egg-laying females or if the risk of infestation is minimal. Even if moth counts do not appear to be peaking yet for your region, consider scouting fields if they are tasseling.

Females prefer to lay eggs in pre-tassel corn in order to synchronize egg hatch and preferred larval feeding on pollen, followed by ear feeding. Therefore, if the crop is in the late-whorl stage and approaching vegetative tasseling (VT) and this coincides with increasing trap counts, the risk of WBC infestation (and therefore potential damage) increases. Once scouting is triggered, we recommend the egg mass scouting method to determine if the action threshold is met. Action thresholds can range from approximately 4 to 8% of sampled plants containing 1 egg mass. Even more proactive thresholds (~2%) have been used where the pest is perennially observed and especially if the risk of ear rot is high.

The recommended scouting method for WBC includes checking 20 plants in at least 5 areas of each field. Inspect each plant from the ear leaf on up, looking for egg masses on the top and even bottom sides of leaves. Look for larvae in the axils as well as on tassels and ears. Late-whorl stage corn is preferred, but plan to scout regardless of stage during a sustained moth flight. The crop will remain attractive to egg-laying moths throughout the season with the risk of economic damage decreasing in the mid-milk stage as kernels are soon to harden as they mature, becoming less susceptible to damage from smaller larvae.

> *"A major consideration for areas with higher ear rot pressure is the risk of reduced grain quality, resulting from a western bean cutworm infestation."*

With significant foliar application campaigns throughout an area, populations may be temporarily suppressed, but given the long period of moth activity, consider scouting fields throughout the season if flight activity continues. In some regions, a second moth peak may take place later in the season. That peak is still part of the same annual generation, but once the majority of insecticide treatments have taken effect, the continued moth pressure is once again seen in the trapping network. These observations are most prevalent in Nebraska and the Great Lakes region where the pest is now a perennial concern. Egg laying later in the season may escape earlier foliar applications and lead to unacceptable levels of ear damage as well as reduced grain quality. In some cases, one application may not provide sufficient protection. A well-timed application is the key to realizing the value of an insecticidal product. Similarly, simply adding an insecticide to an aerial fungicide application may not provide the optimal timing for insect control.

Conclusions

A streamlined approach to monitoring this pest allows for assessment of risk and treatment, if warranted. In areas where WBC is well established, utilize your trusted detection methods to time treatments, and rotate insecticide modes of action to limit the risk of pesticide resistance. The action box (below) reflects key phases to consider in developing your program for this pest. Contact your agronomist, sales representative, consultant, or extension specialist for additional guidance.

INFORM custom *application partners* if you plan to contract services for the coming season.

MONITOR adult flights with *pheromone traps* to decide when to scout.

SCOUT fields for *egg masses and larvae.*

Use **ACTION** thresholds relevant to your risk tolerance to *inform management tactics.*

Acknowledgments

The authors wish to thank field agronomists from Corteva Agriscience™, Agriculture Division of DowDuPont, Pioneer sales representatives, WBC trapping team partners, the Canadian Corn Pest Coalition's western bean cutworm trapping network, and the Integrated Field Sciences Innovation and Continuous Improvement team.

Figure 6. Exit holes made by mature western bean cutworm larvae that will migrate to the soil to overwinter.

Grape Colaspis in Corn

*by **Samantha Teten,** Agronomy Sciences Intern*

Pest Facts and Impact on Crop

- Grape colaspis *(Colaspis brunnea)* is an insect pest that can feed on both corn and soybean as well as numerous other host species.
- Economically significant damage to crops is rare but possible.
- Larvae can cause significant damage to root systems, most commonly in corn, by eating root hairs and mining channels on the root surface. This limits water and nutrient uptake.
- Adults feed on leaves and corn silks but rarely cause economic levels of damage.
- Grape colaspis completes one generation per year in the Corn Belt.
- Seed treatments may help reduce larvae damage to roots.

Pest Identification

Larvae

- Slightly curved, small white body with a tan head
- Approximately $\frac{1}{8}$ to $\frac{1}{6}$ in (3-4 mm) in length
- Resembles a very small white grub
- Has three pairs of short legs and hair bunches on bumps at the underside of the abdomen

Adults

- Oval-shaped beetle of yellow-brown color
- Approximately $\frac{1}{6}$ to $\frac{1}{5}$ in (4-5 mm) long
- Wings have rowed, shallow indentions, which give the beetle a striped appearance.

Grape colaspis larva.

Grape colaspis larvae size in comparison to a penny.

Grape colaspis pupa.

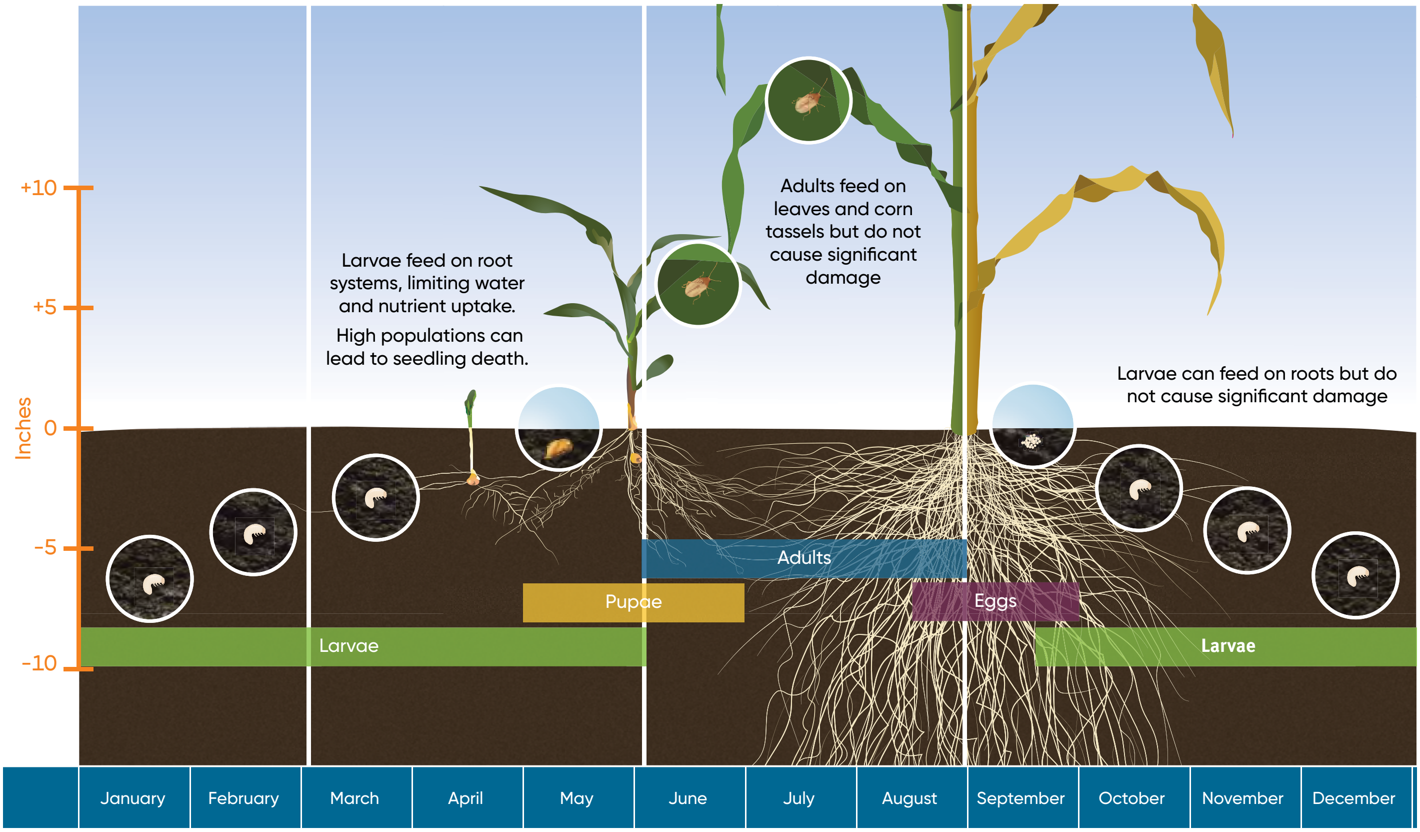
Grape colaspis adult feeding on soybean leaf.

Adult grape colaspis.

Pest Life Cycle

- The grape colaspis completes only one generation per year in the Corn Belt.
- It overwinters as a small larva in the soil at a depth of 8 to 10 in (20-25 cm). Larvae become active early in the spring, feeding on the roots of host plants.
- Root feeding occurs in late May and early June.
- Adults typically emerge between middle to late June and lay eggs from July through early September.
- Adults feed on leaves and silks as well as soybean leaves but do not typically cause economic damage.
- Newly hatched larvae will feed on roots during the fall before moving deeper in the soil profile to overwinter.

Annual Life Cycle of Grape Colaspis in Corn



Pest Symptoms in Corn

- Larvae feed on the root hairs which can cause:
  - » Stunting and wilting
  - » Purpling (from phosphorus deficiency)
  - » Yellowing or browning on the edges of leaves
  - » In extreme cases, plant death and reduced populations
- Injury is more likely to appear early in the season on seedlings, especially if seedling growth is slow due to unfavorable weather or other conditions.

Seedling showing the symptoms of wilting and deficiencies from grape colaspis.

Feeding damage on corn leaf from grape colaspis beetles.

Integrated Pest Management

Favorable Conditions

- Adequate soil moisture during late summer and fall appears to promote higher grape colaspis populations the following season.

Cultural Practices

- Manage the crop to promote early, rapid, and uniform seedling emergence to the extent possible.
- Promote strong root development through fertilization and proper drainage or irrigation.

Chemical Practices

- Seed treatments may help reduce damage.
- Insecticide application in July to control adults has been suggested as a method to reduce populations and limit larvae damage in the subsequent spring but would likely not be practical due to a short application window and population movement.

Common Stalk Rots of Corn

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Anthracnose

Disease Facts

- Caused by *Colletotrichum graminicola,* a fungal pathogen
- Most common stalk disease of corn
- Favored by plant stress following pollination

Identification and Symptoms

- Shiny black coloration on outside of stalk late in the season (Figure 1)
- Internal stalk discoloration (Figure 2)
- Stalk may be easily crushed when squeezed at base.
- Stalk may lodge when pushed sideways.
- For a positive identification of the disease with a hand lens, look for the presence of setae, which are bristle-like hair structures on the stalk surface. Setae are often found within a mucous-like droplet. (Figure 3).

Management

- Crop rotation: At least one year out of corn
- Tillage: Encourages breakdown of crop residue, reducing disease inoculum
- Genetic resistance
    - Pioneer plant breeders select hybrids and parent lines for resistance, using induced and natural infection.
    - Hybrids differ significantly in resistance to anthracnose. Scores for Pioneer® brand hybrids generally range from 2 to 7 on a 1 to 9 scale (9=resistant).

Figure 1. External stalk discoloration caused by anthracnose.

Figure 2. Internal stalk symptoms of anthracnose.

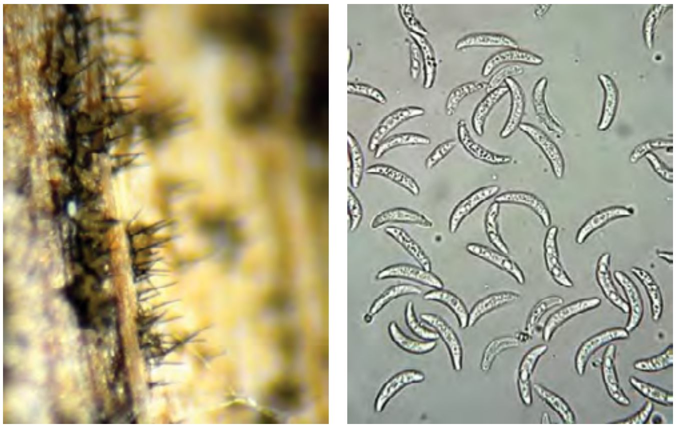


Figure 3. Left – Setae visible on the stalk surface using a hand lens; Right – Curved anthracnose spores as seen under a microscope.

Gibberella

Disease Facts

- Caused by the fungus *Gibberella zeae*
- Ascospores produced in perithecia are disseminated to corn plants by wind and rain splash.
- Insect injury often allows pathogen to enter the plant.
- Can infect corn at the leaf sheaths, brace roots, or roots. Infection continues from roots into lower stem.
- Infection often occurs after pollination. Disease can progress rapidly with warm, wet weather during corn reproductive stages.
- Environmental and physiological stresses may weaken the plant and allow disease development.

Identification and Symptoms

- Rotting at roots, crown, and lower internodes
- Perithecia (small black fungal fruiting structures), may develop on the stalk surface near the node (can be scraped off with fingernail).
- Pink to reddish coloration of pith and vascular strands (Figure 4)
- Pith of the inner stalk may deteriorate, leaving only the vascular bundles intact.
- Destruction of the nodal plate (Figure 4)
- Later stages – plant turns gray-green; internodes turn straw colored or dark brown and are easily pinched between fingers.
- Late-season snapping of stalks at the node (Figure 5)

Management

- Select hybrids with good stalk strength and resistance to leaf diseases. Control leaf diseases with fungicides, if necessary.
- Rotate crops. Corn following soybeans often has less stalk rot and higher yield than continuous corn.
- Use a tillage system that chops and incorporates residue to break it down.
- Soil test and follow fertilizer recommendations; maintain proper nitrogen:potassium balance.

Figure 4. Pink to reddish discoloration characteristic of Gibberella.

Figure 5. Stalk breakage at the node caused by Gibberella.

Fusarium

Disease Facts

- Caused by *Fusarium verticilioides* fungus (formerly called *Fusarium moniliforme*), found everywhere corn is grown
- Overwinters as mycelia in infected crop debris, spread by wind and rain splash
- Can infect the plant directly through the roots, causing root and lower stalk rot. Can also infect at the nodes when dispersed to leaves and washed down into the sheath
- Favored by warm, relatively dry weather, plant stress following pollination, and other diseases
- Disease generally progresses during reproductive stages of corn development.
- Typically occurs in a complex with other root/stalk rots, including Gibberella, Diplodia, and anthracnose.
- European corn borer adults have been shown to vector the disease from plant to plant. Corn borer larvae create wounds that allow the fungus to enter the plant.

Identification and Symptoms

- Rotting at roots, crown, and lower internodes
- When split, inner stalk shows a light-pink to tan discoloration but no black specks (fungal fruiting bodies) in or on the stalk.
- Pith disintegrates; vascular bundles remain intact (Figure 6).
- Stalks feel spongy when squeezed and may be easily crushed or crimped at lower internodes.
- Plants may lodge when pushed sideways or impacted by wind.
- Fusarium may look similar to Gibberella stalk rot and is distinguished by inner stalk color – Fusarium: white/pink/salmon; Gibberella: red/pink (Figure 7).

Management

- Select hybrids with good stalk strength and resistance to leaf diseases. Control leaf diseases with fungicides, if necessary.
- Rotate crops. Do not plant corn after wheat infected with head scab, which is caused by same fungus.
- Use a tillage system that chops and incorporates residue to break it down.
- Reduce stresses when possible; stalk rots are favored by plant stress following pollination.

Figure 6. Disintegrated stalk pith caused by Fusarium.

Figure 7. External and internal fusarium stalk rot symptoms.

Diplodia

Disease Facts

- Caused by *Stenocarpella maydis* fungus (formerly called *Diplodia maydis*). Corn is the only host of this pathogen.
- Survives on corn stalk residues; spores are spread by wind or splashing rain.
- Favored by warm, wet weather two to three weeks after pollination

Identification and Symptoms

- Diplodia stalk rot may first be evident when affected plants die suddenly during mid to late ear fill.
- Upon examination, dark brown lesions can be found extending in either direction from the node.
- Small black spots (pycnidia) may develop just beneath the stalk epidermis near the nodes (Figure 9). The black dots are not easily removed, which distinguishes Diplodia from Gibberella.
- Diplodia results in rotted stalks that are disintegrated and discolored (brown), allowing the stalk to be crushed or easily broken (Figure 10).
- Although the pith disintegrates, vascular bundles remain intact.

Management

- Genetic resistance: Choose hybrids with high scores for stalk strength.
- Crop rotation: At least one year out of corn
- Tillage to help break down crop residue
- Use moderate plant population if field has a history of stalk rot.
- Control stalk-boring insects to prevent wounds stalk rot organisms can enter.

Figure 8. Diplodia stalk rot.

Figure 9. Corn stalk showing Diplodia stalk rot symptoms. Note pycnidia on corn stalk node.

Figure 10. Broken corn stalks due to Diplodia stalk rot infection.

Charcoal Rot

Disease Facts

- Caused by the soil fungus, *Macrophomia phaseolina*
- Charcoal rot begins as a root infection, which spreads into the lower stalk internodes and causes early ripening, shredding, and breaking at the crown of the corn stalk.
- Corn is infected during dry periods where the temperature hits 80 to 85 °F (27-29 °C). The sclerotia germinates on the root surface and penetrates the host epidermal cells of the corn.
- The very tiny black fungal bodies, known as sclerotia, on the vascular strands of the interior of the stalks contained on the shredded pith give them a charred appearance.
- This "charring" of the interior of the stalk contributes to its namesake as it is a distinguishing characteristic of the disease.
- The pathogen overwinters on host crop residue and survives in the soil.

Identification and Symptoms

- Charcoal rot first becomes noticeable when corn is in the tassel stage or later. Upper leaves of the corn will dry out.
- Infected corn plants have shredded stalks, and the pith will have completely rotted, leaving only stringy vascular strands intact.

- The sclerotia of the fungus are small, black, and spherical and are found on and inside the vascular strands, numerous enough to give the internal stalk tissue a grey coloring.
- Translocation of water and nutrients are disrupted due to hyphae of the fungi growing intercellularly through the xylem and into the surrounding vascular tissue.
- The fungus can grow into the lower internode of the stalk as the plant matures, causing plants to ripen prematurely and weaken their stalks, causing breakage.

Management

- Hybrid selection: Use hybrids resistant to Diplodia and Gibberella stalk rot as these tend to offer genetic resistance to charcoal stalk rot as well.
- Crop rotation: Rotation to a non-host crop, such as small grains, can help reduce the disease potential. Many crops are host to this disease besides corn, including soybean, grain sorghum, sunflowers, and other weed hosts.
- Insect management: Controlling insect damage and wounding to the crop will help minimize potential points of infection.

Figure 11. The very tiny black sclerotia on the vascular strands of the shredded pith are a characteristic sign of charcoal rot.

Figure 12. Charcoal rot begins as a root infection, which spreads into the lower stalk internodes, and causes early ripening, shredding, and breaking at the corn crown of the corn stalk. Charcoal rot is favored by heat and drought stress.

Physoderma

Disease Facts

- Physoderma stalk rot and the more commonly observed foliar symptoms known as Physoderma brown spot are both caused by the fungal pathogen *Physoderma maydis*.
- This pathogen was first documented in India in 1910 and in the United States in 1911.
- Historically, Physoderma stalk rot has generally been of little economic importance in the U.S., although instances of severe localized outbreaks have been reported.
- However, prevalence has increased in the U.S. Corn Belt within the last few years, possibly due to wetter conditions early in the growing season.

Identification and Symptoms

- Symptoms of Physoderma stalk rot includes blackening of lower stalk nodes and potentially some stalk rot of the pith, which can result in breakage at the node.
- Physoderma stalk rot can occur in fields in which foliar symptoms (Physoderma brown spot) are not present.
- Plants in which Physoderma stalk rot symptoms are observed are often otherwise healthy with large ears.

Management

- Tillage and crop rotation may be helpful in reducing disease inoculum as the fungus survives in infected crop residue.
- Specific management for this disease is not typically required as the occurrence is sporadic and the effect on yield should be minimal.
- Field observations suggest some variability among hybrid susceptibility to Physoderma stalk rot; however, Pioneer® brand corn products are not currently rated for genetic resistance to this disease.

Figure 13. Stalk breakage and dark lesions on lower nodes of plants affected by Physoderma stalk rot.

Disease Lesion Mimic Mutants in Corn

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Disease Lesion Mimic Mutants

- Disease lesion mimic mutants are a class of mutants in plant species that cause the formation of lesions resembling disease symptoms without the presence of a pathogen.
- Lesion mimic mutants (abbreviated *Les* or *les* to indicate dominant or recessive mutants) are common in plant species.
- Over 50 lesion mimic loci have been identified in the corn genome, and research suggests more than 200 may exist.

Photo courtesy of Michael Wardyn.

Lesion Formation

- The formation of lesions on plant tissue is part of a defense system against attacks by pathogens.
- Lesions are formed when the plant responds to the presence of a pathogen by triggering the rapid death of the cells surrounding the infection site, known as the hypersensitive response.
- This response is an active process in which the cells undergo programmed cell death.
- Lesion mimic phenotypes in plants have generally been attributed to mutations that cause the triggering of the hypersensitive response mechanism independent of the presence of a pathogen or affect the control of this process once it has been initiated (hence the term, disease lesion mimic mutants).
- This is true of some mutations; however, the sheer number of lesion mimic loci in corn and their presence throughout the genome suggest that pathways other than disease response could be involved as well.
- Recent research has shown that lesion mimic phenotypes can be caused by mutations associated with a variety of pathways.

Appearance of Lesion Mimics

Frequency and Timing

- Lesion mimic mutations do not occur at high frequencies, so symptoms will often appear on an individual plant surrounded by unaffected plants.
- The majority of lesion mimic mutants in corn will begin expressing visual symptoms within a few weeks of emergence.
- A smaller number of lesion mimic mutants will show up around the time of tasseling.
- Symptoms can appear similar to those of a residue-borne foliar disease because they can begin on the lower leaves and spread up the plant.

Phenotypes

- Phenotypes associated with lesion mimic mutants vary in the size, number, and color of lesions.
- In most cases, lesions appear only on leaf tissue, but some mutants will produce lesions on the leaf sheath and stalk.

Photo courtesy of Michael Wardyn.

Factors Affecting Phenotypic Expression

Light and Temperature

- Expression of lesion mimic mutants is often light and temperature dependent with intense light and high temperatures often favoring higher levels of expression. Low night temperatures are also known to favor expression in some cases.

Field Conditions

- Expression of lesion mimic mutants appears to be favored by saturated soils and environmental stresses. Symptoms tend to be observed more frequently in corn following corn and in irrigated fields.

Hybrid Genetics

- Hybrid genetics are known to have a large influence on the expression of lesion mimic mutants, although symptoms have been observed in numerous hybrids from multiple seed companies.

Management Considerations

- Yield of affected plants can be reduced due to the loss of photosynthetically active leaf area. Yield impact varies based on the amount of leaf area affected.
- Since symptoms are caused by a genetic mutation and not a fungal pathogen, fungicides have no effect.
- Lesions can often resemble those caused by various fungal and viral diseases of corn. A diagnostic lab can test a sample to determine whether or not the symptoms are due to a pathogen.

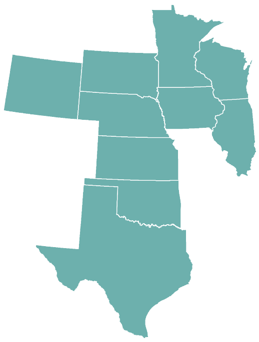
Photo courtesy of Michael Wardyn.

Bacterial Leaf Streak in Corn

by ***Samantha Teten,*** *Agronomy Sciences Intern*

Disease Facts

- Caused by the bacterium *Xanthomonas vasicola pv. vasculorum.*
- First identified in 2016 in Nebraska corn field.
- Currently confirmed in 10 states: Nebraska, Colorado, Illinois, Iowa, Kansas, Minnesota, South Dakota, Oklahoma, Texas, and Wisconsin
- Can be found in field corn, seed corn, popcorn, and sweet corn.
- Plant does not have to be injured for disease to enter the plant. Bacterium can enter plant through stomatal openings.
- Bacterial inoculum overwinters on plant residue and causes symptoms on several host plants.
- Many diseases look similar to bacterial leaf streak, so it is recommended to confirm disease through a diagnostic laboratory.
- A different but closely-related pathogen affects sorghum, *Xanthomonas vasicola pv. holcicola.*



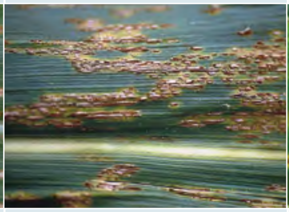
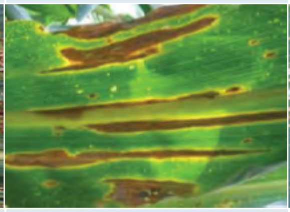
Symptoms and Impact on Crop

Symptoms

- Narrow tan, yellow, brown, or orange lesions that have a bright yellow halo when backlit.
- Lesions can extend to several inches long and stay in between leaf veins (interveinal).
- Edges of the lesions are wavy and have a jagged appearance. This is one of the biggest distinguishing features from other diseases.
- Lesions can also appear greasy or water-soaked.
- Symptoms often appear on the bottom leaves of a plant and travel upwards. Can start in the upper canopy, often after large rain event.

Impact on Corn Yield

- Extent of potential damage or yield loss is currently unknown.
- Expected losses are minimal as long as extensive symptoms are not present before or during grain fill.

Bacterial Leaf Streak	Gray Leaf Spot	Common Rust	Diplodia Leaf Streak	Southern Corn Leaf Blight
Bacterial	Fungal	Fungal	Fungal	Fungal
Long lesions with a wavy edge	Rectangular lesions that have very straight sides	Often more oval or circular in shape	Lesions are mostly oval to elongated.	Lesions are rectangular to oblong in shape
When backlit, has a translucent appearance with a yellow halo	Light does not shine through easily (more opaque)	Appear dark when leaf is backlit	Lesions have bright yellow edges, especially when backlit	Appears tan in color
Will exhibit bacterial streaming under a microscope	Can have dark, finger-like fungal structures	Lesions are raised above leaf surface.	Often contain black pycnidia (fungal fruiting structures) embedded in leaf tissue	Lack of uniformity makes it difficult to identify. Laboratory testing can help differentiate
				
Photo courtesy of Jennifer Chaky	*Photo courtesy of Steve Butzen*	*Photo courtesy of Dan Wilkinson*	*Photo courtesy of Jennifer Chaky*	*Photo courtesy of Gary Munkvold*

Factors Favoring Bacterial Leaf Streak

Weather

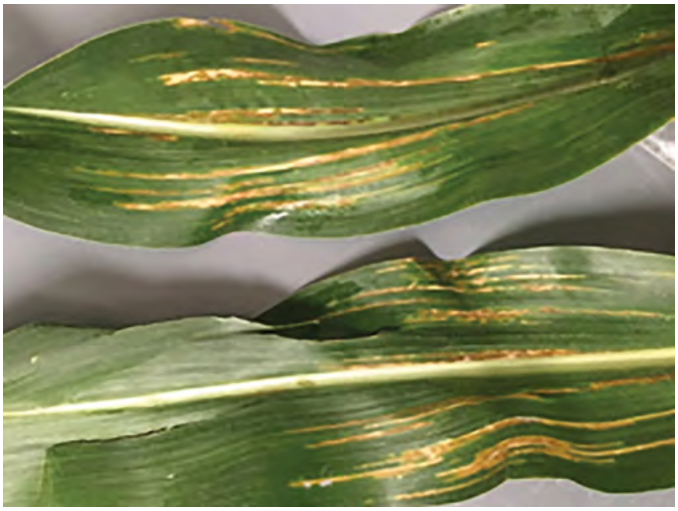
- Warm conditions with a high relative humidity.
- Can withstand cooler temperatures (different from gray leaf spot) and can be found as early as V4 in corn.
- Thought to be spread by wind-driven rain and overhead irrigation.

Management Systems

- More common in continuous corn fields but has been found in other rotation systems, particularly those that include another host crop.
- Favored by minimum tillage systems where inoculum can remain on residue.

Plant species that display symptoms of bacterial leaf streak and are potential disease hosts:

- **Crops:** Corn, oats, and rice
- **Prairie grasses:** Big bluestem, little bluestem, indiangrass, orchardgrass, and timothy
- **Weeds:** Green foxtail, bristly foxtail, and yellow nutsedge



Photos courtesy of Jennifer Chaky

Disease Management

- Proper identification of the disease is crucial since it cannot be treated by chemical controls unlike many similar-appearing diseases.
- Minimize continuous exposure to the crops and weeds that have been identified as susceptible hosts to bacterial leaf streak.
    - » Control volunteer corn, which can serve as a host.
    - » Proper weed management and pasture grass control.
- Harvest infected fields last to reduce the spread of inoculum.
- Tillage and residue management are possible considerations.
- There appears to be some variability among corn hybrids in susceptibility to bacterial leaf streak.

Photo courtesy of Mike Wardyn; near Elsie, NE, June 26, 2018.

Tar Spot in Corn in the Midwestern U.S.

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Causal Pathogen and Occurrence in the U.S.

- Tar spot is a relatively new disease of corn in the Midwestern U.S., first appearing in Illinois and Indiana in 2015 (Bissonnette, 2015; Ruhl et al., 2016) and subsequently spreading to Michigan, Wisconsin, and Iowa (Figure 1). Its presence was also confirmed in Florida in 2016 (Miller, 2016).
- Tar spot in corn is caused by the fungus *Phyllachora maydis,* which was first observed in high valleys in Mexico.
- *P. maydis* has not typically been associated with yield loss by itself; however, it can form a complex with another pathogen, *Monographella maydis*, the combination of which is referred to as tar spot complex. In Mexico, the tar spot complex of *P. maydis* and *M. maydis* has been associated with yield losses of up to 30% (Hock et al., 1995).
- In some cases, a third pathogen, *Coniothyrium phyllachorae*, has been associated with the complex
- Only *P. maydis* is known to be present in the United States.
- Tar spot reappeared in 2016 and 2017 but remained a relatively minor cosmetic disease of little economic concern.
- In 2018, however, it became much more severe with significant outbreaks reported in Illinois, Indiana, Wisconsin, Iowa, and Michigan.

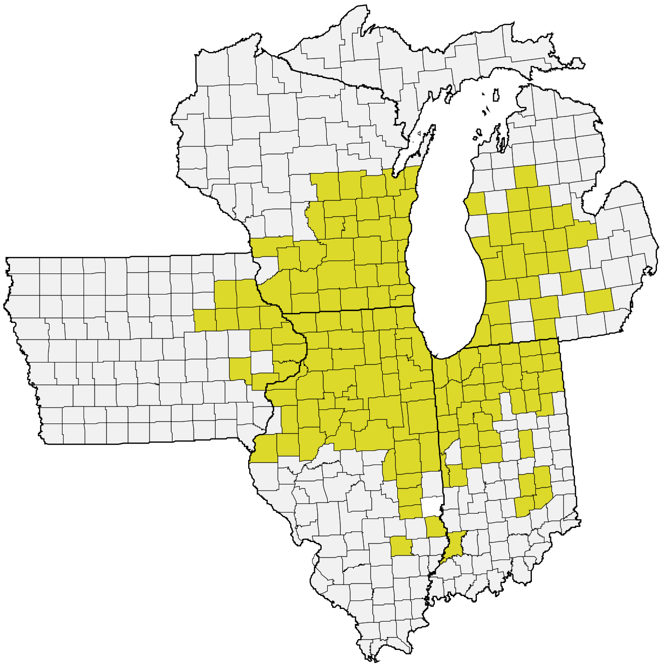


Figure 1. Counties with confirmed incidence of tar spot as of October 2018 (University of Illinois, Purdue University, University of Wisconsin, Iowa State University, and Michigan State University Extension).

Identification and Symptoms

- Tar spot is the physical manifestation of fungal fruiting bodies, the ascomata, developing on the leaf.
- The ascomata look like spots of tar, developing black oval or circular lesions on the corn leaf. The texture of the leaf becomes bumpy and uneven when the fruiting bodies are present.
- These black structures can densely cover the leaf and may resemble the pustules of rust fungi (Figure 2).
- Tar spot spreads from the lowest leaves to the upper leaves, leaf sheathes, and eventually the husks of the developing ears (Bajet et al., 1994).
- *P. maydis* alone produces small, round, dark lesions; *M. maydis* causes a brown necrotic ring around the *P. maydis* ascomata. Together, they produce the characteristic "fish-eye" symptom of tar spot complex (Figure 3).
- Under a microscope, *P. maydis* spores can be distinguished by the presence of eight ascospores inside an elongated ascus, resembling a pod containing eight seeds (Figure 4).

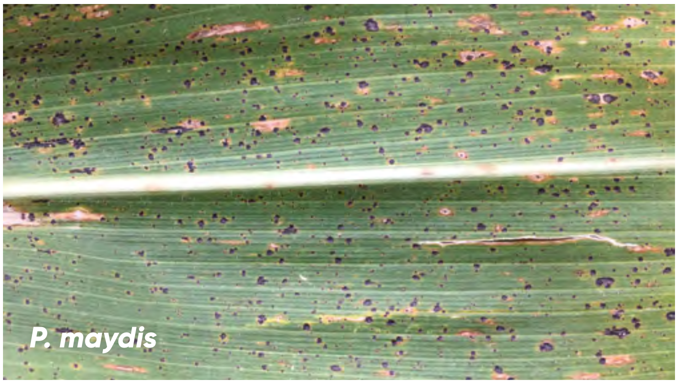


Figure 2. A corn leaf with symptoms of *P. maydis* (tar spot).

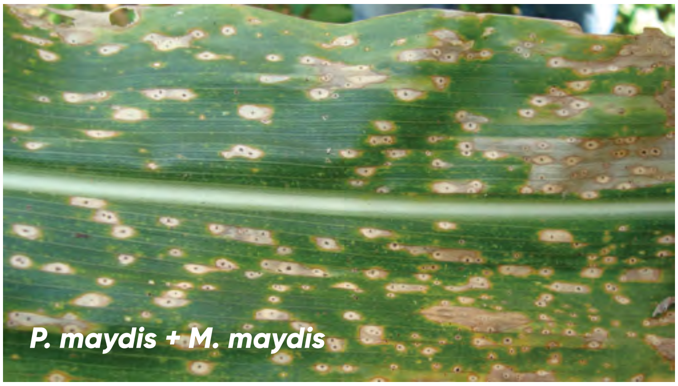


Figure 3. A corn leaf demonstrating "fish-eye" symptoms of tar spot complex (*P. maydis* + *M. maydis*).

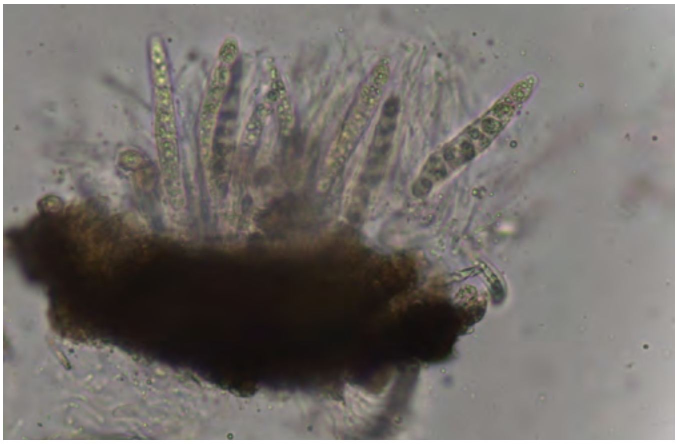


Figure 4. Microscopic view of fungal spores of *P. maydis*.

Tar Spot Arrival in the U.S.

- Numerous reports have speculated that *P. maydis* spores may have been carried to the U.S. via air currents associated with a hurricane in 2015, the same mechanism believed to have brought Asian soybean rust to the U.S. several years earlier.
- However, Mottaleb et al. (2018) believe that this scenario is unlikely and that it is more plausible that spores were brought into the U.S. by movement of people and/or plant material.
  - » Ascospores of *P. maydis* are not especially aerodynamic and are not evolved to facilitate spread over extremely long distances by air.
  - » Tar spot was observed in corn in Mexico for over a century prior to its arrival in the U.S., during which time numerous hurricanes occurred that could have carried spores into the U.S.
- Chalkley (2010) notes that *P. maydis* occurs in cooler areas at higher elevations in Mexico, which coupled with its lack of alternate hosts would limit its ability to spread across climatic zones dissimilar to its native range.
- Chalkley also notes the possibility of transporting spores via fresh or dry plant material and that the disease is not known to be seedborne.
- The risk of importation of the second pathogen associated with tar spot complex, *M. maydis*, into the U.S. via people and/or materials is believed to be high (Mottaleb et al., 2018).

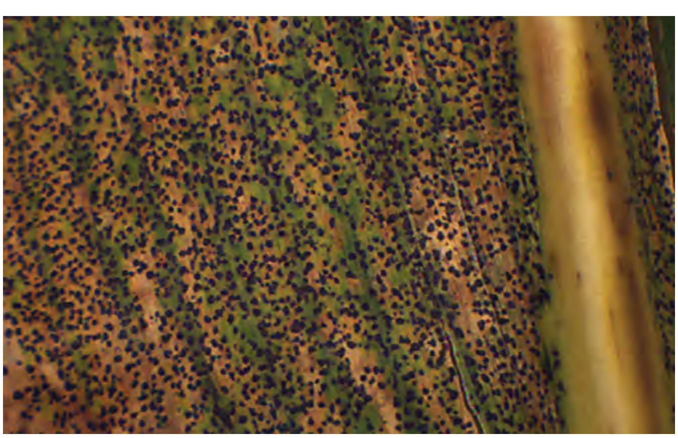


Figure 5. Corn leaf under magnification showing dense coverage with tar spot ascomata.

Tar Spot Epidemiology

- Much remains unknown about the epidemiology of tar spot, even in its native regions, and especially in the U.S.
- *P. maydis* is part of a large genus of fungal species that cause disease in numerous other species; however, *P. maydis* is the only *Phyllachora* species known to infect corn, and it appears to only infect corn (Chalkley, 2010).
- Tar spot has been reported every year since its initial confirmation, which suggests that *P. maydis* is overwintering in the Midwestern U.S.
- *P. maydis* is favored by cool temperatures (60-70 °F, 16-20 °C), high relative humidity (>75%), frequent cloudy days, and 7+ hours of dew at night.
- It appears to have windborne spores and tends to release them in periods of high humidity.
- So far, *M. maydis* has not been detected in the U.S.
  - » "Fish-eye" lesions, consistent in appearance with those caused by tar spot complex in Mexico, were observed in some Midwestern fields in 2018 (Smith, 2018; personal observation).
  - » *M. maydis* was not detected in association with fish-eye symptoms in these cases. The cause of the fish-eye symptoms and why they showed up in some fields but not others remains undetermined.

Figure 6. Corn leaves infected with tar spot in a field in Stephenson Co., IL; September 1, 2018. Tar spot was prevalent in this field, but symptoms appeared late in the season when senescence was already beginning. Stalk lodging was minimal in this field, and yield data suggested that tar spot likely had little to no impact.

Management Considerations

Yield Impact

- The potential yield impact of tar spot in corn in the Midwestern U.S. is undetermined at this point.
- Anecdotal reports associated tar spot infection with yield loss and increased rates of stalk lodging; however, weather conditions were highly conducive for foliar diseases, reduced stalk quality, and stalk rots in many areas in 2018, so it is not clear how much tar spot may have caused or exacerbated these issues relative to other factors.

Differences in Hybrid Response

- Observations in hybrid trials in 2018 showed that hybrids differed in severity of tar spot symptoms (Kleczewski and Smith, 2018).
- The extent to which differences in leaf symptoms may correspond to differences in yield is unknown at this time.
- Pioneer agronomists and sales professionals collected data on disease symptoms and hybrid performance in locations where tar spot was present in 2018 and will use those findings to assist growers with hybrid management in 2019.

Fungicide Treatment

- Research in Mexico has shown that fungicide treatments can be effective against tar spot (Bajet et al., 1994), although no fungicides are currently labeled for tar spot control in the U.S.
- Efficacy of fungicides in managing tar spot in the Midwestern U.S. is still undetermined. University trials were conducted in 2018 and will continue in 2019 to help determine if and how fungicides may be used to help manage tar spot.

Tillage and Rotation

- The pathogen that causes tar spot appears to be overwintering in corn residue but to what extent the amount of residue on the soil surface in a field affects disease severity the following year is unknown.
- If spores are able to disperse over large distances within a region (also unknown), local effects of crop residue in continuous corn and/or reduced tillage systems may be relatively inconsequential.

Mycotoxins

- There is no evidence at this point that tar spot causes ear rot or produces harmful mycotoxins (Kleczewski, 2018).

Will Tar Spot Continue to Spread in the U.S.?

- Mottaleb et al. (2018) used climate modeling based on long-term temperature and rainfall data to predict areas at risk of tar spot infection based on the similarity of climate to the current area of infestation.
- Model results indicate the areas beyond the current range of infestation at highest risk for spread of tar spot are central Iowa and northwest Ohio.
- Results indicate the potential for further expansion to the north and south but primarily to the east and west, including New York, Pennsylvania, Ohio, Missouri, Nebraska, South Dakota, eastern Kansas, and southern Minnesota.

Figure 7. Corn husk and leaf with tar spot symptoms (Stephenson Co., IL; September 1, 2018).

Water and Nutrient Uptake During the Corn Growing Season

*by **Stephen Strachan, Ph.D.,** Global Program Leader,*
*and **Mark Jeschke, Ph.D.,** Agronomy Manager*

Summary

- Soil must provide adequate quantities of 13 of the 16 nutrients essential for high grain yields.
- In addition, soil must release these nutrients quickly enough to meet daily high nutrient demands of the corn plant during the V6 to R1 growth stages.
- The greatest nutrient demand occurs at V6 to R1 when the corn plant is: (1) generating new tissue to complete vegetative growth; (2) creating the harvestable ear; (3) supporting ear growth in preparation for pollination and grain fill; and (4) storing additional nutrients in vegetative tissue as a reserve to supply nutrition to the ear during the latter portion of grain fill.
- Rates at which soil-supplied nutrients enter the corn plant depend on nutrient bioavailability in soil, nutritional demand of the corn plant, and the amount of water transpiring through the corn plant.
- Daily extraction of nutrients from soil during R3 to R6 is considerably less than daily nutrient extraction during V6 to R1 due to the sharp decline in new root growth beginning around VT.
- The corn plant compensates for this limited nutrient extraction from soil by transferring nutrients stored in vegetative plant tissue.

Introduction

Sixteen elements are essential for corn growth (Salisbury and Ross, 1978). The soil supplies thirteen. The surrounding atmosphere and soil water supply the remaining three – carbon, hydrogen, and oxygen. Table 1 summarizes the estimated total nutrient content in harvested grain when corn yield is 300 bu/acre. Research at Iowa State University has shown that nutrient concentration in corn grain remains relatively constant across a wide range of yields (Mallarino et al., 2011). One can estimate nutrient removal per acre of soil for a particular grain yield by multiplying the amount of nutrient extracted in lbs/bu (Table 1) by the desired or observed grain yield in bu/acre. Values listed in Table 1 include only nutrient amounts in the grain. During the growing season, the corn plant must extract additional nutrients from the soil to supply the vegetative part of the corn plant. Estimated amounts of several nutrients in grain plus stover to support a 300 bu/acre corn yield are shown in Table 2.

Table 1. Nutrient content per bushel of corn grain and total amounts of nutrients removed from the field when grain yield is 300 bu/acre.

Nutrient	Content per Bushel* (15.5% moisture)	Total Removal 300 bu/acre
	lbs/bu	lbs
Nitrogen (N)	0.615	184.5
Phosphorus (P_2O_5)	0.428	128.4
Potassium (K_2O)	0.273	81.9
Sulfur (S)	0.0506	15.18
Magnesium (Mg)	0.0733	21.99
Calcium (Ca)	0.0132	3.96
Iron (Fe)	0.00168	0.504
Zinc (Zn)	0.00126	0.378
Boron (B)	0.00028	0.084
Manganese (Mn)	0.00023	0.069
Copper (Cu)	0.00015	0.045
Molybdenum (Mo)	Trace	Trace
Chlorine (Cl)	Unknown	Unknown

* Source: Heckman et al., 2003.

Table 2. Estimated amounts of selected nutrients in corn at maturity to support a 300 bu/acre grain yield.

Nutrient*	Nutrient Content per Bushel of Grain: Grain	Stover	Total	Total Uptake: 300 bu/acre Corn Crop
	lbs/bu			lbs/acre
N	0.67	0.45	1.12	336
P_2O_5	0.35	0.16	0.51	153
K_2O	0.25	1.10	1.35	405
Mg**	0.09	0.14	0.23	69
S	0.08	0.07	0.15	45

* Source: IPNI, 2014.
** Source: IPNI, 2008.

Barber and Olson (1968) published research to illustrate quantities of macronutrients and micronutrients that corn plants remove from soil to support a grain yield of 150 bu/acre (Table 3). Corn hybrids in these studies are from approximately 50 years ago. Although grain yields have improved substantially over the past 50 years, estimated quantities of nitrogen, phosphorus, potassium, magnesium, and sulfur to support grain yields of 300 bu/acre with hybrids from 50 years ago (Table 3) are similar to the amounts of these same nutrients to support corn yields of 300 bu/acre in today's hybrids (Table 2).

Table 3. Estimated amounts of selected nutrients in corn at maturity to support a 300 bu/acre grain yield for hybrids produced before 1968 based on the 1968 nutrient concentrations for 150 bu/acre corn.

Nutrient*	Nutrient Content of a 150 bu/acre Corn Crop: Grain	Stover	Total	Total Nutrient Content of a 300 bu/acre Corn Crop
	lbs/acre			
N	115	55	170	340
P_2O_5	64	16	80	160
K_2O	42	169	211	422
Ca	1.3	35	36.3	72.6
Mg	10	29	39	78
S	11	8	19	38
Cl	4	68	72	144
Fe	0.10	1.80	1.9	3.8
Mn	0.05	0.25	0.3	0.6
Cu	0.02	0.08	0.1	0.2
Zn	0.17	0.17	0.34	0.68
B	0.04	0.12	0.16	0.32
Mo	0.005	0.003	0.008	0.016

*Source: Barber and Olson, 1968.

In addition, the corn plant must extract supplemental nutrients to support root growth. Nutrient contents of roots are not included in this analysis. During the growing season, corn plants must extract approximately 336 lbs of nitrogen (N), 153 lbs of potassium (P_2O_5), 405 lbs of potassium (K_2O), 69 lbs of magnesium (Mg), and 45 lbs of sulfur per acre to support a grain yield of 300 bu/acre. In this article, we shall focus on nitrogen, phosphorus, and potassium and explore how nutrient uptake relates to water uptake during the life cycle of the corn plant. As we develop a better understanding of nutrient and water uptake, we may discover one or more potential factors that limit grain yield.

Daily Nutrient Uptake in Corn

Iowa State University (Ritchie et al., 1997) and the University of Illinois (Bender et al., 2013) have published two documents that illustrate daily nutrient uptake of nitrogen, phosphorus, and potassium from the soil as a function of corn growth stages during the growing season. Figure 1 contains estimated averages of nutrient uptake at key corn growth stages based on information presented in these research reports.

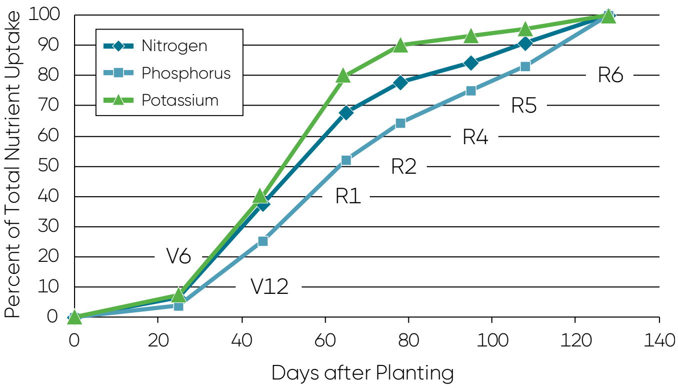


Figure 1. Estimated uptake of nitrogen, phosphorus, and potassium from the soil at critical corn growth stages. Estimates from ISU and University of Illinois research.

Information presented in Figure 1 is converted to a pounds/acre/day basis to illustrate quantities of nitrogen, phosphorus, and potassium uptake from the soil estimated to support a corn grain yield of 300 bu/acre (Figure 2).

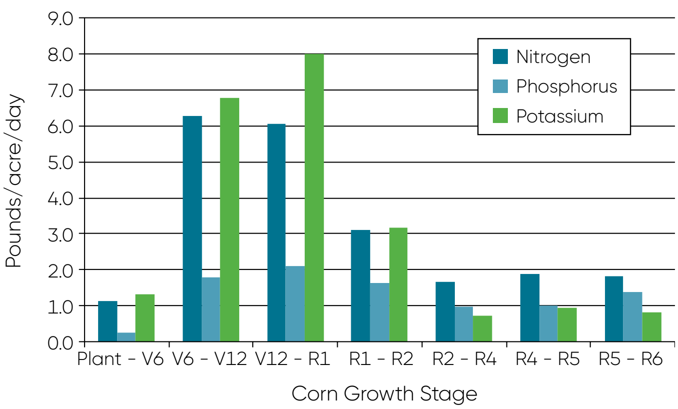


Figure 2. Estimated uptake of nitrogen, phosphorus, and potassium from the soil required to support a grain yield of 300 bu/acre at different corn growth stages.

Maximum grain yields require that nutrient supply continuously meets crop demand. From planting to V6, the corn seedling first relies on the nutrient reserve in the seed to initiate seedling growth. As seedling roots become established, the corn plant extracts nutrients from the soil. Nutrient demand from planting to V6 is low because the corn plant is small and crop demand is low.

Figure 3. Dissected corn plant at the V6 growth stage. Three ear shoots are visible at lower nodes. The primary ear shoot has been initiated at this stage but is not visible without magnification.

Photo courtesy of Iowa State University.

The physiology of the corn plant changes dramatically and nutrient demand increases substantially during V6 to V12. For many hybrids, initiation of the harvested ear begins at about V6 (Abendroth et al., 2011) (Figure 3).

Daily nutrient supply from V6 to V12 is supporting initial growth and development of the harvested ear. In addition, the plant is increasing greatly in size and stature. Daily nutrient supply is supporting the demand to feed substantial growth in leaf and stalk structures. New leaves subsequently provide photosynthetic factories that supply sugar to the grain. An ample supply of sugar to the grain creates maximum opportunity to convert sugar into harvestable starch.

Physiological processes initiated at V6 to V12 continue from V12 to R1. At about V10 to V12, initial formation of the harvestable ear is complete and the maximum number of ovules that can mature to produce harvestable grain is established (Figure 4). Maximum yield potential in terms of harvestable kernels per plant is established. The majority of daily nutrient supply during V12 to R1 is consumed by the ear; ovules require food, cob growth must increase to provide space for all ovules, and ear development continues to prepare for and support pollination. Nutrients are also consumed to complete the formation of the vegetative portion of the plant. In addition, the corn plant is extracting nutrients from the soil and storing these nutrients in vegetative tissue. Stored nutrients are later released between about R3 to R6 to support the final phases of ear growth and development.

Figure 4. Dissected corn plant at the V12 growth stage. Eight ear shoots are visible at this stage, including the primary ear shoot.

Photo courtesy of Iowa State University.

Daily nutrient uptake from the soil slows dramatically between R1 and R2. At this growth phase, nutrients support the growth of fertilized embryos that eventually become harvested kernels of grain. Fertilized embryos consume as many nutrients and as much sugar as they can on a daily basis. If nutrient or sugar supply is limited, embryos toward the base of the ear continue to consume these nutrients while fertilized embryos toward the tip of the ear starve. Fertilized embryos, starting at the tip of the ear and working toward the base of the ear, will starve and die if daily nutrient, sugar, and water supplies are insufficient to support growth of the entire ear.

Figure 5. Dissected corn plant at the R1 growth stage (left) and developing ears (above).

Photo courtesy of Iowa State University.

Daily extraction of nutrients from soil continues during R3 to R6 but is considerably less than daily nutrient extraction during V6 to R1. This seems counter-intuitive because nutrient demand to support kernel growth is very high from R3 to R6. Corn root growth mirrors vegetative corn shoot growth. Corn roots are close to their maximum size at about VT, and new corn root growth slows dramatically (Ordóñez et al., 2018). Young, newly formed corn roots are responsible for the majority of nutrient uptake from soil. Very little new root growth between R3 and R6 causes corn to have a relatively low ability to extract additional nutrients from soil. The corn plant compensates for this limited nutrient extraction from soil by transferring nutrients stored in vegetative plant tissue (the main stalk and older leaf tissues) to the ear. From an agronomic perspective, good early vegetative growth is a critical requirement for high corn yields. Nutrients stored in vegetative tissues are later moved to the ear to feed latter-stage kernel growth. If corn plant growth during vegetative stages is stunted, it is highly likely that late-season growth will also be poor, resulting in lower grain yield.

Daily Water Uptake During the Growing Season

Researchers at Iowa State University published a document showing an average of the daily rate of corn plant transpiration and evapotranspiration for 35 environments (Licht and Archontoulis, 2017). This information is summarized

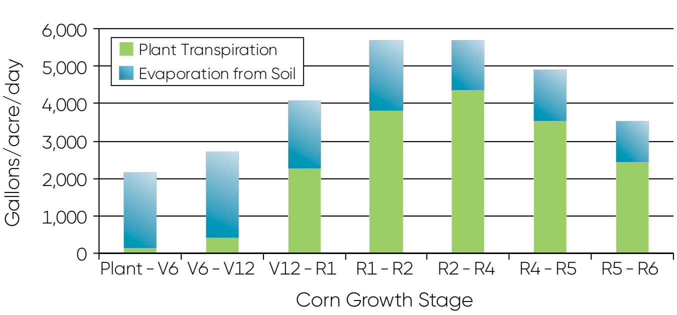


Figure 6. Evapotranspiration of water in gallons/acre/day to support corn growth in Iowa during different stages of corn growth.

in Figure 6. Some of us like to think in terms of gallons of water per acre while others like to think in terms of acre-inches of water. This same information is presented in terms of acre-inch per day in Figure 7. One acre-inch of water is equivalent to 27,154 gallons of water evenly distributed across an acre.

Seasonal evapotranspiration is highly dependent on environmental conditions. For example, the higher temperatures and drier climates of north Texas and Kansas require higher evapotranspiration rates than the generally cooler and more humid climates of Iowa and Minnesota, and sunny windy days require more evapotranspiration than cloudy, calm days. The green bars in Figures 6 and 7 illustrate the amount of water that enters and passes through the corn plant. As water moves from soil into corn roots, nutrients dissolved in this water also enter corn roots. Soil water movement into the corn plant influences the daily flux of nutrients from soil into the plant.

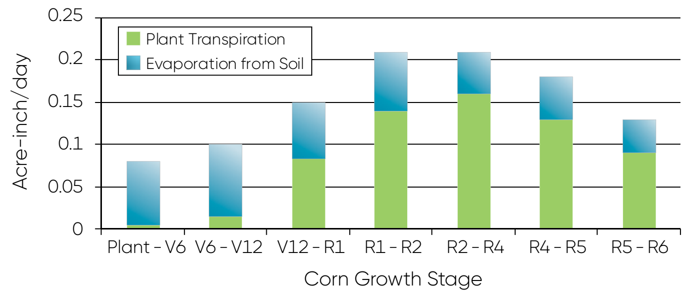


Figure 7. Evapotranspiration of water (acre-inch basis) to support corn growth in Iowa during different growth stages.

Daily Nutrient Flux During the Growing Season

Nutrient flux is the amount of nutrient dissolved in a unit of soil water that enters the corn plant every day. Figure 8 shows the daily nutrient flux of nitrogen, phosphorus, and potassium into corn at different growth stages.

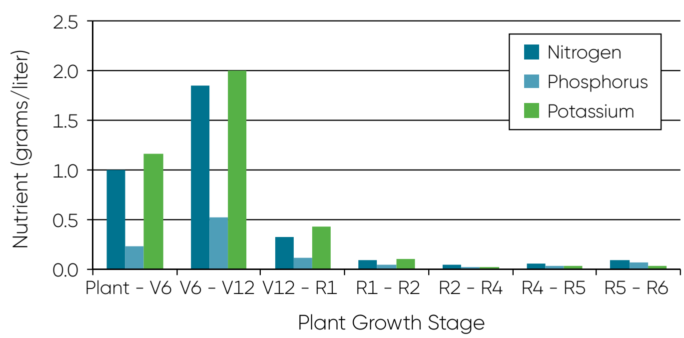


Figure 8. Estimated amounts of nutrient flux to support a corn grain yield of 300 bu/acre under environmental conditions based on Iowa weather data.

Nutrient flux is greatest during the vegetative growth phase. This is consistent with the physiology of corn growth. Corn roots must "mine the soil" for nutrients. Roots must penetrate new portions of the soil profile as they grow to extract nutrients. Newly formed roots are most efficient for nutrient uptake. Root growth mirrors shoot growth, so the formation of new roots is most prevalent during vegetative growth. Nutrient influx is particularly high during V6 to V12 when new root growth is most prolific. Nutrient flux during the late vegetative phase is about 10 to 20 times greater than nutrient flux during ear fill. Figure 9 shows a more detailed look at changes in nutrient flux during grain fill.

The greater amounts of nutrient flux during R1 to R2 are probably residual effects of new root growth as corn plants switch from very late vegetative stages to very early reproductive growth stages. Between R2 and R6, nutrient flux increases as the corn plant approaches physiological maturity (R6). This increase in nutrient flux from R5 to R6 may be due to the decrease in water uptake during R5 to R6. Nutrient uptake of nitrogen, phosphorus, and potassium between R2 and R6 tends to be linear during this growth interval, so total nutrient demand on a daily basis will change little during this growth interval (Figure 1). However, the daily water uptake tends to decrease as the corn plant progresses from R2 to R6 (Figure 7). As the corn plant matures, similar total amounts of nutrients are entering the corn plant daily, but less water enters the corn plant daily. During the latter growth stages, water must contain higher concentrations of nutrients (Figure 9).

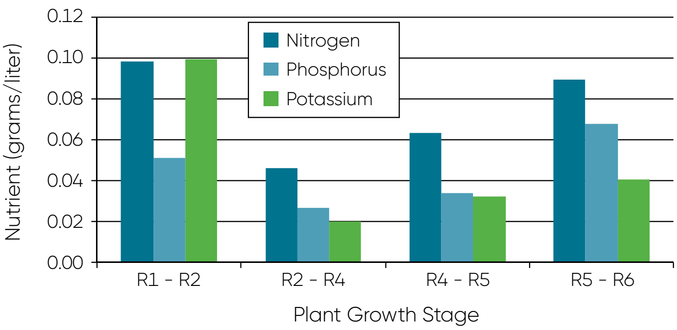
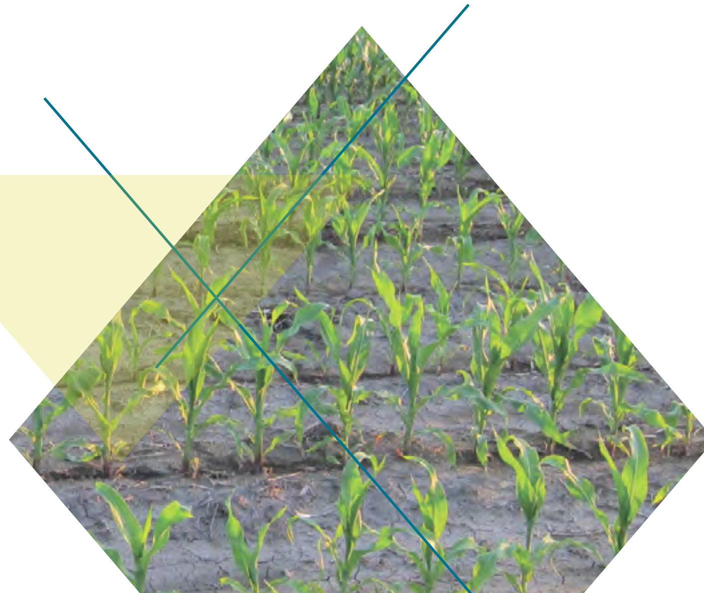


Figure 9. Estimated amounts of nutrient flux during ear fill to support a corn grain yield of 300 bu/acre under environmental conditions based on Iowa weather data.

Based on these observations, the soil must meet two nutritional requirements to support high corn grain yields. First, the soil must provide adequate amounts of all soil-applied nutrients to support grain yield. Years of comparing soil test results with grain yields have established recommended ranges of nutrients in soil to support desired yield levels. A proper soil test program is therefore essential to achieve maximum corn grain yield. Second, the soil must release these nutrients rapidly enough to meet the demand of nutrient flux into the corn plant, especially during the vegetative and very early reproductive growth stages. Nutrients must be bioavailable and readily extractable from soil. For example, Pioneer researchers have shown that multiple nitrogen applications to corn in smaller amounts during the periods before emergence to early brown silk (about R2) improve corn grain yield and increase the efficiency of nitrogen fertilizer relative to a single pre-plant broadcast application of a large amount of nitrogen fertilizer (French et al., 2015). In these studies, nitrogen use efficiency increased from 1.3 pounds of N per bushel of corn to 0.8 pounds of N per bushel of corn. Perhaps similar results can be obtained with potassium, phosphorus, and other nutrients supplied by the soil. One problem with nutrients other than nitrogen is that currently no easy and economical method exists to "spoon-feed" these nutrients through an irrigation system or apply these nutrients as fertilizer in tall, non-irrigated corn.

Summary

Soil must feed corn plants daily to provide all of the necessary soil-applied nutrients in proper amounts to support high grain yields. For example, the soil must provide approximately 336 pounds of nitrogen, 153 pounds of phosphorus (P_2O_5), 405 pounds of potassium (K_2O), 69 pounds of magnesium, and 45 pounds of sulfur per acre to support a grain yield of 300 bu/acre. In addition to supplying total amounts of nutrients, the soil must also supply these nutrients rapidly enough on a daily basis to meet the high flux demand during V6 to R1. During this interval, corn roots must extract sufficient nutrients to: (1) complete vegetative growth; (2) support ear growth in preparation for pollination and grain fill; and (3) store additional nutrients in vegetative tissue as a reserve to supply nutrition to the ear during late grain fill. If nutrient demand exceeds nutrient supply, this stress response will probably appear in the ear. Depending on when nutrient supply is limiting, ear response could be a reduction of kernel rows along the ear, tip kernel die-back, and/or reduced individual kernel weight. Whole corn plant response could be vegetative tissues showing nutrient deficiencies, decreased stalk strength, or a higher incidence of stalk diseases. All of these responses reduce potential grain yield. A thorough diagnostic of corn ear and plant responses near harvest provide the basic information to alter appropriate agronomic and production practices to mitigate or eliminate these yield-robbing responses in future production cycles.



Unsaturated Water Flow and Nutrient Uptake in Corn

by ***Stephen D. Strachan, Ph.D.,***
Global Program Leader, and
Mark Jeschke, Ph.D.,
Agronomy Manager

Summary

- Soil must provide adequate quantities for 13 of the 16 nutrients essential for high grain yields.
- Soil water carries these nutrients from the soil matrix to corn roots for nutrient uptake.
- Water movement during nutritional uptake occurs via unsaturated flow, a slow-moving process in which corn roots pull water and nutrients from the soil into corn roots.
- Chemical constituents in the corn root produce osmotic and matric forces that pull water from micropores in soil into the corn root.
- There are three mechanisms for plant nutrient uptake from the soil: mass flow, diffusion, and root interception.
- Mass flow and diffusion are responsible for the majority of nutrient uptake and are both dependent upon the presence of water in contact with the soil surface and the corn root.
- Newly-formed, rapidly-growing corn roots are responsible for nearly all nutrient uptake from soil. Maximum grain yields, therefore, require that newly-formed corn roots, plant-available nutrients, and ample water capable of unsaturated flow are present in the same slice of soil at the same time throughout each day of the growing season.

Introduction

Soil must supply an estimated 336 pounds of nitrogen, 153 pounds of phosphorus (P_2O_5), and 405 pounds of potassium (K_20) per acre to the corn plant to support a grain yield of 300 bushels per acre (IPNI 2014). In addition to this total seasonal demand, soil must also supply these nutrients rapidly enough to properly feed the corn plant daily during the highest nutrient-demanding growth stages from V6 to R1 (Figure 1) and at sustainable rates during the rest of the growing season (Strachan and Jeschke, 2018). Water carries these nutrients and all other soil-supplied nutrients as the corn plant pulls water from the soil profile into the corn root. A better understanding of how water moves in the soil profile may provide added insight regarding soil fertility. This article discusses how plant-available water moves in soil as the soil provides water and associated nutrients to feed the plant.

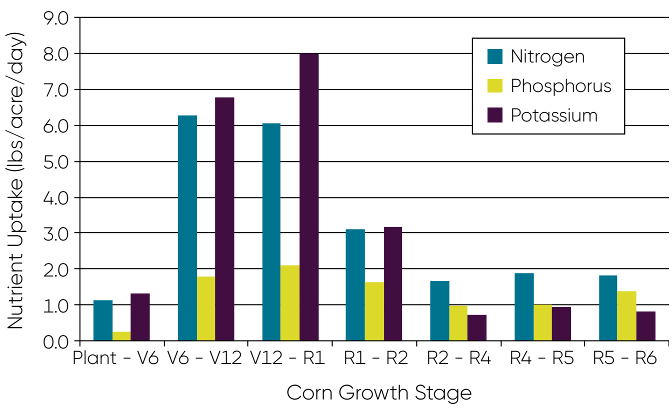


Figure 1. Estimated uptake of nitrogen, phosphorus, and potassium from the soil required to support a grain yield of 300 bu/acre at different corn growth stages.

Water Moves via Saturated Flow and via Unsaturated Flow in the Soil Profile

Behavioral characteristics of water movement in soil change dramatically as soil water content decreases from saturated soil conditions through plant-available water conditions to plant-wilting water conditions (Hillel, 1980). Immediately after a saturating rainfall or an irrigation event, very nearly all soil micropores and macropores near the soil surface fill with water, and water moves via saturated flow. Rate of water infiltration into the soil profile depends on soil porosity. Soil porosity is a function of soil texture, structure, and bulk density. These three physical characteristics of soil determine the amount and size of macropores and connective channels that enable water flow.

During saturated flow, water moves as a singular mass over and through the soil profile. Water movement at this stage is much like water flowing down a stream. Farmers have spent billions of dollars shaping the land and adding waterways to allow surface water to withdraw from a field while mitigating soil erosion resulting from this moving mass of water and even more money to tile the soil to remove excess water from the plant root zone. During saturated flow as water soaks into the soil, this water moves as a series of continuous bands deeper into the soil profile (Figure 2).

Saturated flow is responsible for removing excess water from the soil profile. This water is not available for plant uptake. Unless rainfall or irrigation is excessive, saturated flow occurs for approximately the first day after the rainfall or irrigation event until conductive forces of soil colloids to hold water in the soil profile negate the force of gravity to pull water through the soil profile. The soil is at field water-holding capacity when the osmotic and matric forces produced by soil colloids and chemicals associated with soil colloids are in balance with the force of gravity (Figure 2C). Subsequent movement of water is only via unsaturated flow until the next rainfall or irrigation event.

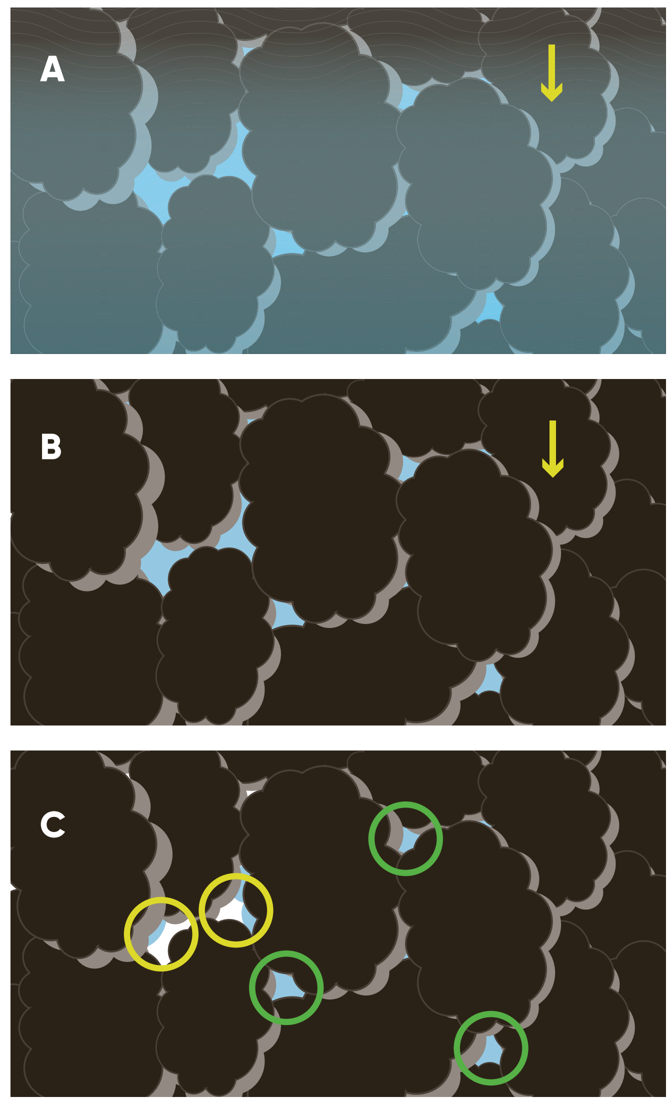


Figure 2. Saturated flow of water. (A) Immediately after rain or irrigation, gravity pulls surface water as a series of bands down through the soil. (B) After water enters the soil profile, gravity continues to pull water downward until the macropores drain. (C) The soil is at field capacity when micropores are filled with water (green circles) and macropores (yellow circles) are drained. Soil micropores contain water available for plant uptake.

During unsaturated flow, water moves like water in a sponge. Micropores in the sponge retain water. An external force stronger than the force of retention in sponge micropores must be expressed for water to move from saturated micropores to different locations in the sponge. It is, therefore, possible to simultaneously have a portion of the sponge wet while another portion of the sponge is dry. This same phenomenon is true in soil. Chemical constituents in the corn root produce osmotic and matric forces that pull water from micropores in soil into the corn root (Figure 3).

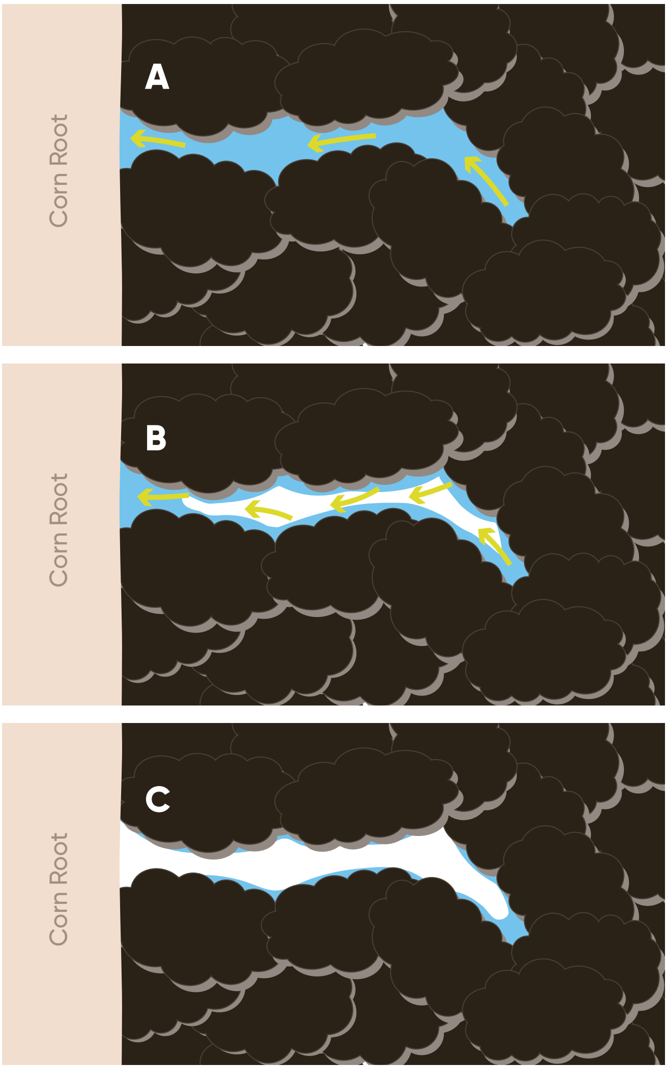


Figure 3. Unsaturated water flow from soil to the corn root. (A) Chemical constituents in the corn root pull water from filled micropores toward the corn root. (B) As corn roots remove water from soil, centers of micropores empty first because these water molecules are least tightly held by the pulling forces of soil colloids. (C) Eventually, pulling forces of soil colloids equal or exceed pulling forces of the corn root. When this occurs, the corn plant can no longer extract water from the soil, and the plant wilts.

Unsaturated flow in soil moves water very slowly. Pulling forces of corn roots are only slightly stronger than pulling forces of soil colloids when soil is at field capacity. This slightly greater strength originating from corn roots pulls water toward the roots. As water molecules are removed from soil, these water molecules move along the edges of soil colloids. Although a direct path from the soil to the root may be very short, the tortuous path that water molecules follow can be relatively long. When enough water is removed, pulling forces originating from soil colloids negate pulling forces originating from corn roots, and the corn plant no longer can pull enough water into the plant to sustain growth. Water content of the soil has then reached the wilting point. When this occurs, corn plants wilt and show moisture or drought stress. The last remaining water in the soil is hygroscopic water, which is a thin layer of water held tightly to soil particles that cannot be taken up by plants. Figure 4 illustrates the different moisture levels and how water moves at each of these moisture levels for a well-granulated silt loam soil (Brady, 1990).

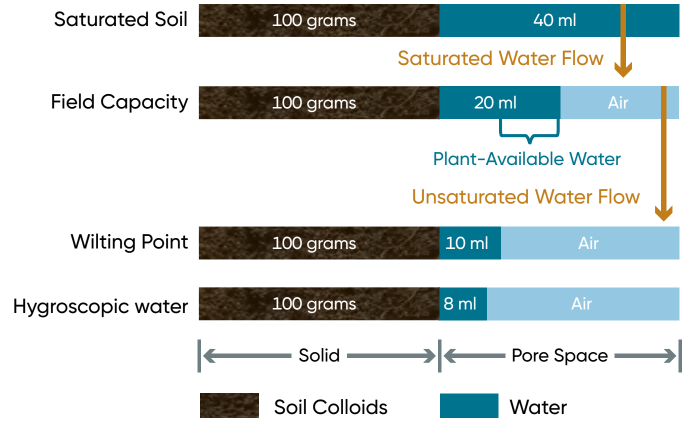


Figure 4. Volumes of water and air associated with soil pores in 100 grams of well-granulated silt loam soil.

Soil Physical Structure and Cation Exchange Sites Influence Nutrient Mobility

Essentially all water movement from the point of field capacity to the wilting point is via unsaturated flow. We need to understand where the nutrients are within the soil structure to understand better how nutrients flow toward

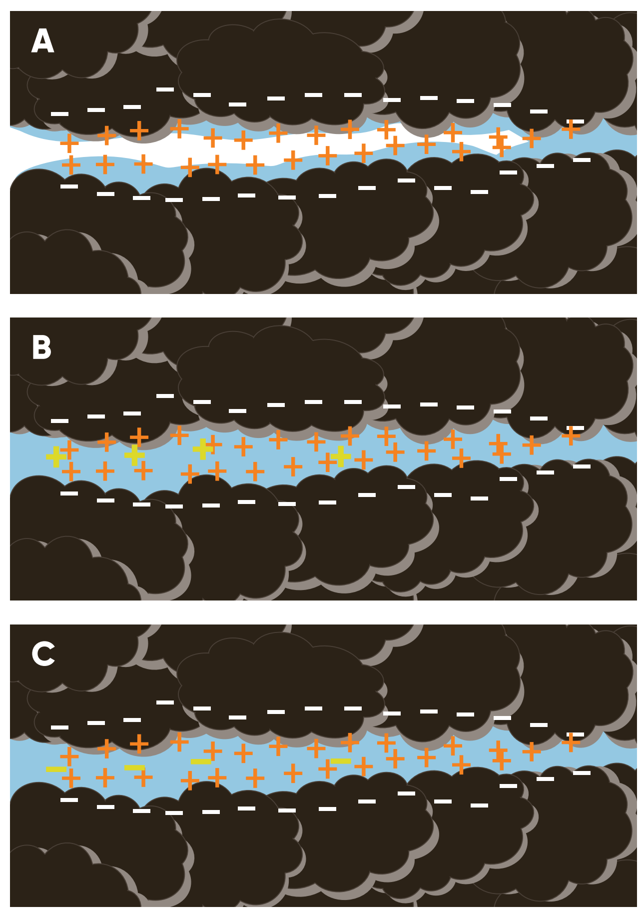


Figure 5. Cation exchange sites influence locations of cations and anions in the soil water phase. (A) When soils are relatively dry, cations associate very closely with net negative charges of colloidal surfaces. (B) As soil moisture content increases, some cations (represented by yellow +) tend to diffuse into the water until a new equilibrium is established. (C) Anions (represented by yellow -) are repelled by the net negative charge of colloidal surfaces but are attracted to the positive charges of cations next to colloidal surfaces.

the corn root. Electrostatic charges of cation exchange sites and the physical structure of the soil influence the solubility and mobility of nutrients in soil water (Hillel, 1980). Cation exchange sites on soil colloids and soil organic matter have net negative charges dispersed along surfaces of the colloids (Figure 5).

Soils cycle from saturated to very dry water conditions. When soils are relatively dry, cations in soil water associate very closely with net negative charges on colloidal surfaces to form an electrostatic double layer (Figure 5A). As soil moisture content increases, cations diffuse farther into soil water as they evenly spread ion concentrations throughout the soil water phase. Anions are repelled by the net negative charge of colloidal surfaces but are attracted to positively charged cations near these colloidal surfaces. Nutrients in soil tend toward a dynamic equilibrium between nutrients dispersed in water available for plant uptake and water associated very closely with colloidal surfaces. Cations, anions, and their salts have limited solubility in water. As the water content in the soil decreases, cations and anions may precipitate out of the soil water phase to form complex hydrated salts. Nutrients contained in these hydrated salts dissolve back into the plant-available soil water solution as the soil water content increases and as corn roots remove nutrients already dissolved in this plant-available water.

Nutrient mobility is related to water solubility of the nutrient and nutrient charge. Cations are highly associated with net negative charges of cation exchange sites and are more difficult to remove from these colloidal surfaces. In addition, if the water solubility of the cation is very low, very few cations will be in the plant-available water phase. Cations tend to be immobile in soil because it requires a lot of water to move a substantial amount of a cation (Table 1).

Table 1. Essential nutrients for plant growth, forms available for plant uptake, and relative mobility in soil water.

Nutrient	Plant-Available Form(s)	Soil Mobility
Nitrogen	NO_3^- NH_4^+	Mobile Immobile
Phosphorus	HPO_4^{2-}, $H_2PO_4^-$	Immobile
Potassium	K^+	Somewhat mobile
Sulfur	SO_4^{2-}	Mobile
Calcium	Ca^{2+}	Somewhat mobile
Magnesium	Mg^{2+}	Immobile
Boron	$B(OH)_3$, $B(OH)_4^-$	Very mobile
Chlorine	Cl^-	Mobile
Copper	Cu^{2+}	Immobile
Iron	Fe^{2+}, Fe^{3+}	Immobile
Manganese	Mn^{2+}	Mobile
Molybdenum	MoO_4^-	Somewhat mobile
Zinc	Zn^{2+}	Immobile

The slow mobility of water during unsaturated flow also influences nutrient mobility and root uptake by the corn plant (Figure 6). As the corn root pulls water from the pore, nutrients closest to the corn root are extracted from the soil. This method of nutrient uptake is called *mass flow* because nutrients move with the mass of water that enters the root.

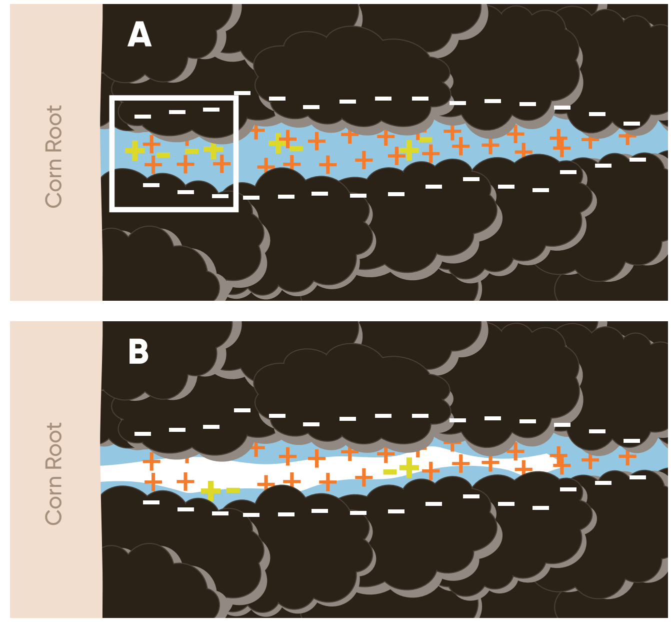


Figure 6. Nutrient mobility and uptake from soil micropores. (A) With unsaturated water flow, nutrients closest to corn roots (highlighted in the white box) move with the soil water. These nutrients are most available for plant uptake. (B) As water is pulled from the pore, water deeper in the pore moves toward the surface edge of the pore, and nutrients located within this water become more tightly associated with these pore surfaces. Nutrients in this water fraction are less available for plant uptake.

Another process for nutrient uptake is called *diffusion*. For diffusion, nutrients are present at higher concentrations in water very near surfaces of soil colloids or as hydrated salt complexes that have precipitated on colloidal surfaces. Some of these nutrients diffuse into water farther from the colloidal surface. If this water is near a plant root, the plant root then extracts this nutrient from the water. Diffusion is active over short distances only – no more than about ¼ of an inch. Diffusion is the major route for phosphorus uptake into corn roots. For both processes – mass flow and diffusion – to work, water must be present and in contact with the soil surface and the corn root.

As the corn root extracts water from the micropore, water deeper in the pore drains from the center of the pore and moves closer to pore colloidal surfaces. Nutrients associated with this deeper water also move toward these colloidal surfaces and are less available for plant uptake.

A third mechanism of nutrient uptake, called *root interception*, does not directly depend on soil water but rather involves direct contact between growing roots and soil colloids, leading to the absorption of nutrients. Root interception is an important means of uptake for certain nutrients but contributes less to overall nutrient uptake than the other two mechanisms (Table 2).

Table 2. Mechanisms of plant uptake for soil nutrients (Barber, 1984).

Nutrient	Mass Flow	Diffusion	Root Interception
	%		
Nitrogen	99	1	0
Phosphorus	6	91	3
Potassium	20	78	2
Calcium	71	0	29
Magnesium	87	0	13
Sulfur	95	0	5
Copper	98	0	2
Zinc	33	33	33
Boron	97	0	3
Iron	52	37	11
Manganese	80	0	20
Molybdenum	95	0	5

Nutrient Availability and Mobility Must Meet Corn Nutrient Flux Demand for Maximum Yield

Nutrients strive to maintain a dynamic equilibrium between plant-unavailable, plant-available, and water-soluble forms in the soil profile (Figure 7). Typically, the conversion of nutrients from a form not available to plants to a form available to plants is a slow process. This is partly why soils must be fertilized with nutrients in a plant-available form to maximize corn grain yield. The conversion of nutrients from a plant-available to a water-soluble form is a much more rapid process. Once the nutrient is soluble in water, it is readily available for root uptake. The key to obtaining maximum grain yield is to have sufficient amounts of water-soluble and plant-available nutrients in supply to meet corn root demand throughout the entire growing season. This is particularly important during the vegetative and early reproductive growth stages (Figure 8).

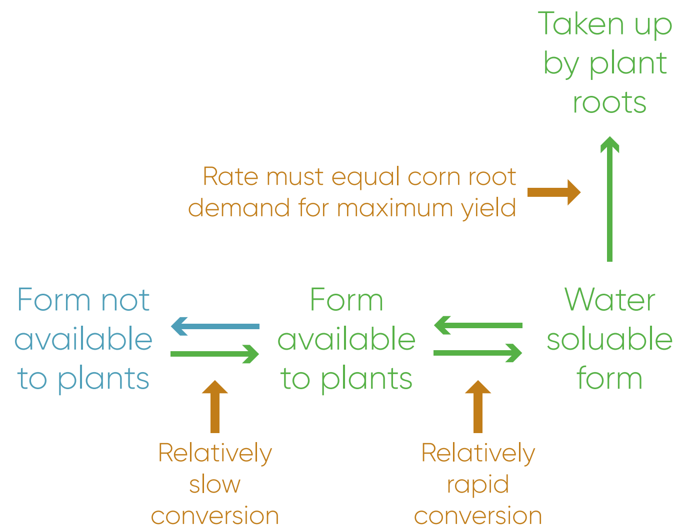


Figure 7. Different forms of plant nutrients in the soil.

Newly-formed, rapidly growing corn roots are responsible for nearly all nutrient uptake from soil. Maximum corn yields, therefore, require that newly-formed corn roots, plant-available nutrients, and ample water capable of unsaturated flow are present in the same slice of soil at the same time throughout each day of the growing season.

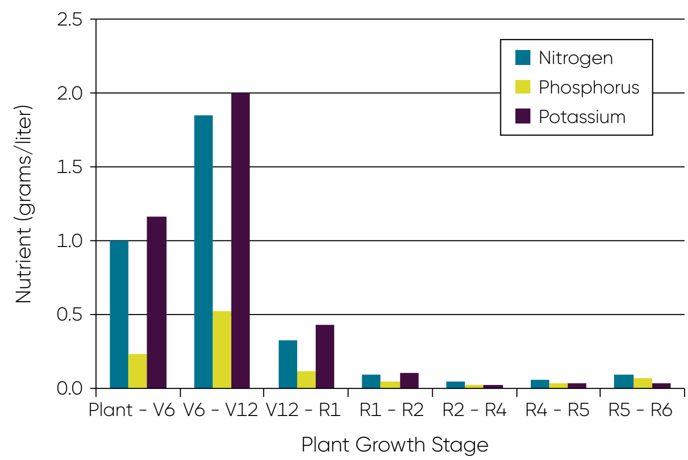


Figure 8. Estimated amounts of nutrient flux to support a corn grain yield of 300 bu/acre under environmental conditions based on Iowa weather data.

Analytics of *Nitrogen Management with Encirca® Services*

*by **Andy Heggenstaller, Ph.D.,** Encirca Services Commercial Unit Lead,*
***Eugenia Munaro, Ph.D.,** Scientist - Crop Modeling, **Phil Bax,** Agronomy Science Lead, Granular,*
*and **Bob Gunzenhauser,** Agronomy Science Lead, Granular*

Summary

- Nitrogen is one of the most uncertain and costly corn production inputs. Because soil nitrogen varies dynamically in response to weather, it is not possible to know in advance the optimal nitrogen application to achieve desired yield levels for any year or location.
- Nitrogen Management with Encirca® services incorporates a simulation model that predicts changes in soil nitrogen in response to interactions between weather, soils, crop growth, and management.
- Encirca services analytics bring together industry-leading, high resolution soils and weather information developed by Pioneer through strategic collaborations.
- Encirca services nitrogen analytics simulate the major processes that affect soil nitrogen, including crop growth, nitrogen mineralization, leaching, denitrification, and volatilization.
- Encirca services nitrogen analytics make use of historical and forecasted weather information to visualize the risk associated with management decisions and to generate variable rate nitrogen recommendations that minimize risk of profit loss and unnecessary fertilization.

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 most used guidelines for nitrogen management. Neither of these approaches account for how variability in soils and weather affect crop growth as well as 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.

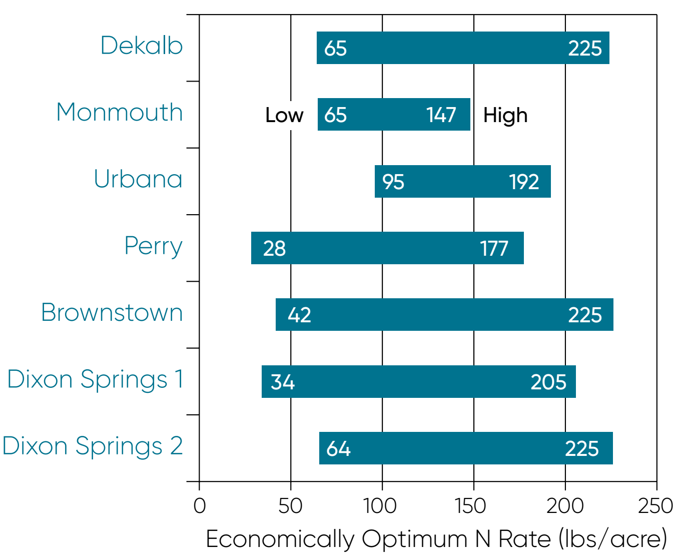


Figure 1. Variability in corn economic optimum nitrogen fertilization rate observed over six years at seven locations in Illinois (adapted from Nafziger et al., 2008).

Encirca® Services Nitrogen Model

Nitrogen Management with Encirca services is based on a suite of crop and soil models developed by 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).

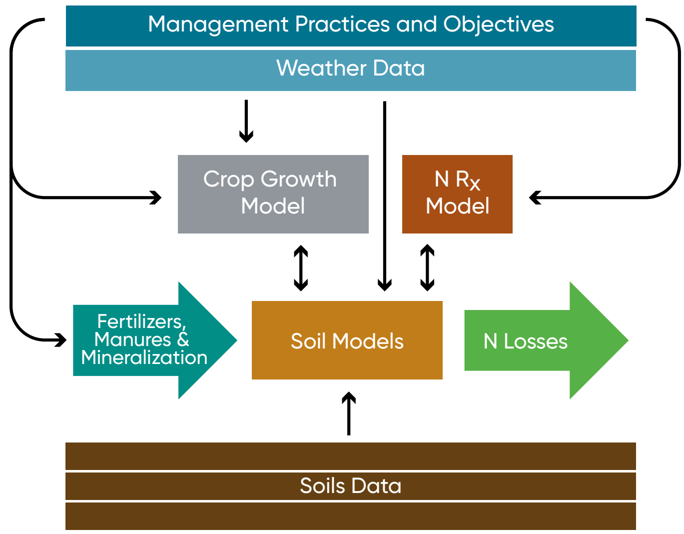


Figure 2. Schematic representation of the inputs and models comprising Encirca services nitrogen analytics.

Inputs for Encirca Services Nitrogen Model

Weather Data

The Encirca services nitrogen model is updated daily with high-resolution weather data from the industry-leading weather network of The Weather Company (TWC). TWC accesses over 250,000 global weather stations and provides high-quality forecasts and current conditions at resolutions as high as 0.5 kilometers.

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 within fields based on high-resolution digital elevation data and provide a more precise definition of the field-scale hydrological, physical, and chemical attributes that drive productivity as well as 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 Nitrogen Management with Encirca services as well as utilize their as-planted data to include accurate hybrid, planting rate, and date information.

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. This includes indicating whether a nitrification or urease inhibitor has been used to potentially reduce nitrogen losses.

Components of Encirca Services Nitrogen Model

Crop Growth and Nitrogen Uptake

One of the core components of 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 specific to individual Pioneer® brand hybrids and controlled by the relative maturity for other brands of corn hybrids.

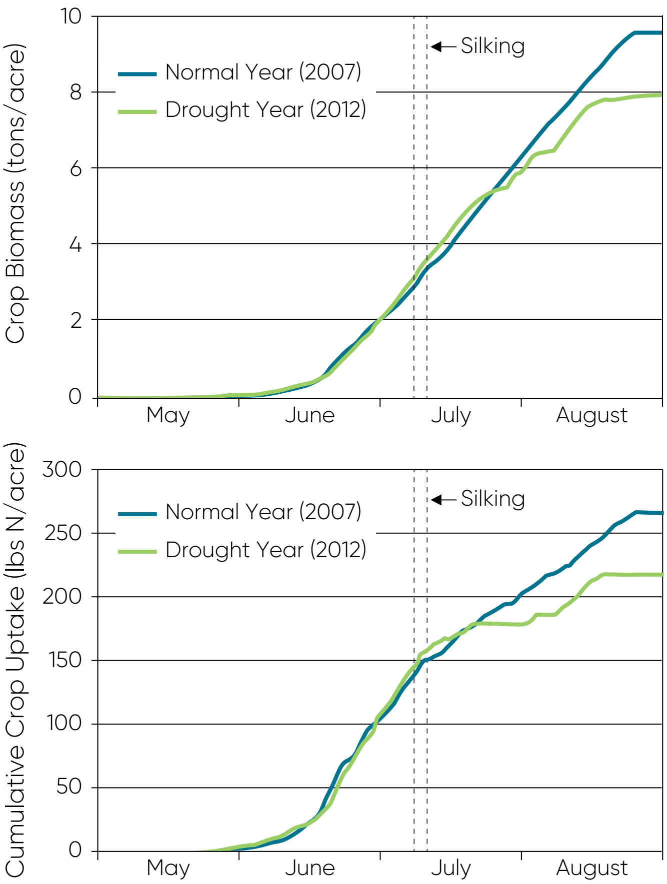


Figure 3. Model-estimated crop growth (upper panel) and nitrogen uptake (lower panel) for corn grown in Story Co., IA, in 2007 and 2012. See Table 1 for simulation details.

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 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 nitrogen mineralization potential. All else equal, nitrogen mineralization will be greatest for warm, moist soils with high organic matter content (Figure 4).

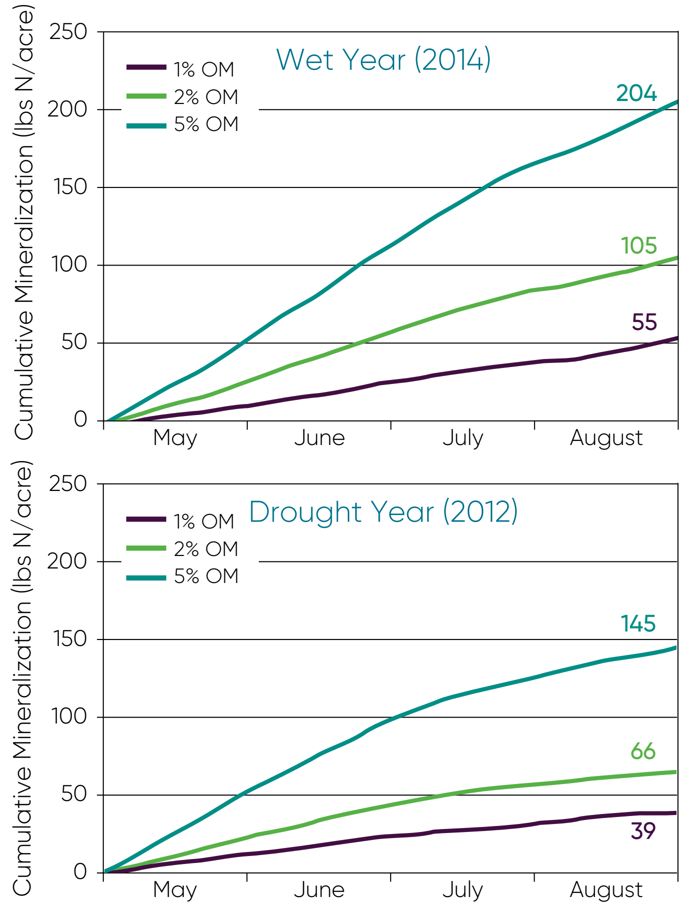


Figure 4. Model-estimated, cumulative soil nitrogen mineralization in Clay Co., NE, in 2014 (upper panel) and 2012 (lower panel). See Table 1 for simulation details.

Nitrate Leaching

Soil texture, soil temperature, drainage, precipitation, and crop growth all interact in 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.

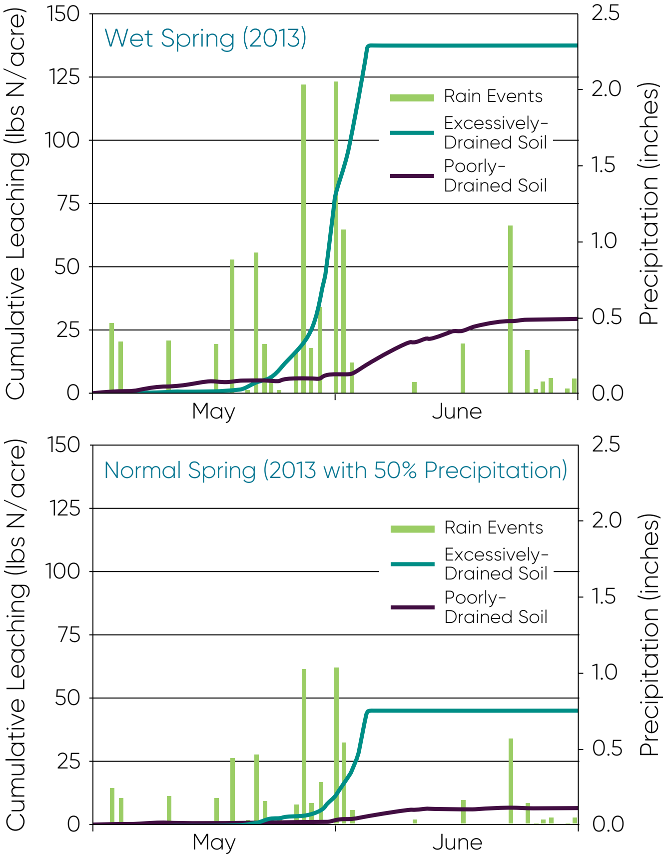


Figure 5. Model-estimated cumulative nitrogen leaching in Woodford Co., IL, in 2013 (upper panel) and a hypothetical year with half as much May-June precipitation as 2013 (lower panel). See Table 1 for simulation details.

Denitrification

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 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 6a & 6b).

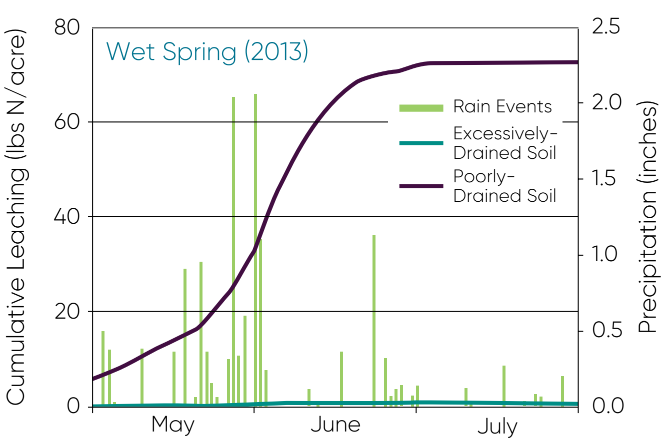


Figure 6a. Model-estimated cumulative denitrification in Woodford Co., IL, in 2013 (Figure 6a) and a hypothetical year with half as much May-June precipitation as 2013 (Figure 6b). See Table 1 for simulation details.

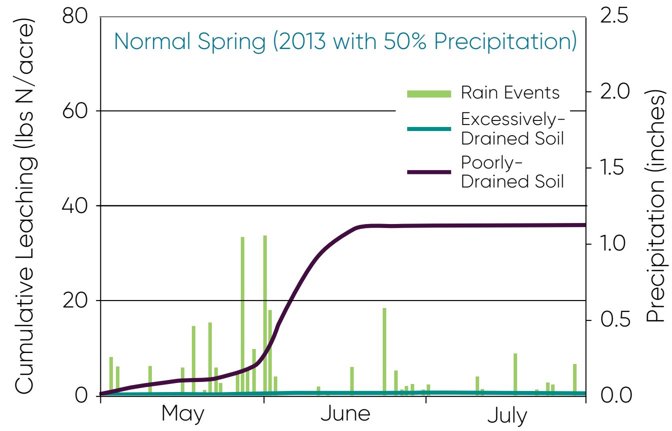


Figure 6b. Model-estimated cumulative denitrification in Woodford Co., IL, in 2013 (upper panel) and a hypothetical year with half as much May-June precipitation as 2013. See Table 1 for simulation details.

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, as well as the presence/absence of a urease inhibitor. 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.

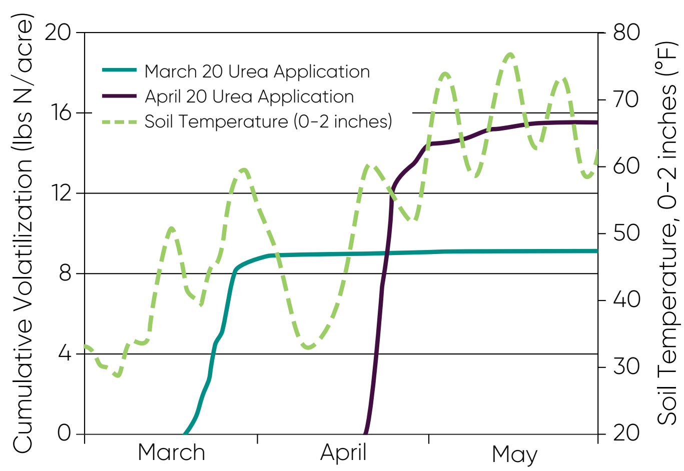


Figure 7. Model-estimated cumulative nitrogen volatilization for two surface-applied urea applications in Putman Co., OH, in 2007. See Table 1 for simulation details.

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, Encirca services nitrogen analytics simulate historical and forecasted weather in conjunction with grower yield goals to estimate the availability of adequate nitrogen associated with planned management actions. The level of risk for a given management plan or set of plans is displayed in the Encirca services user interface using an intuitive color-coded system (Figure 8). In addition, the impact of weather on crop-available nitrogen through the growing season can be tracked in real time on an easy-to-follow season chart (Figure 9).

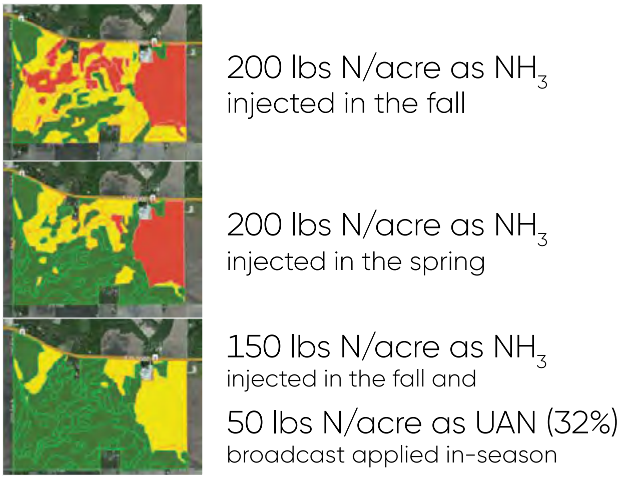


Figure 8. Risk associated with three hypothetical nitrogen management plans for 2015 based on simulations conducted on November 15, 2014. Green field areas represent low risk potential, while yellow and red field areas represent moderate and high-risk potential, respectively.

Figure 9. Season chart of modeled soil nitrogen for a 2018 field with 100 lbs/acre fall-applied anhydrous ammonia and variable rate UAN (28%) Rx applied mid-June.

Variable Rate Nitrogen Recommendation Model

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 10).

Figure 10. Encirca services nitrogen model uses soil and weather information in conjunction with yield goals to generate variable rate nitrogen recommendations that can minimize risk of yield loss from insufficient nitrogen and reduce environmental losses due to over application.

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/acre on May 1. Soybean was the previous crop in all simulations.

Scenario	Related Figure	State	County	Weather Year(s)	Soil(s)	N Fertilization
Corn Growth/ N Uptake	3	IA	Story	2007; 2012	Webster clay loam	April 20: 150 lbs N/acre (injected NH_3); May 1: 30 lbs N/acre (broadcast UAN)
Mineralization	4	NE	Clay	2012; 2014	Thurman loamy sand; Hastings silt loam	April 20: 150 lbs N/acre (injected NH_3); May 1: 30 lbs N/acre (broadcast 32% UAN)
Leaching	5	IL	Woodford	2013; 2013^	Plainfield sand; Sawmill silty clay	April 20: 150 lbs N/acre (injected NH_3); May 1: 30 lbs N/acre (broadcast UAN)
Denitrification	6	IL	Woodford	2013; 2013^	Plainfield sand; Sawmill silty clay	April 20: 150 lbs N/acre (injected NH_3); May 1: 30 lbs N/acre (broadcast UAN)
Volatilization	7	OH	Putman	2007	Toledo clay	March 20: 150 lbs N/acre (broadcast urea) April 20 : 150 lbs N/acre (broadcast urea)

^Modeled as 2013 with each precipitation event reduced in magnitude by 50%.

Effectiveness of Split Nitrogen Applications in the Midwestern U.S.

*by **Jason Clark, Ph.D.,** South Dakota State University, and **Fabian Fernandez, Ph.D.,** University of Minnesota*

Rationale and Objectives

- Nitrogen (N) fertilizers are used to supplement the soil's natural N supply to increase corn grain yield and maximize economic profit.
- However, the use of N fertilizer has been associated with increased nitrate levels of ground and surface waters. High nitrate levels can cause negative environmental, human, and animal health effects.
- Splitting N fertilizer across multiple application timings during the growing season is a suggested method to lower the risk of N loss by applying N fertilizer in amounts and at timings that more closely match corn N uptake.
- The objectives of this study were:
  - » Determine the effects of split N application on soil nitrate (NO_3-N) at VT, N uptake at maturity, and corn grain yield
  - » Classify environmental conditions in which split N application is likely to increase corn yield
  - » Compare the effect of split N application when a low or high N rate is applied near planting on soil N concentrations, corn N uptake, and corn yield

Study Description

- Research was targeted to two sites (representing higher- and lower-yielding environments) in each of eight Midwestern states over three years (2014-2016). A total of 49 site-years were included in the study (Figure 1).

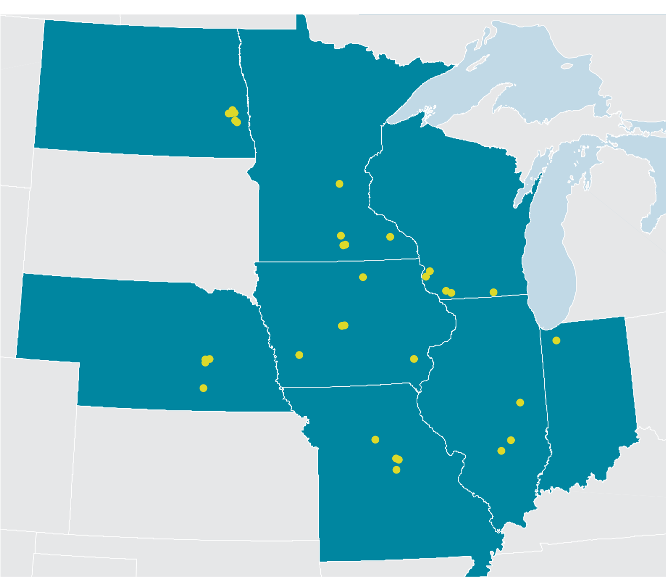


Figure 1. Research locations across eight states included in the 3-year split nitrogen application study, 2014-2016.

Study Factors:

Total Nitrogen Rates:

160 lbs/acre (near economic optimum rate)

240 lbs/acre (above economic optimum rate)

Nitrogen Application Timings:

S	Single application near planting
40+SD	40 lbs at planting + remainder at V9 side-dress
80+SD	80 lbs at planting + remainder at V9 side-dress

Data Collection

- **Soil Sampling:** Percent sand, silt, and clay; cation exchange capacity (CEC); organic matter; organic C; total N; pH; and bulk density (0-1 ft). Soil NO_3-N at VT development stage only at 160 lbs/acre (0-2 ft)
- **Plant Sampling:** N content at physiological maturity and grain yield
- **Weather Measurements:**
  - » **Daily:** Minimum and maximum temperature and precipitation
  - » **Calculations:** Growing degree days, cumulative precipitation, and Shannon diversity index (SDI) (SDI = 1 implies complete evenness (i.e., equal amounts of rainfall in each day of the period); SDI = 0 implies complete unevenness (i.e., all rain in one day))

Results – Soil NO_3-N at VT

- Nitrogen fertilizer application timing did not affect soil NO_3-N at VT (65-77%) in the majority of the sites (Figure 2).
- In the sites where application timing affected soil NO_3-N at VT, single N applications were always less than split N applications. Thus, splitting up the application of N only increased the amount of soil NO_3-N available at VT in a small percentage of sites.
- The amount of N fertilizer applied at planting (40 vs. 80 lbs/acre) within the split N applications did not alter the amount of NO_3-N available for the corn crop at the VT development stage in 98% of the sites.
- These results demonstrate that applying a low or high rate of N at planting with a split-N application did not significantly alter the amount of soil NO_3-N available for the corn at VT.

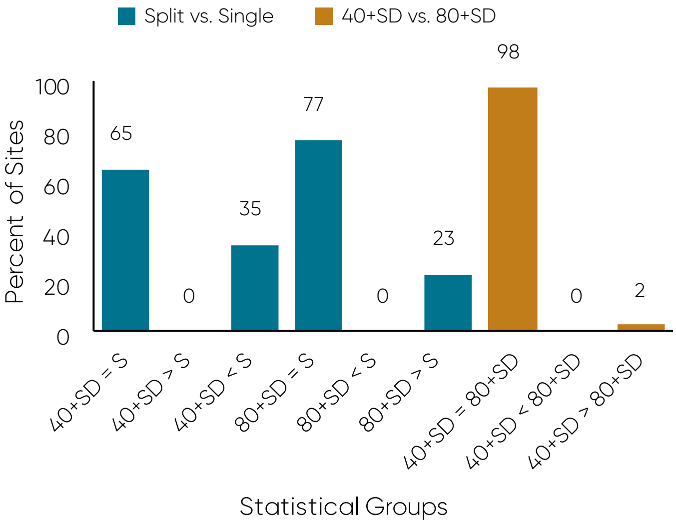


Figure 2. Percent of sites where soil nitrate at tasseling was affected by N application timing (S, 40+SD, and 80+SD) only at the 160 lbs/acre total N application rate.

Results – Nitrogen Uptake at Maturity

- Nitrogen timing had no effect on corn N uptake at physiological maturity 77 to 84% of the time regardless of N rate (Figure 3).
- When differences occurred, N uptake was greater 9 to 10% of the time using split N applications and 6 to 15% of the time using a single N application.
- For split N applications, there were no differences in N uptake at physiological maturity when applying 40 or 80 lbs/acre at planting 98% of the time regardless of the N rate.
- When there was a difference, applying less N at planting and more at sidedress (40+SD) led to greater N uptake at physiological maturity.

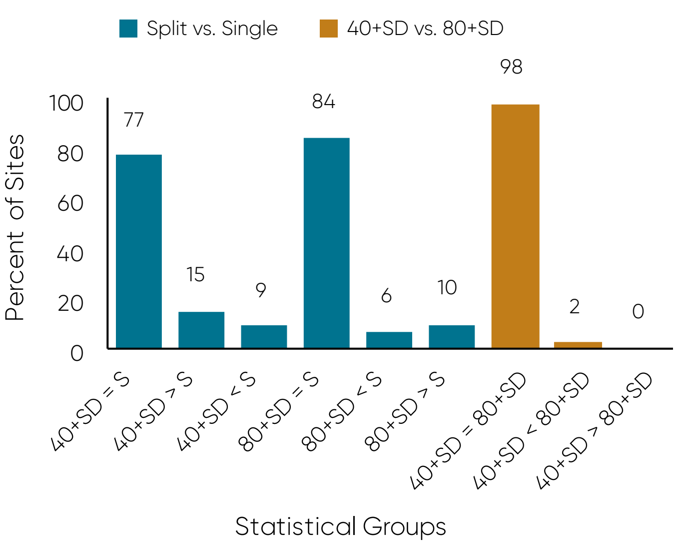


Figure 3. Percent of sites where nitrogen uptake at maturity was affected by N application timing (S, 40+SD, and 80+SD) at a total N application rates of 160 and 240 lbs/acre.

Results – Corn Yield

- Corn yields ranged widely across the 49 site-years of the study, although yield ranges were similar among nitrogen rates and application timings (Table 1).

Table 1. Corn yield ranges across all site-years of the study associated with N rates and application timings.

N rate	N Application Timing		
	S	40+SD	80+SD
lbs/acre	*bu/acre*		
160	48-278	81-285	85-280
240	65-280	70-293	96-280

- Nitrogen timing had no affect on corn yield in 80 to 84% of the sites regardless of N rate (Figure 4). When differences occurred, corn yields were greater 14 to 15% of the time using split N applications and 1 to 6% of the time using single N applications.

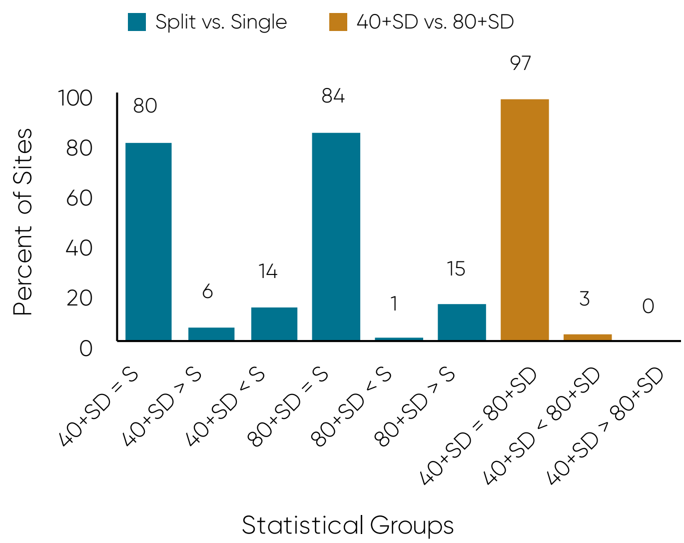


Figure 4. Percent of sites where grain yield was affected by N application timing (S, 40+SD, and 80+SD) at a total N application rates of 160 and 240 lbs/acre.

- Split N applications increased corn yield over single N applications as sand content, bulk density, and evenness of rainfall over the season increased greater than the critical values shown in Table 2.

Table 2. Critical soil or weather values where larger values were associated with greater corn yield for split-N applications (40+SD or 80+SD) and smaller values were associated with greater corn yield for single N applications.

Variable	Critical Value	
	40+SD	80+SD
Sand, %	10	4
Bulk density, g/cm^3	1.2	1.2
SDI†	0.59	0.56

† SDI, Shannon diversity index (measured from 30 d before to 30 d after sidedress).

- Single N applications increased grain yield over split N applications as clay, silt, CEC, total N, and early season temperatures increased above the critical values shown in Table 3.
- Corn yields associated with 40+SD and 80+SD applications were similar 97% of the time. In the remaining 3%, corn yield was less with 40+SD than 80+SD.

Table 3. Critical soil or weather values where larger values were associated with greater corn yield for single N applications and smaller values were associated with greater corn yield for split-N applications (40+SD or 80+SD).

Variable	Critical Value	
	40+SD vs. Single	80+SD vs. Single
Clay, %	34	37
Silt, %	66	74
CEC†, meq/100 g	27	31
Total N, %	2.1	2.4
Mean temp‡., °F	66	68

† CEC, Cation exchange capacity.

‡ Mean temp. was measured from planting to V5 development stage.

The results from this study are part of a regional study as described in Kitchen, N.R., J.F. Shanahan, C.J. Ransom, C.J. Bandura, G.M. Bean, J.J. Camberato, P.R. Carter, J.D. Clark, R.B. Ferguson, F.G. Fernández, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, Z. Qing, J.E. Sawyer, and M. Shafer. 2017. A public-industry partnership for enhancing corn nitrogen research and datasets: project description, methodology, and outcomes. Agron. J. 109:2371-2388. doi: 10.2134/agronj2017.04.0207

Conclusions

- No differences in corn yield among 40+SD, 80+SD, and single N applications were found in the majority of site-years (77-84%) regardless of N rate.
- Overall, split N applications had greater corn yield in areas with consistent rainfall around the time of sidedress application that incorporated the fertilizer and in soils with greater potential for N loss early in the growing season (i.e., sandy soils that have greater leaching potential).
- In general, single N applications had greater corn yield in soils with greater potential for mineralization throughout the season (i.e., greater total N content) and better nutrient and water retention as indicated by greater CEC, silt content, and clay content.
- No differences between 40+SD and 80+SD were found in 97 to 98% of the sites, indicating that applying 40 lbs/acre near planting is all that may be needed when using split N applications.

Corn Yield Following Delayed Application of Nitrogen Fertilizer

*by **Emerson Nafziger, Ph.D.,** University of Illinois*

Objectives

- To measure the effect on corn yield of delaying application of half or all nitrogen (N) fertilizer to one of eight stages from early vegetative growth (stage V3) to after pollination (stage R3) in late July
- To see if corn yield response to delay in providing N is different for corn following soybean and corn following corn
- To use SPAD readings as a measure of leaf greenness to see how N deficiency develops and to see how timing of N application affects the ability of the plant to recover healthy green leaf color

Study Description

- **Location:** Crop Sciences Research & Education Center near Urbana, Illinois
- **Soil:** Highly productive Flanagan silt loam
- **Years:** 2015-2017
- **Hybrid/Brand[1]:**
  - P0987AMX™ (AMX, LL, RR2) - 2015
  - P1197AMXT™ (AMXT, LL, RR2) - 2016, 2017
- **Cropping Sequence:**
  - Corn following soybeans
  - Corn following corn
- **Nitrogen Applications:**
  - **Split Applications:** 100 lbs N/acre applied at planting followed by 100 lbs N/acre applied at V3, V6, V9, V12, V15, VT/R1, R2, or R3
  - **Single Application:** 200 lbs N/acre applied at planting, V3, V6, V9, V12, V15, VT/R1, R2, or R3
- Trials were planted in the second half of April at 35,000 to 36,000 seeds/acre; final stands ranged from 30,000 to 34,100 plants/acre.
- Plots were four 30-inch rows wide by 47 ft long. Treatments were assigned to plots in a randomized complete-block design.
- N applications at planting were applied as UAN injected between the rows soon after planting. In-crop applications were made using a hand boom to stream UAN near the row.
- Time between planting and V3 averaged 32 days. After V3, the interval between applications ranged from 7 to 12 days, and the last application at R3 was in late July or early August about 14 weeks after planting.
- Yields were taken by harvesting the center two rows with a plot combine.
- SPAD readings were taken in 2016 and 2017 using a Minolta SPAD-502 Chlorophyll Meter at each application date on both the plots to which N was applied on that date and also on all of the plots to which N had been applied earlier.
- Measurements were taken on the uppermost leaf with a leaf collar visible through late vegetative growth stages, then on the leaf below the ear at and after tasseling.

Results

Corn Following Soybeans

- Applying 100 lbs N/acre at planting yielded an average of 197 bu/acre over the 3 years of the study (Table 1).
- When a second 100 lbs of N was applied in-season, corn yield did not significantly differ for application timings from V3 through R2 stage; applying at V3 yielded 232 bu/acre, and applying at R2 yielded 228 bu/acre.
- The only treatment that yielded less than these treatments was the application of the second 100 lbs of N at R3; this treatment yielded 210 bu/acre, not significantly more than when only 100 lbs N/acre was applied at planting.

Table 1. Effect of delaying half or all of the N on yield of corn following soybean. Data are averages over three years at Urbana, Illinois. Yields followed by the same letters are not statistically different at the 10% level.

Stage at Application	Nitrogen Applications: 100 lb N at Planting + 100 lb N Delayed		Nitrogen Applications: 200 lb N at Planting or Delayed	
	bu/acre			
Planting	197	fg	215	cde
V3	232	ab	228	abc
V6	228	abc	235	a
V9	231	ab	228	abc
V12	236	a	221	abcd
V15	226	abc	220	bcd
VT/R1	230	ab	201	ef
R2	228	abc	184	g
R3	210	def	144	h

- When all 200 lbs N/acre was applied at once, the highest yield came with application at V6; this treatment yielded 235 bu/acre, not significantly different from most of the treatments with N split into planting time and delayed applications and more than the treatment with 200 lbs N/acre at planting, which yielded 215 bu/acre (Table 1).

- Yields decreased when application of all 200 lbs N/acre was delayed to V15 or later; yields at V15, VT/R1, R2, and R3 were 93, 86, 78, and 61%, respectively, of the yield with all of the N applied at V6.

Corn Following Corn

- Responses to delaying N were very different between the first two years and the third year of the study, so 2015-16 data were analyzed separately from the 2017 data.
- In 2015-16, applying 100 lbs N/acre at planting yielded 152 bu/acre.
- Applying the second 100 lbs of N at any stage from V3 through VT/R1 produced similar yields; applying at V3 yielded 212 bu/acre, and applying at VT/R1 yielded 214 bu/acre (Table 2).
- Applying the second 100 lbs of N at R2 and R3 yielded 197 and 198 bu/acre, significantly less than yields with the second 100 lbs of N applied earlier but 92% of the highest yield.

Table 2. Effect of delaying half or all of the N on yield of corn following corn, averaged over 2015 and 2016 at Urbana, Illinois. Yields followed by the same letters are not statistically different at the 10% level.

Stage at Application	Nitrogen Applications: 100 lb N at Planting + 100 lb N Delayed	Nitrogen Applications: 200 lb N at Planting or Delayed
	bu/acre	
Planting	152 g	202 bcd
V3	212 ab	222 a
V6	211 abc	204 bcd
V9	210 abc	207 bcd
V12	212 ab	188 ef
V15	204 bcd	182 f
VT/R1	214 ab	149 g
R2	197 de	120 h
R3	198 cde	108 h

- When all 200 lbs N/acre was applied at once, the highest yield averaged across the 2015 and 2016 trials came with application at V3; this treatment yielded 222 bu/acre.
- Yields did not differ among applications at planting, V6, and V9.
- Yields dropped with later applications from 188 bu/acre with all 200 lbs of N applied at V12 to only 108 bu/acre – 49% of the yield when all of the N was applied at V3 – when all of the N was applied at R3.
- In 2017, the yield of corn following corn with only 100 lbs of N applied at planting was 206 bu/acre, not statistically different than any of the split-N treatments except when the second application was made at V9 with a yield of 233 bu/acre (Table 3).
- With 100 lbs N/acre producing almost as much yield as 200 lbs N/acre, it is not surprising that timing of the second increment had little effect on yield; application at V3 and at R3 both yielded 228 bu/acre.
- Applying all of the N at planting produced 219 bu/acre, not statistically more than the 211 bu/acre produced when the N was applied at VT/R1.

Table 3. Effect of delaying half or all of the N on yield of corn following corn in the 2017 trial at Urbana, IL. Yields followed by the same letters are not statistically different at the 10% level.

Stage at Application	Nitrogen Applications: 100 lb N at Planting + 100 lb N Delayed	Nitrogen Applications: 200 lb N at Planting or Delayed
	bu/acre	
Planting	206 de	239 a
V3	222 abcd	232 ab
V6	227 abcd	208 cde
V9	233 ab	231 ab
V12	222 abcd	228 abc
V15	217 abcd	205 de
VT/R1	215 bcd	213 bcd
R2	220 abcd	207 cde
R3	221 abcd	186 e

- Yields dropped with the latest applications to 190 bu/acre with application at R2 and to 163 bu/acre at R3. These are 81 and 69% of the yield from application at V6; these percentages are similar to those with applications at V15 and VT/R1 in the 2015-16 trials.
- Corn following corn usually is unable to take up as much N from the soil as corn following soybeans because corn residue ties up some N as it breaks down. It is unclear why the soil supplied so much more N to corn following corn in 2017, but this was found in other trials that year as well. The weather was warm and dry in early June, which may have both increased mineralization rates and decreased N losses.

SPAD Readings

- Trends in SPAD readings in the corn following corn experiment in 2016 are shown as an example of how corn plants visibly respond to delayed N application.

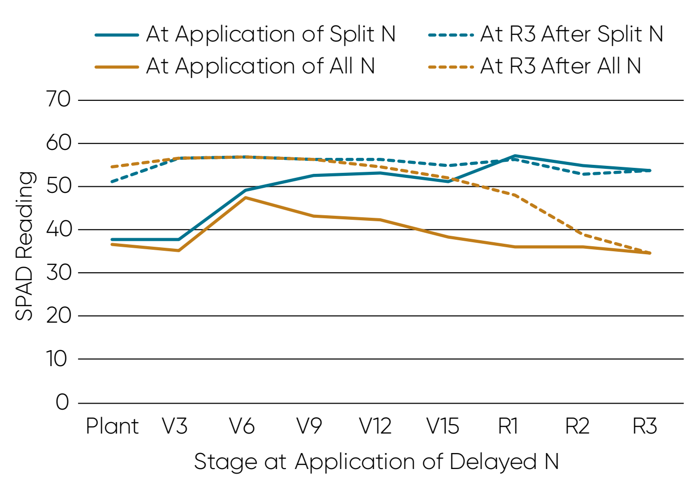


Figure 1. SPAD (leaf chlorophyll) readings of corn following corn in 2016. Solid lines are readings at the time of application of split (100 lb) N and of all of the N, while dashed lines show SPAD readings at stage R3.

- The solid lines in Figure 1 are SPAD readings taken at the time of delayed application of half or all of the N. They show that both are quite N deficient (readings less than 40) early, but after V6, those with 100 lbs of N applied early continue to green up all the way to pollination, while those without any N early become more deficient the later the N is delayed.
- The important difference between the split and all-delayed N is the difference in the ability of the plants to recover their green color after the delayed application of N.
- As measured by the difference between the solid and dashed lines, the split-N treatments were able to recover their green color no matter when the delayed N was applied, and delaying application until R2 yielded 234 bu/acre, not different than when all of the N was applied early.
- When all 200 lbs of N was applied at one time, plants were unable to regain their green color if application was later than mid-vegetative stages and as SPAD readings at R3 declined, so did yields.
- It appears that if conditions or presence of previous crop residue result in less N availability early, N-deficient plants may not recover full yields.

Conclusions

- When corn follows soybean in a productive soil with high organic matter and with 100 lbs of N applied at planting, the second increment of N can be applied as late as a week after pollination (stage R2) with little or no loss in yield. This is also true for corn following corn, though depending on the year, this decline may begin a little earlier. The study did not include different rates for the delayed application, but with most of the N already in the plant by V15 to VT, applying less than 100 lbs of N after late vegetative stages would likely have been adequate to maximize yield.
- When corn follows soybean and application of all 200 lbs of N is delayed, yield begins to decline as application time approaches pollination; N needs by the developing plant appear to be adequately supplied by N mineralized by the soil up to this point. For corn following corn, delaying N application to V12 to V15 produces lower yields, and yields continue to decline as N application is delayed further.
- Leaf chlorophyll (SPAD) measurements reflect the supply of soil N and development of deficiency symptoms in corn. In this soil, if 100 lbs N is applied at planting, N deficiency is fully corrected by applying 100 lbs N at any time, up to several weeks after pollination. Waiting until late vegetative stages to apply any N means that deficiency symptoms cannot be fully corrected, and yield is lost. The ability of the plant to recover, not the severity of the deficiency, determines how much yield is lost when N is delayed.
- This work was done in good soils and in years with good growing conditions, which very likely meant a good supply of N from the soil early in the season even where no fertilizer N was applied early. In soils with lower organic matter or with cooler, wetter (or drier) soil conditions during the establishment of the nodal root system, we have seen N deficiency symptoms develop much earlier than we saw here, and in some cases, yield potential might be lost even if N is applied as sidedress.

Making a Corn Canopy Sensor Algorithm Better for Nitrogen Recommendations

*by **G. Mac Bean,** University of Missouri, and **Newell R. Kitchen, Ph.D.,** USDA-ARS*

Rationale

- Canopy sensors use light reflectance from a corn canopy as an indicator of the plant's N health status.
- Studies have shown canopy sensor algorithms used in partnership with light reflectance for corn N fertilizer recommendations are not consistently accurate (Bean et al., 2018).

Objectives

- Compare red and red-edge waveband sensitivity to soil and crop measurements
- Evaluate across the U.S. Midwest region the performance of the University of Missouri Corn Canopy Sensor Algorithm (ALGMU)
- Improve ALGMU N fertilizer recommendations with site-specific soil and weather information

Study Description

- A public-industry partnership between Pioneer and eight U.S. Midwest land-grant universities (IA, IL, IN, MN, MO, ND, NE, and WI; Figure 1)
- A total of 49 site locations over 3 growing seasons (2014-2016)

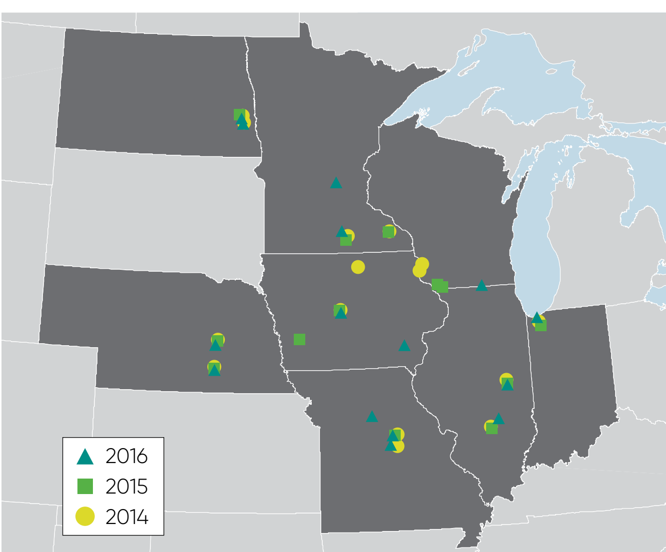


Figure 1. Research locations across 8 states included in the 3-year split N application study (2014-2016).

- Used a RapidSCAN (Holland Scientific Inc., Lincoln, NE) corn canopy sensor with measurements at V9 ±one corn growth development stage
- The ALGMU developed using the red reflectance waveband to calculate in-season N fertilizer recommendations
- The economically optimal N fertilizer rate (EONR) was calculated for each site using $4.00/bu corn and $0.40/lb of N prices.
- Performance of ALGMU N fertilizer recommendations was measured by comparing to end-of-season calculated EONR.
- Weather information used for ALGMU adjustment was from the time of planting to the time of side-dress. Soil properties used for ALGMU adjustment were from pre-plant soil samples. Soil nitrate samples were collected at V5. The relative yield (RY) was calculated by dividing the individual plot yield by the averaged site-level EONR.

Results – Objective 1

- Sufficiency indices (SI; N deficient corn reflectance / N reference corn reflectance) calculated with either red or red-edge wavebands were significantly related to V5 soil nitrate (Figure 2; $\alpha = 0.05$).
- As V5 soil nitrate increased, the SI approached "1", a point at which V5 soil nitrate was ~ 16 ppm. This suggests 16 ppm soil nitrate at V5 leads to equivalent canopy reflectance between V9 unfertilized corn and N reference corn.
- The red-edge waveband ($R^2 = 0.51$) was better related to V5 soil nitrate than the red waveband ($R^2 = 0.32$).

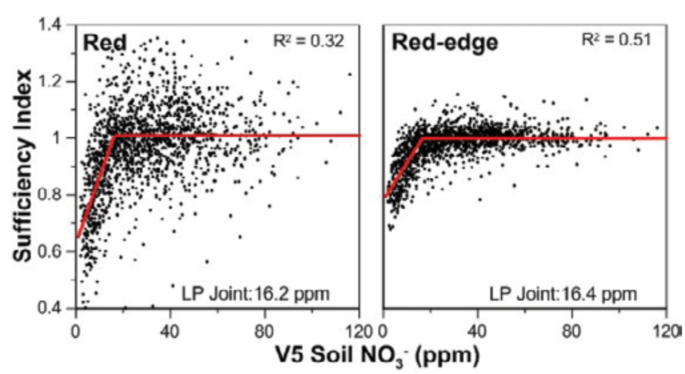


Figure 2. The relationships between red and red-edge sufficiency indices (calculated from V9 collected canopy sensor reflectance measurements) and V5 soil nitrate.

- Sufficiency indices were also related to relative yield using both the red and red-edge wavebands (Figure 3; $\alpha = 0.05$).
- As RY approached "1", meaning there was no additional yield increase with added N fertilizer, the SI also reached "1". This was expected. Corn that received additional N fertilizer with no yield increase "looked" the same as the N reference corn. Similar to V5 soil nitrate, the red-edge waveband better related to changes in RY than the red waveband.

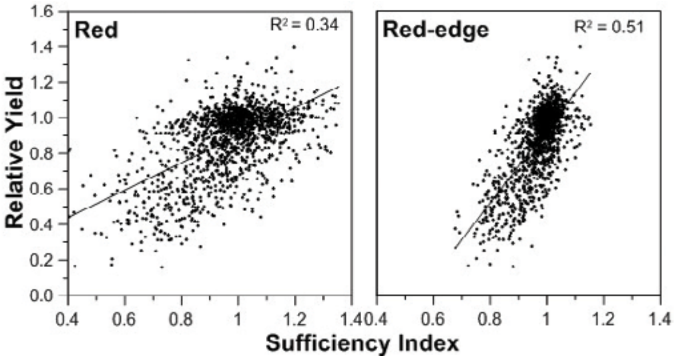


Figure 3. The relationships between relative yield and the red and red-edge sufficiency indices (calculated from canopy sensor reflectance measurements collected at V9).

Results – Objective 2

- The ALGMU N recommendations did not relate well to EONR (Figure 4). For most sites needing greater than 100 lbs N/acre, the ALGMU underestimated crop N need.
- The range in ALGMU N fertilizer recommendations was between 50 and 160 lbs N/acre, while the range in EONR was from 0 to 240 lbs N/acre, showing a lack of sensitivity to site-specific N need.
- A state-by-state analysis revealed the ALGMU performed better outside of MO than it did inside MO. Interestingly, sites where the ALGMU performed best were those with greater than 3.4% organic matter.

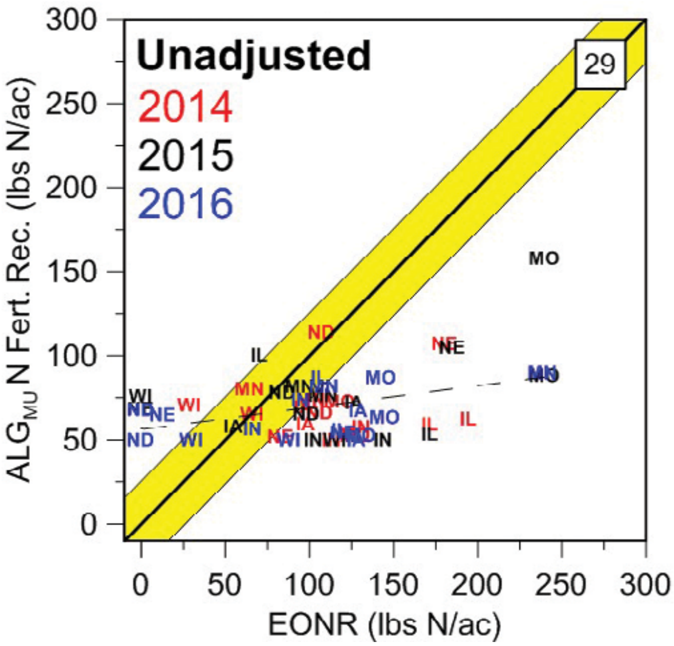


Figure 4. The performance of the unadjusted ALGMU compared to the end-of-season calculated EONR. Data points on or near the 1:1 diagonal line were sites that the ALGMU performed reasonably well for making an in-season N fertilizer recommendation. Sites below and above the 1:1 line represent recommendations that under- and over-estimated N need, respectively. Sites that fell within the yellow shaded region are those within 30 lbs N/acre of EONR (the percent of sites in the white box in the top right-hand corner). The dashed line shows the linear relationship between the ALGMU and EONR.

Results – Objective 3

- Adjusting the ALGMU N fertilizer recommendations with site-specific soil and weather information resulted in improved EONR estimation (Figure 5). This was helpful since early-season precipitation and soil properties greatly influence corn N response, especially over a geographically diverse area.
- Following adjustment, 51% of the sites (11 additional sites over the unadjusted ALGMU) fell within 30 lbs N/acre of EONR.
- The range of adjusted ALGMU recommendations more accurately mirrors the range in EONR values.

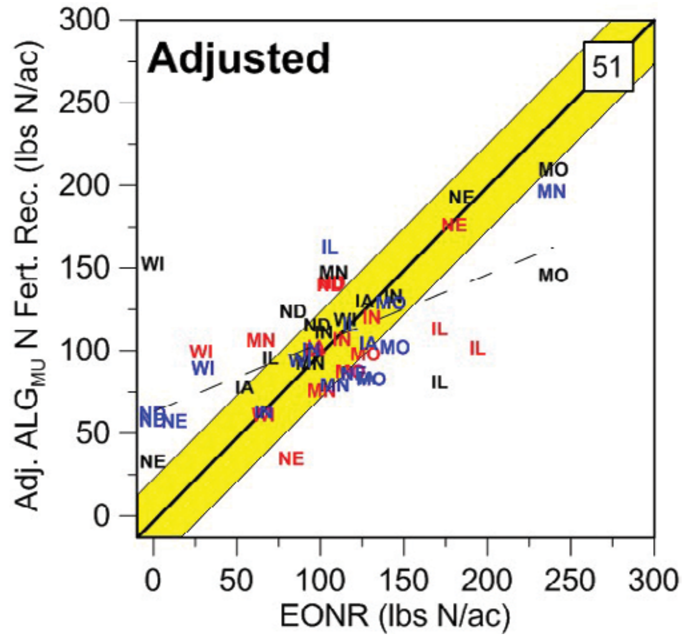


Figure 5. The performance of the adjusted ALGMU using soil and weather information compared to calculated EONR (see Figure 4 caption for details).

Conclusions

- Canopy sensor measurements, especially the red-edge waveband, was related to V5 soil nitrate and yield response to added N fertilizer.
- ALGMU recommendations may have improved if the algorithm employed the red-edge waveband instead of the red waveband.
- The unadjusted ALGMU was poor in estimating EONR values across a large geographical region.
- Using site-specific soil and weather information improved the ALGMU N fertilizer recommendations.
- Use of the ALGMU algorithm regionally only would be advised when including site-specific soil and weather adjustments.

Corn Response to High pH Soil Environments - Nebraska

*by **Chris Zwiener,** Technical Product Manager, **William McClure,** Technical Product Manager, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Soil pH is a measure of the relative acidity or alkalinity of the soil solution.
- Alkaline or high pH (>7) soils can be naturally occurring, caused by over-liming or by using high pH irrigation water in arid areas.
- High soil pH can limit the uptake of several nutrients, such as phosphorous, zinc, iron, manganese, boron, and copper.
- High soil pH caused by excess calcium carbonate is different than high pH caused by excess sodium (>15% exchangeable sodium), or sodic soils.
- Corn products can respond differently to high soil pH environments, and the response may not be the same in calcareous and sodic soils (Figures 1 and 2).

Figure 1. Visual differences in early season chlorosis among Pioneer® brand corn products in high pH soil.

Objectives

- Evaluate performance of Pioneer® brand corn products in high soil pH environments.
- Characterize corn product performance differences in calcareous versus sodic soils.
- Provide better product placement recommendations for high soil pH fields.

Figure 2. Visual differences in late-season chlorosis among hybrids in sodic soil.

Study Description

- Trials were placed on soils with a historic high pH (>7.9) where iron chlorosis symptoms are likely to be observed.
- Field observations were collected at 12 locations across Nebraska (Figure 3) and nearly 200 individual data points collected.
- Observations were collected early in the season (V7-V8) as well as late in the season (R3-R4), and pre-harvest yield estimates were collected.
- Pioneer brand corn products were evaluated based on color (chlorosis), vigor, and ear uniformity.
- A three-bucket (ASC) rating system was used:
  S = Strength, A = Acceptable, and C = Consideration.
- Observations were combined, and a final rating was assigned to each hybrid for calcareous and sodic adaptability.

Figure 3. Locations where observations were taken.

Results

- Pioneer® brand corn products responded differently to calcareous versus sodic soils.
- Some products showed visual symptoms (yellowing) associated with high pH soil but still maintained yield across the field.
- Performance ratings of Pioneer brand products in calcareous and sodic soils based on results of this study are shown in Table 1.
  - S = Strength – tolerates the condition better than other Pioneer brand products observed in the same environment
  - A = Acceptable – has an average tolerance to the condition relative to other Pioneer brand products observed in the same environment
  - C = Consideration – the hybrid is less tolerant of the environment relative to other Pioneer brand products observed. Consider another product choice.

Table 1. Corn product suitability to calcareous and sodic soils.

Hybrid/Brand[1]	Calcareous	Sodic
P9998AMXT™ (AMXT, LL, RR2)	S	A
P0306AMXT™ (AMXT, LL, RR2)	S	S
P0339AM™ (AM, LL, RR2)	S	C
P0657AMXT™ (AMXT, LL, RR2)	S	S
P0707AMXT™ (AMXT, LL, RR2)	S	A
P0950AM™ (AM, LL, RR2)	A	C
P1093AMXT™ (AMXT, LL, RR2)	S	S
P1138AM™ (AM, LL, RR2)	A	A
P1151AMX™ (AMX, LL, RR2)	S	S
P1244AM™ (AM, LL, RR2)	A	A
P1366AM™ (AM, LL, RR2)	A	A
P1370AM™ (AM, LL, RR2)	C	C
P1379AM™ (AM, LL, RR2)	A	A
P1563AM™ (AM, LL, RR2)	A	C
P1828AM™ (AM, LL, RR2)	A	A

Conclusions and Management Considerations

- Management practices for high pH soils include:
  - Aggressive utilization of starter fertilizer
  - Manure application to areas with known micronutrient issues
  - Limiting early water applications, if possible, to keep soils from sealing over.
- Corn product selection:
  - Select corn products that show optimum yield performance.
  - Select corn products that can maintain acceptable plant and ear height.
  - Select corn products that can tolerate elevated soil pH levels.
  - Visit with your local Pioneer sales representative or dealer for information on Pioneer brand corn product options.

Figure 3. Low tolerance to high pH soils can impact grain set and fill.

Measuring and Reducing Corn Field Losses

by **Steve Butzen, M.S.,**
Agronomy Information Consultant

Summary

- Pre-harvest losses (ears dropped from plants) are greatest when wet conditions extend the drydown period and cause deterioration of the crop.
- Harvesting losses are those associated with the combine, including header, threshing, and separating losses.
- Header losses may be ears or kernels; threshing losses are kernels attached to ejected cob fragments; separating losses are shelled kernels lost out the back of the combine.
- Distinguishing the source and extent of harvesting losses can help growers reduce them by changing combine settings.
- Each lost ear in 100 plants represents about 1% yield loss. 20 kernels in a 10 ft^2 area equals about 1 bu/acre lost.
- Growers are advised to set the combine to manufacturer-recommended settings as a starting point and then adjust to the condition of the crop.
- When crop conditions change due to hybrid, field, or weather changes, combine adjustments may be necessary.

Introduction

Corn yield is effectively set at the R6 stage of kernel development, also referred to as physiological maturity. After that milestone is reached, crop yield cannot be gained, only lost. Weather plays a key role in how much of the yield is eventually captured at harvest. Dry weather is conducive to fast drydown and timely harvest of the crop. Wet weather, on the other hand, can lead to increased stalk and ear rots; potential harvest delays; and increased field losses.

Optimizing combine settings throughout harvest is another important key to achieving highest harvestable yields. This step is critical in order to reduce ear and kernel losses that can occur when combining. Unlike weather conditions, combine settings are completely under the grower's control.

To optimize harvested yields, growers should:

- Closely monitor crop condition as harvest approaches and time harvest accordingly
- Recognize the causes and extent of any field losses
- Set the combine properly in order to capture as much of the crop yield as possible
- Re-check field losses and combine settings when fields, hybrids, or weather conditions change

Corn Pre-Harvest Losses

Corn field losses consist of pre-harvest and harvesting losses. Pre-harvest losses are primarily due to ears dropped from plants. Kernels (rather than whole ears) may also be lost prior to harvest, usually due to hybrid/environmental effects or wildlife damage, but these are relatively rare compared to other causes and are not discussed here.

Losses prior to harvest are greatest when crop condition deteriorates as the crop stands in the field, drying to an acceptable harvest moisture. Wet, fall weather delays grain drying and thus subjects the crop to an extended period in the field following maturity. Under these conditions, ears may drop as ear shanks weakened by insect feeding or weathering eventually break at a node, detach from the stalk, or detach from the cob. Dropped ears may or may not include the husks.

Corn Harvesting Losses

Harvesting losses refer to those associated with the combine including header, threshing, and separating losses.

Header Losses

Header or "gathering" losses usually contribute the most to harvesting losses because whole ears as well as kernels can be lost at the header. Whole ear losses result when:

- Ears fall to the ground in front of the corn head at first contact
- Ears bounce out of the corn head when separated by the snapping rolls and stripper plates
- Entire stalks and the ears on them are missed by the corn head because of stalk or root lodging

Kernel losses occur at the corn head because of shelling due to impact by the moving parts (gathering chains, snapping rolls, and cylinder) as well as the stationary parts of the head.

Threshing and Separating Losses

Threshing losses refer to those occurring in the cylinder and concave where corn is shelled from the cob. When kernels remain attached to the cob, they are usually lost out the back of the combine as the crop residue is ejected. Separating losses are unattached kernels that fail to make it into the clean grain stream, so they remain in the crop residue as it passes through the chaffer as well as shoe sieves and is blown out the back of the combine.

Distinguishing Corn Field Losses

To distinguish the causes of corn field losses, a process of pre-harvest and in-harvest steps is necessary. This is because ears can be lost both pre-harvest as well as at the corn head, and kernels can be lost at the corn head or in the threshing and separating phases of combining. Basically, lost ears must be measured both in front of and behind the combine; lost kernels must be measured behind the corn head and behind the combine to distinguish their source. Then:

- Preharvest ear losses are ears counted in front of the combine.
- Header ear losses are ears behind the combine minus preharvest ear losses.
- Header kernel losses are counted behind the corn head but in front of the area of crop residue ejected from the back of the combine.
- Threshing losses are counted as those kernels found behind the combine that are still attached to a cob fragment.
- Separating losses are unattached kernels found behind the combine minus kernels found behind the corn head.

Measuring Pre-Harvest Ear Losses

To measure pre-harvest ear losses, count the number of dropped ears in 100 plants at 3 or more sampling locations in the field. Ears with husks attached will be much harder to detect, especially if there is lodging or crop residue on the ground. Because today's hybrids planted at their optimum density generally produce 1 ear/plant, each ear dropped in 100 plants inspected represents about a 1% yield reduction. Multiply the percent reduction by the estimated yield for the field to convert yield loss to bu/acre. If the dropped ears are not full-size ears, convert small ears to normal ear equivalents in making the yield loss calculation. (For example, three small ears are equal to two normal ears.)

Measuring Header Losses

To distinguish kernels lost at the header from those lost out the back of the combine, stop the combine, and back up about 20 ft. Inspect the area already passed over by the corn head but not by the back of the combine. Inspect a 10 ft^2 area by dropping a 2 ft by 5 ft frame on the ground. 20 kernels found in this area equals approximately 1 bu/acre yield loss.

To measure the header losses incurred due to whole ears lost, count the number of ears dropped in 100 plants behind the combine. Subtract from that the number of pre-harvest ears lost. The remainder represents ears lost at the header. One dropped ear in 100 plants is equal to ~ 1% yield loss.

Measuring Threshing and Separating Losses

Threshing losses are represented by kernels still attached to cob fragments found behind the combine. Again, count these still-attached kernels found inside a 10 ft^2 frame opening behind the combine. Each 20 kernels equals approximately 1 bu/acre yield loss.

> **Yield Loss Math**
>
> **Kernels:** 20 kernels lost per 10 ft^2 = ~ 87,000 kernels/acre. One bushel of corn is assumed to contain about 90,000 average-sized kernels.

To determine yield lost during the separating phase of combining, count unattached kernels in a 10 ft^2 area behind the combine. Subtract from this number the kernels counted in the area passed over by the corn head only. For each 20 kernels in the remainder, approximately 1 bu/acre of yield is lost.

Combine Considerations

Combine settings and operation are critical to minimize harvesting losses. The combine is a complex machine that gathers, threshes, and cleans the grain. Poor combine adjustment can result in not only lost yield but reduced grain quality as well. When set properly, most combines, both cylinder and rotor types, can do a good job of preserving yield while separating kernels from the non-grain portion of the crop.

Growers are advised to set the combine to manufacturer-recommended settings as a starting point and then adjust to the condition of the crop. Frequent checking and re-adjusting can then keep the combine set appropriately to reduce both harvest losses and kernel damage. When crop conditions change during the day, small adjustments may be necessary.

The goal of proper combine settings is to achieve a smooth, even flow of crop material moving through the machine. The combine should run nearly full to minimize impact on the grain. A near-empty machine, on the other hand, leads to multiple contacts of the machine and the grain, which increases breakage.

Gathering Snouts: Adjust snouts so that they just touch the ground under normal conditions. If plants are lodged, let snouts float on the ground, and reduce ground speed as needed.

Snapping Roll and Stripper Plate Spacing: Set snapping roll spacing according to stalk thickness. Set the stripper plates (aka, deck plates or snapping bars) as wide as possible without losing ears or shelling corn off the ear. (This reduces the amount of stover taken into the machine.) Plates should be set slightly narrower (⅛ to 3⁄16 inches) in front than in back to prevent wedging. If ears are small in diameter due to drought, narrow the stripper plates accordingly so ears are not pulled through and lost.

Ground and Snapping Roll Speed: The ground speed depends on the condition of the crop but should generally be as fast as possible without plugging the head or threshing mechanism. Snapping rolls should be set relative to ground speed. When set too fast, snapping rolls increase the impact of the ear on the stripper plates. This causes kernels to be shelled and lost, increases breakage of ear butt kernels, and results in ear bounce.

Cylinder/Rotor and Concave: The cylinder or rotor is designed to thresh corn from the cob. It is no surprise then that cylinder/rotor speed is the leading cause of grain damage by the combine. In one study, increasing the cylinder speed from 300 to 600 rpm increased kernel damage from below 5% to over 30%. However, if threshing is too gentle, unshelled kernels can be lost with the cobs.

Growers should use the lowest possible cylinder/rotor speed that will shell the grain within acceptable loss levels (less than 1% in good-standing fields). To reduce unthreshed losses without increasing grain damage, try decreasing the concave clearance before increasing cylinder/rotor speed. If this does not achieve satisfactory threshing, then begin to increase cylinder/rotor speed, as required.

Concave clearance should be set so as to avoid breaking the cobs excessively, which can lead to kernels left on cob fragments. Cobs should only be broken into 3 or 4 pieces for best threshing results and minimal threshing losses.

Separation and Cleaning: After threshing, the grain is separated from non-grain crop material by the chaffer and shoe sieves and the cleaning fan. Lighter chaff is blown out the back of the combine, while heavier unthreshed cob segments are returned to the thresher by the tailings system. Screens allow fine grain particles and foreign matter to be removed in the cleaning process.

The goal of separation and cleaning is to achieve a clean, high-quality end product while minimizing grain losses. To accomplish this, sieve and fan settings are critical. If the fan speed is too high, kernels will be lost. If too low, excess foreign material is retained in the grain. Begin with manufacturer suggested settings; then, check and adjust frequently. Crop conditions, including non-grain crop moisture, can change rapidly during autumn days. Monitor losses behind the combine and grain quality in the grain tank throughout the day.

Safety First!

The dangers of a combine in operation are readily apparent, so do not take chances! The following safety tips are given by Dr. Mark Hanna, Extension Ag Engineer at Iowa State University (Hanna, 2008).

- Disengage power, and shut off the engine before leaving the operator's station.
- Keep shields in place.
- Mechanically lock and block the corn head before getting underneath it.
- Carry two fire extinguishers – a small one in the cab and a 20lb unit at ground level.
- Know where all bystanders are during machine operation.
- Take a break to reduce fatigue and stay alert.

Timing Corn Harvest

*by **Steve Butzen, M.S.,** Agronomy Information Consultant*

Summary

- Proper timing of corn harvest has important implications for harvestable yield, grain drying costs, and profits.
- Monitoring maturity stages and then grain moisture as well as crop condition during the drydown period are useful tools in making the best possible harvest timing decisions.
- Deterioration of stalks and ear shanks leads to unharvested ears and is the most common cause of field losses.
- Wet fall conditions extend the drydown period and increase the rate of stalk and ear degradation.
- Most studies have refuted the notion that unknown causes of kernel dry matter loss occur during field drydown. Thus, base harvest timing decisions on known causes.
- Studies that measured kernel respiration discount the theory that respiration results in significant losses of dry matter.
- Comparing the additional cost of drying with the expected yield savings due to early harvest is a straightforward way to strike the right balance between the two.
- Pioneer studies in 18 locations showed a 1.5% advantage for early harvest – not enough to cover added drying costs.

Introduction

Timing of corn harvest is a critical crop management decision for growers. Early harvest can reduce field losses but increases drying costs and may reduce grain quality and storability if kernels are damaged during combining and handling. Harvesting later reduces drying costs but may result in excess deterioration of the crop that may decrease harvestable yield and quality. Thus, there is a right time to harvest each field, but competing demands and weather play an important role in achieving the goal of harvest on a specific date. Nevertheless, growers taking a systematic approach to monitoring their fields during drydown and evaluating loss potential can make the best possible decision in prioritizing their fields for harvest.

Corn Development After Silking

A review of the corn development process during the grain fill period is a helpful tool in monitoring crop progress as maturity approaches. As kernels develop, they progressively gain in dry weight as starch accumulates and displaces moisture in the kernel. Beginning at the dent stage (R5), a line of demarcation is visible between the hard, structural starch deposited in the crown of the kernel and the milky content of the rest of the kernel (toward the tip). This border is known as the "milk line" (Figure 1 and Table 2).

Table 1. Approximate time after silking to beginning of each reproductive growth stage.

Reproductive Stage	Description of Stage	Weeks after Silking
R1	Silking	--
R2	Blister	2 weeks
R3	Milk	3 weeks
R4	Dough	4 weeks
R5	Dent	5-6 weeks
R6	Physiological maturity	8-9 weeks

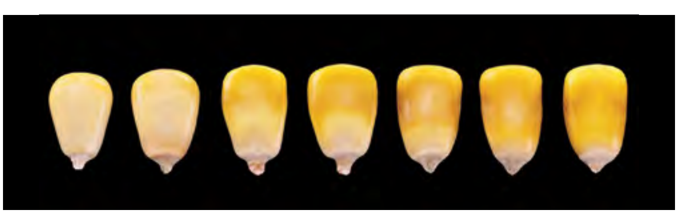


Figure 1. Progression of milk line in corn kernels from R5, or early dent (left), to R6, or physiological maturity (right).

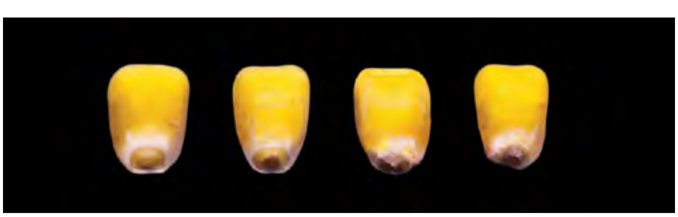


Figure 2. Progression of black layer development in kernels (at tip of kernels), indicating physiological maturity (R6).

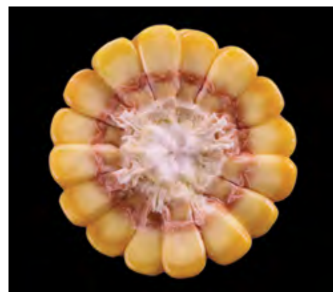
Physiological maturity is defined as the point at which dry matter accumulation ceases in the grain. This point is visually indicated by the formation of a black abscission layer between the corn kernel and the cob (Figure 2). This abscission layer halts further nutrient transport from the plant into the grain and so represents the point of maximum dry matter accumulation (i.e., yield) in the grain.

Table 2. R5 to R6 kernel stages, grain moisture, and GDUs remaining to maturity.

Stage R5
Beginning dent
Milk line starting to appear at top of kernel

Grain Moisture: ~50-55%

~400 GDUs remaining to maturity



Stage R5.25
¼ milkline

Grain Moisture: ~45-50%

~300 GDUs remaining to maturity

Stage R5.5
½ milkline

Grain Moisture: ~40-45%

~200 GDUs remaining to maturity

Stage R5.75
¾ milkline

Grain Moisture: ~35-40%

~100 GDUs remaining to maturity

Stage R6
Black layer
or "no milkeline"

Grain Moisture: ~28-32%

0 GDUs remaining to maturity

Corn Kernel Drydown

The period from black layer to harvest is defined as the "drydown" period. Kernel moisture loss during the drydown period is entirely due to evaporative moisture loss affected by air temperature, relative humidity, and wind. When corn reaches maturity early in the season, field drydown is faster due to warmer air temperatures. For example, according to Ohio State University Extension, corn drying rates as high as 1% per day in September will usually drop to ½ to ¾% per day by early to mid-October, ¼ to ½% per day by late October to early November, and only ¼% per day or less by mid-November (Thomison, 2011).

Pioneer research indicates that it takes approximately 15 to 20 GDUs to lower grain moisture each point from 30% down to 25%, 20 to 25 GDUs per point of drydown from 25 to 22%, and 25 to 30 GDUs per point from 22 to 20% (Pioneer, unpublished).

Grain moisture at harvest affects the time and cost required to dry the grain to acceptable storage moisture levels, as well as grain quality. Wet grain can incur damage during combining, handling, and drying. If grain quality is significantly reduced during harvest and drying, allowable storage time is also reduced, dockage may result, and losses of fines as well as broken kernels can trim bushels of saleable grain. Consequently, choosing the optimum moisture for corn harvest is a critical management decision.

Can Field Drying Result in Corn Dry Matter Losses?

A rural legend has persisted in some circles over the decades that corn left to dry in the field after black layer is susceptible to so-called "mystery" or "phantom" yield loss. The reason for the "mystery" label is because the phenomenon is not ascribed to the most common yield-robbing culprits: dropped ears, lodged stalks, insect feeding, or ear rots. Rather, "kernel respiration" is hypothesized to be the primary cause for the supposed dry matter losses.

The narrative first gained credibility following testimonials in farm publications and a university study in the early 1990s (Nielsen et al., 1996). Following this, other researchers began to report data from previous studies that had measured grain weight as corn drying progressed. Additional studies were planned and conducted as well with the express objective of documenting kernel weight changes during field or lab drying. Results of these studies are summarized below.

- An Iowa State University study at 2 locations of 4 hybrids and 6 harvest dates documented no yield reductions as corn field-dried from 35 to 19% (Knittle and Burris, 1976).
- A University of Illinois study tested four hybrids and four harvest dates. No hybrid showed significant changes in dry weight as moistures decreased from 27 to 18%. (Nafziger, 1984).
- Pioneer researchers measured kernel moistures and dry weights of eight hybrids at sequential harvest dates in 1983 and 1984 (Cerwick and Cavalieri, 1984). No hybrids showed yield reductions during drydown.
- Pioneer agronomists studied two hybrids at two locations (Reese and Jones, 1996). Dry weight did not decrease as drydown progressed from black layer to 15% grain moisture.
- In field and lab drydown studies conducted at the University of Nebraska from 1995 to 1997, a total of six hybrids and nine drying environment/harvest method combinations were examined (Elmore and Roeth, 1996). The study found no evidence of kernel dry matter loss following physiological maturity.
  - » Importantly, the study included one of the same hybrids tested in the Purdue study but with conflicting results. The authors concluded that the different results were likely due to different methods in measuring grain moisture; the Nebraska study used oven-dry weights rather than an electronic moisture meter because meters may be inaccurate at moistures above 25%.
  - » The authors concluded that their results showing stable grain dry matter following maturity do not support the need for early harvest and the associated energy expense for grain drying.
- In 2002 to 2004, field studies were conducted by Ohio State University researchers at three locations to determine effects of three harvest date periods and four plant densities on four corn hybrids differing in maturity and stalk strength (Thomison et al., 2011). They found no evidence of dry matter losses with harvest delays.
- In 2016 and 2017, Iowa State University conducted replicated studies at two locations to determine if corn dry matter loss occurred in the field after maturity (Licht et al., 2017). At each environment, three hybrids of differing maturity were planted at two planting dates and harvested on six (2016) or seven (2017) separate dates during the post-physiological maturity drydown period.
  - » In this extensive study in which grain moistures ranged from over 30% down to 15% during drydown, kernel dry matter weight showed no change over progressive harvest dates (Figure 3).

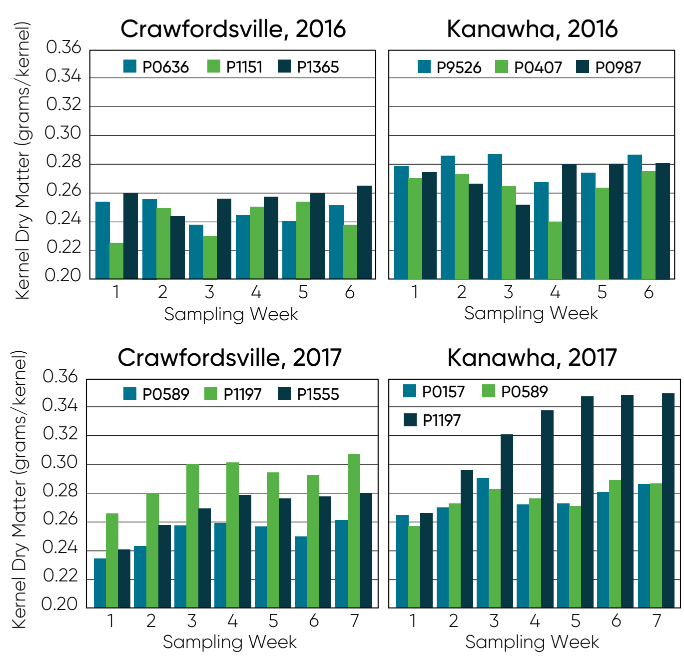


Figure 3. Corn kernel dry matter weights over the post physiological maturity dry down period (Sept. and Oct.) for 2 planting dates and 2 Iowa locations in 2016 and 2017.

Therefore, it appears that yield losses observed in on-farm studies with late compared to early harvest are due to other field loss factors. These factors may not be readily noticeable, but 1 bu/acre is lost with only 2 corn kernels per square foot, which can add-up quickly when corn is less than 20% grain moisture (Nafziger, 2018). Combine adjustments to minimize these losses are reviewed in the *Crop Insights* titled, "Measuring and Reducing Corn Field Losses" (Butzen, 2018).

Kernel Respiration Effect on Yield

Prior research studies were examined to determine if there was evidence of corn kernel respiration rates high enough to explain large yield losses in the field during drydown. A study conducted at Iowa State University showed that when kernel moisture dropped below 30%, the respiration rate slowed dramatically and was only a fraction of the rate measured at the dent stage (Knittle and Burris, 1976).

In another study conducted by ag engineers at the USDA, shelled corn samples were evaluated for dry matter losses in storage at six temperatures (Saul and Steele, 1966). Samples were at 28% moisture at the beginning of the storage period. Researchers measured the amount of carbon dioxide given off by the samples over time and converted this number to dry matter loss (DML). Results are shown in the following table:

Days Required for 1% Dry Matter Reduction in Stored Corn*

Temperature	35 °F	50 °F	65 °F	80 °F	95 °F	110 °F
Days	129	50	25	10	6	4

These results represent the undamaged control sample in the study.

Average temperatures in the Midwest U.S. are 55 to 65 °F in the last half of September, and 50 to 60 °F in the first half of October. At these temperatures in the storage study, 1% dry matter loss would not occur for 25 to 50 days. This level of dry matter loss due to kernel respiration does not warrant early harvest and substantially higher drying costs for wet corn.

Stalk Quality Considerations on Corn Harvest Timing

Many different stresses to the corn plant can lower stalk quality with the result that stalk problems occur in some fields each year. Drought stress; reduced sunlight; insect and disease pressure; and hail damage are stresses that can result in poor stalk quality. Even high yields are a stress on the plant that may lead to stalk problems. Many additional factors, including cropping history, soil fertility issues, hybrid genetics, and microenvironment effects, can heighten the problem in particular fields.

Growers are encouraged to monitor their fields as harvest approaches to identify stalk quality problems and prepare to harvest before field losses occur. Scouting fields approximately two to three weeks prior to the expected harvest date can identify fields with weak stalks predisposed to lodging. Fields with high-lodging potential should be slated for early harvest. Weak stalks can be detected by pinching the stalk at the first or second elongated internode above the ground. If the stalk collapses, advanced stages of stalk rot are indicated. Another technique is to push the plant sideways about 8 to 12 in at ear level. If the stalk crimps near the base or fails to return to the vertical position, stalk rot is indicated. Check 20 plants in 5 areas of the field. If more than 10 to 15% of the stalks are rotted, that field should be considered for early harvest.

Grain Quality Considerations on Corn Harvest Timing

Maintaining grain quality through harvest and storage is a critical goal to optimize profitability. Harvest timing is the primary factor under control of the grower to optimize grain quality. Harvesting grain at too high of moisture content can result in severe kernel damage during threshing and drying. Conversely, allowing corn in the field too long can lead to reduced yield and quality if stalk or ear rot diseases or insect feeding damage are increasing.

Ear rots are a particular concern if weather conditions turn wet in the fall. If ears are in contact with the ground under these conditions, ear rots may develop quickly. Growers should scout fields regularly during the drydown period to inspect ears and for possible disease development. Strip back the husks on five plants in five areas of the field to check for insect feeding or ear rots. If these problems are severe, consider harvesting early and drying grain to below 18% moisture to stop progression of both insects and diseases as well as to maintain the best possible grain quality.

Most growers have experienced the need to harvest corn at high moistures when late planting or cool temperatures have delayed crop development and are well aware of the devastating effects on grain quality. For this reason, grain quality experts would like to see corn field dry below 20% moisture before harvesting. However, if grain quality is deteriorating, beginning harvest at about 25% moisture may be necessary, especially if there are many at-risk fields to follow. The key to which of these suggestions is appropriate for your fields is to closely monitor both moisture and crop condition, beginning at physiological maturity.

Cost of Extra Drying

Removing 1 point of moisture from a bushel of corn requires about 0.02 gallons of propane. At the cost of $1.50/gal propane, the cost would be 3 cents/bushel. Thus, the additional drying cost incurred by harvesting at 25% moisture instead of field drying to 20% would be 15 cents

Table 3. Bu/acre of corn required to offset additional drying costs when harvesting early.

Yield Level (bu/acre)	Extra Points of Moisture Due to Early Harvest					
	1	2	4	6	8	10
	Bu/Acre Needed to Offset Extra Drying Costs					
100	0.9	1.7	3.4	5.1	6.9	8.6
125	1.1	2.1	4.3	6.4	8.6	10.7
150	1.3	2.6	5.1	7.7	10.3	12.9
175	1.5	3.0	6.0	9.0	12.0	15.0
200	1.7	3.4	6.9	10.3	13.7	17.1
225	1.9	3.9	7.7	11.6	15.4	19.3
250	2.1	4.3	8.6	12.9	17.1	21.4
275	2.4	4.7	9.4	14.1	18.9	23.6
300	2.6	5.1	10.3	15.4	20.6	25.7

Propane cost = $1.50/gal. Corn price = $3.50/bu.

per bushel (this does not account for any costs attributable to the extra time involved in drying). At $3.50/bu of corn, 4.3% of yield ($0.15/$3.50) would have to be saved to pay for the cost of removing an additional 5 points of moisture in drying. Table 3 shows the bushels per acre of corn needed to pay for the additional drying costs of early harvesting at various yield levels.

Studies on Harvest Timing

For more than 5 decades, researchers have conducted studies that address the harvest timing decision. These studies have usually shown that yields are reduced with delayed harvest due to progressive deterioration of the crop caused by weather factors. As growers might expect, studies often showed differences between years, locations, and hybrids that were related to specific weather conditions occurring between the harvest dates.

Many previous studies indicated that stalk lodging was a major factor contributing to yield losses with delayed harvest. An Ohio State study (Thomison et al., 2011) tested four hybrids differing in maturity and stalk lodging ratings at four plant densities in three locations over three years. Predictably, the study showed that decreases in grain yield and increases in stalk rot as well as lodging associated with harvest delays were influenced by plant population and hybrid characteristics. Stalk rot and lodging increased at the higher plant populations, and this effect was magnified by late harvesting.

In 2013, Pioneer agronomists conducted studies in three states to help determine harvest timing effects on corn yield and moisture (Prestemon, 2013) (Figure 4).

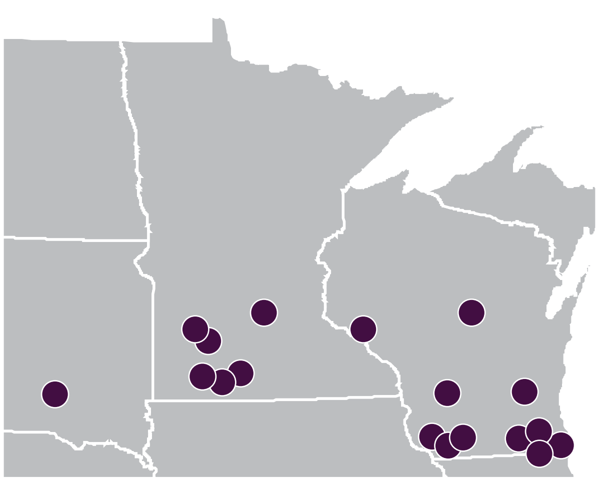


Figure 4. 18 locations evaluated in Wisconsin, Minnesota, and South Dakota for effect of harvest timing on corn yield and moisture, 2013.

A portion of each trial field was harvested "early" with a target moisture around 25%. The remaining portion of the field was harvested a week or more later with final harvest targeted moisture less than 20%. Yield was measured using a weigh wagon to eliminate possible variation due to yield monitor calibration or grain sensitivity. Results are shown in Figure 5.

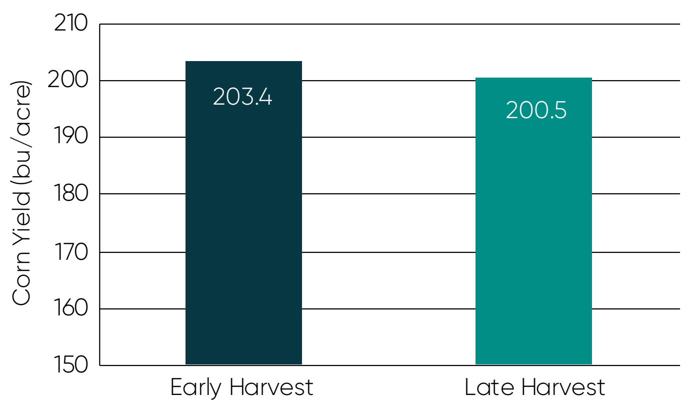


Figure 5. Average corn grain yield with early and late harvest timings across 18 locations, 2013.

As Figure 5 indicates, early harvest yields averaged 2.9 bu/acre higher than late harvest yields. No obvious agronomic issues were noted between early and late harvested areas. Moistures averaged 25.2% for the early harvest and 22.1% for the late harvest. At 3 cents per point of moisture removed per bushel, additional drying costs would be about $18/acre. At a grain price of $3.50/bu, 2.9 additional bushels per acre (~$10 in value) are not sufficient to pay the additional drying cost.

Conclusions

Timing corn harvest to maximize profitability usually means striking a balance between maximizing bushels harvested and minimizing drying costs. Close monitoring of crop condition during drydown is required to make the best possible harvest timing decision. Early harvest with the sole intention of avoiding so-called "dry matter losses" from unknown causes is not recommended.

Proper combine settings are also critical to reduce harvesting losses as well as increase harvested grain and profits. Combine settings must match crop conditions, which change from field to field and even from day to day. Continual monitoring of ears and kernels lost while harvesting is required to make necessary adjustments to the combine (Butzen, 2018).

The Importance of Early Planting for Soybeans in the Midwest

*by **Ryan Van Roekel, Ph.D.,** Field Agronomist*

Yield Potential

Delayed Planting

- Historical planting date research in soybeans has often focused on the negative yield impacts of late planting.
- The potential for significant yield reduction associated with late planting has been well-documented with a rapid decline in yield potential beginning around May 30th in the Midwest at a rate of about 0.7% per day (Figure 1) (Egli and Cornelius, 2009).

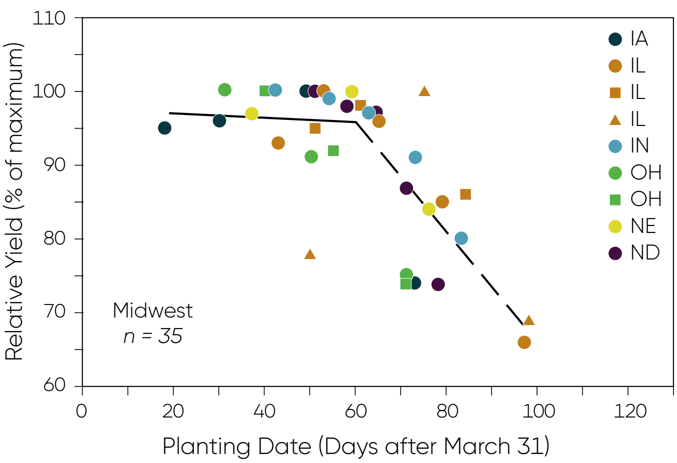


Figure 1. Relative yield by planting date in the Midwest (Egli and Cornelius, 2009).

Early Planting for Higher Yield

- A series of more recent data suggests the potential to increase soybean yield with earlier planting in contrast to prior work which often showed little benefit to late-April or early-May planting compared to mid- to late-May planting.
- Survey data from the Pioneer High Yield Soybean Challenge research effort in Nebraska and Kansas found a 0.41 bu/acre/day linear decrease in soybean yield beginning at the earliest observed planting dates in late-April (Figure 2) (Propheter and Jeschke, 2017).
- A similar trend was observed with Pioneer on-farm soybean plots in Iowa in 2017 with a decline of 0.24 bu/acre/day from the earliest observed planting dates.
- In both of these examples, there were certainly other factors influencing yield at each single location, as indicated by the clusters of data points; however, this yield by planting date trend appears to be real and repeatable.
- Similar trends have been observed in recent planting-date research. A 3-year University of Illinois study showed significant yield benefit with earlier planting in northern and central Illinois (Table 1).

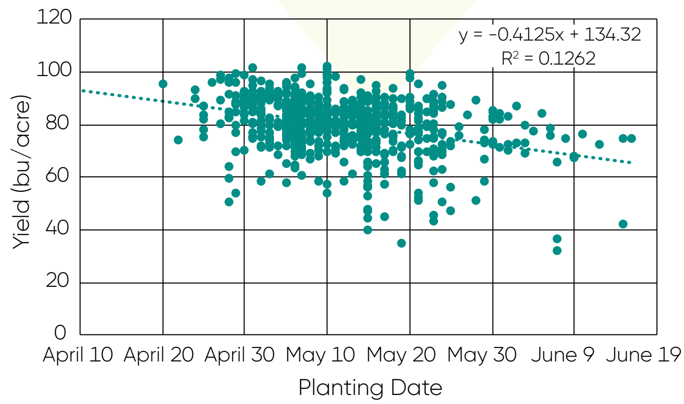


Figure 2. Soybean yield by planting date from High Yield Soybean Challenge entries in Nebraska and Kansas from 2013-2016 (Propheter and Jeschke, 2017).

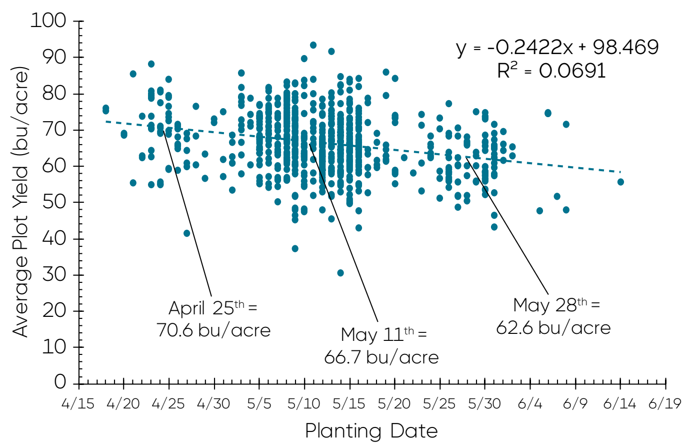


Figure 3. Average plot location yield by planting date from 763 on-farm soybean research locations in Iowa in 2017.

Table 1. Average soybean yield with early and normal planting dates in northern and central Illinois trials conducted from 2012-2014 (Nafziger and Vossenkemper, 2015).

Region	#Site-Years	Planting Date (Average)		Yield	
		Early	Normal	Early	Normal
				bu/acre	
Northern	8	April 28	June 1	70.8	66.1
Central	4	May 5	June 3	69.9	62.0
Average				70.4	64.1

- Recent research exploring the effects of different management factors on soybean yield have often placed planting date near the top of the list.

- A Pioneer sampling effort conducted across 18 states in 2017 to identify important soil and tissue nutrient levels associated with soybean yields found that planting date had the highest correlation with yield of all the nutrient, management, and weather factors investigated.
- Similarly, a university-led research project across 10 states in the North Central U.S. from 2014 to 2015 also found planting date to have the most consistent impact on soybean yield (Edreira et al., 2017). Yield penalties for later planting ranged from 0 to -0.5 bu/acre/day with the variation in yield response related to the amount of water deficit stress during the later stages of pod setting (R3-R5). Locations that experienced water stress generally had less of a yield response to earlier planting.

Physiological Effects

Day length Interactions

- Soybean phenological development is well known to be influenced by day length; shorter day lengths will hasten progression through growth stages, while longer day lengths may prolong development.
- This physiological component is critically important for understanding why a soybean crop is responsive to earlier planting.
- A study represented in Figure 4 showed that mid-April planting allowed soybeans to begin flowering before the summer solstice when the days are still getting longer (Parker et al., 2016).
- Not only did early planting allow soybeans to take better advantage of longer day lengths, it also extended the period of reproductive growth – 52 days to reach the R6 growth stage compared to just 37 days for soybean planted in mid-May.

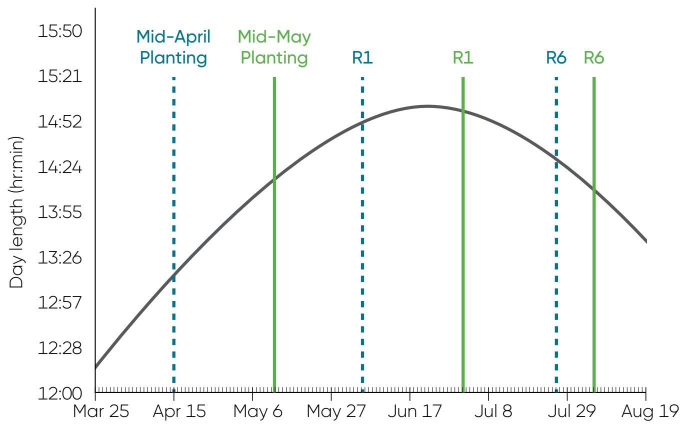


Figure 4. Dates of R1 and R6 growth stages for soybeans planted in mid-April and mid-May near Pittsburg, PA, (40.4° N) from Parker et al. (2016).

Yield Implications

- The reduction in the length of reproductive development with later planting limits the amount of photosynthate that can be produced and allocated to setting pods and seeds.
- Remember that photosynthate production from R1 to R5 is the primary driver of soybean seed number and yield (Van Roekel & Purcell, 2016).
- Certainly, good management, favorable growing conditions or bright sunny days during pod set can result in high photosynthate production and yields, but there is no other way to lengthen the reproductive period than to manipulate planting date and variety relative maturities.
- Of the two, planting date has the larger impact, but there may be additional gains that can be achieved by utilizing slightly later maturities (Nafziger and Vossenkemper, 2015).

Management Factors

- While the yield data make a compelling case for early planting, sometimes the weather in April does not.
- For considering when to begin planting soybeans, a minimum soil temperature of 50 °F (10 °C) is a good rule of thumb as it also is for corn planting (Jeschke et al., 2017).
- Like early-planted corn, soybeans planted into cold soils may take two to three weeks to emerge.
- However, unlike corn, the growing point for soybeans is above the ground upon emergence. This means that the risk of freezing should be weighed more heavily for soybeans. With that said, the large cotyledons are good buffers to protect the growing points from freezing injury, and it takes significant cold to be lethal (<28 °F or -2 °C for >4 hours).
- Utilizing seed treatments is highly encouraged to protect early-planted soybean seeds from prolonged exposure to soil fungi pathogens and early-season insects.
- Finally, like many things in agriculture, nothing is guaranteed. Early planting of soybeans that results in a longer reproductive period will have higher yield potential than later planting. However, final yield still depends upon many other interactions with pest control, fertility, and weather, which remains out of our control.

Soybean Seeding Rate – Past, Present, and VRS Future

*by **Adam Gaspar, Ph.D.,** Integrated Field Sciences*

Summary

- Optimal soybean seeding rates are affected by multiple factors with the inherent productivity of the environment being critical.
- While variable rate seeding (VRS) technology has been rapidly adopted by growers for corn, it has lagged for soybean production.
- Recent research shows there is opportunity for growers to better manage their annual soybean seed investment with variable rate seeding technology.
- Soybean VRS strategies should be the inverse of corn. Raise seeding rates in areas of lower productivity, and lower seeding rates in areas of higher productivity.
- Encirca® Stand service provides the necessary platform, agronomic science, and technology to successfully develop soybean VRS prescriptions.

Introduction

Soybean seeding rate and its relationship with yield has been intensely studied in major soybean-producing regions across the U.S. by industry, universities, and grower on-farm trials. The goal of these studies, as with many agricultural inputs, is to determine an agronomically optimal rate (the minimum level of input required to maximize yield). While many of these studies succeed in identifying optimal soybean seeding rates and quantifying variability between fields, they fail to evaluate the seeding rate response within the field's own inherent variability (De Bruin and Pedersen, 2008; Epler and Staggenborg, 2008; Gaspar et al., 2017; Holshouser and Whittaker, 2002). The adoption of variable rate drives on planters and tools, such as Encirca® services, over the past decade now allow growers to identify and better manage the spatial and temporal variability across a field to increase productivity and return on investment (ROI). This article will discuss the potential to adapt this technology to optimize soybean seeding rates at a more granular level.

Past and Present Soybean Seeding Rates

Historically soybeans were often seeded at rates well over 200,000 seeds/acre. However, since the turn of the current century, on-farm seeding rates have steadily declined by roughly 2,000 seeds/acre/year to an average of 152,000 seeds/acre in 2017. There are numerous reasons for this decline. More accurate planting equipment is now common after many growers have switched from drills to row crop planters (>80%) as the number of crops in rotation has decreased (Jeschke and Lutt, 2016). Seed treatment adoption has reached >80% allowing for more successful stand establishment (Gaspar et al., 2015). Seed quality and vigor has dramatically improved with adoption of better seed handling and cleaning equipment (Shelar, 2008). Furthermore, the adoption of soybean varieties with herbicide resistance traits has shifted the focus away from cultural control tactics, such as higher seeding rates for weed management (Bertram and Pedersen, 2004).

The aforementioned factors have caused growers to question if a further decrease in soybean seeding rates is warranted. Some studies have determined that 100,000 plants/acre at harvest time are required to maximize light interception and thus yield (Gaspar and Conley, 2015; Lee et al., 2008) while other studies have shown economically optimal seeding rates ranging from 95,000 to 130,000 seeds/acre (Gaspar et al., 2017). However, these studies are typically conducted on one soil type that is uniform, well drained, and highly productive, totaling less than one acre in size. This is done in an effort to minimize environmental effects and variability. The same has typically been the case where on-farm trials use strips across an entire field length, which moderates the impact of high and low productivity areas within that strip. In comparison to these studies, others have suggested seeding rates as high as 243,000 plants/acre are needed in more stressful environments (Holshouser and Whittaker, 2002). Thus, there is clearly a wide range of agronomically and economically optimal seeding rates and plant stands that depend on seed costs, grain prices, seed treatment use, and most importantly, the inherent productivity of the environment.

Soybean VRS Future

With the rapid adoption of geo-spatial tools, such as yield maps and variable rate planter drives, growers are better able to manage their annual seed investment by spatially adjusting seeding rates based upon the productivity of the environment and its underlying environmental factors (Smidt et al., 2016). This is applicable at the between-field and within-field levels. Variable rate seeding (VRS) technology has been rapidly adopted for corn production with early research taking place in the late 1990s (Bullock et al., 1998). Research and adoption has not been as intense for soybeans, but recent research from Gaspar et al. (2018) demonstrates that there are significant opportunities in VRS for soybeans. Therefore, we will incorporate the results of Gaspar et al. (2018) and provide guidance for successful soybean VRS implementation to manage the variability present in every field.

Agronomically Optimal Seeding Rates

Growers have typically established a seeding rate that works across their farming operation based upon experience and regional recommendations to maximize yield and agronomic benefits, such as stand establishment, weed control, and disease management. This rate can be considered the agronomically optimal seeding rate (AOSR) for all yield levels (i.e., average or local standard seeding rate). Many have speculated that the philosophy behind soybean VRS should be the inverse of corn VRS, suggesting that soybean seeding rates should be increased in areas of lower productivity and decreased in areas of higher productivity compared to the "average" seeding rate. Many anecdotal reports have confirmed this philosophy as a method to increase yield in lower productivity areas as well as maintain yield and reduce seed costs in higher productivity areas, resulting in greater whole field yield and profit. However, there has yet to be a comprehensive study testing this philosophy until the recent publication of Gaspar et al. (2018).

In this study, soybean seeding rate studies from across the U.S. and Canada were compiled from over 200 environments spanning multiple years and totaling 21,000 data points, which represents the largest replicated soybean seeding rate data set to date (Figure 1).

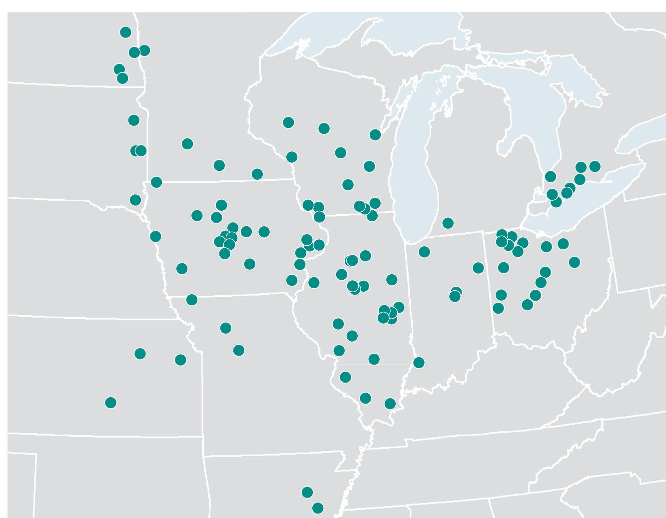


Figure 1. Location of soybean seeding rate studies from Gaspar et al. (2018).

The results of Gaspar et al. (2018) confirmed that soybean VRS strategies should increase seeding rates in areas of lower productivity and decrease seeding rates in areas of higher productivity relative to the average yield level and seeding rate of an individual field (Table 1). In addition, the relative increase (+19%) in seeding rate to reach the AOSR within lower yield levels is approximately 3 times the decrease (-6%) in seeding rate to reach the AOSR within higher yield levels (Table 1). This trend is even greater in the northern Corn Belt where the relative increase in seeding rate is 6 times that of the decrease to reach the AOSR of the low and high yield level (+41% in low vs. -8% in high) (data not shown).

This study also quantified the risk associated with decreasing or increasing the seeding rate from the AOSR within each yield level. Table 1 shows that increasing seeding rates beyond the AOSR by 20% resulted in a 56 to 60% chance of increasing yield above the AOSR across yield levels. In comparison, decreasing seeding rates below the AOSR by 20% provided a 65 to 84% chance of yielding less than the AOSR with greatest risk in high yield levels. Thus, risk-averse growers may choose to increase seeding rates slightly above the AOSR to ensure yield is maximized, while growers who are comfortable with additional risk may choose to decrease seeding rates slightly below the AOSR within each yield level. That being said, all growers should understand that there is considerably more downside risk or potential yield loss with a 20% decrease from the AOSR than upside potential with a 20% increase from the AOSR (Table 1).

Table 1. Agronomically optimal seeding rate (AOSR) relative to the average yield level AOSR and the risk associated with divergence from the AOSR in each yield level.

		Probability of Yield Increase	
Yield Level	*AOSR Divergence from Avg.	AOSR + 20%	AOSR - 20%
High	-6%	59%	16%
Avg.	~	60%	17%
Low	+19%	56%	35%

*AOSR divergence from the average represents the % increase or decrease in seeding rate from the average yield level to reach the AOSR of the high or low yield level.

Ultimately, exact seeding rates employed on a VRS prescription for an individual field will need to be determined on a case-by-case basis driven by grower experience and regional recommendation but should follow the VRS strategy outlined above by Gaspar et al. (2018). Encirca® Stand service can assist with this effort and details are discussed later.

Physiological Drivers of This Strategy

Adequate soybean stand establishment is required for agronomic and economic success. Many growers have adjusted seeding rates based on the theory that stand establishment (early season plant stand ÷ seeding rate) in areas of low productivity is reduced. Therefore, it is reasonable to assume that reduced stand establishment is the driving principal of why seeding rates should be increased in lower productivity areas of the field. However, this is not the case according to Gaspar et al. (2018), who found stand establishment was not affected by yield level, regardless of geographical location in the U.S. Thus, yield level and stand establishment are not connected, and stand establishment is not the driving factor behind the relatively higher seeding rates required in low productivity areas of a field.

Plant attrition is defined as the unexplained plant stand loss from emergence through harvest. Much like that of early season stand establishment, the amount of plant attrition throughout the growing season, and therefore harvest stand, did not differ between yield levels. However, Gaspar et al. (2018) did find that seeding rate affected the amount of plant attrition in that higher seeding rates experienced greater amounts of plant attrition (data not shown).

Averaged over seeding rates, the effect of plant attrition on final yield is displayed in Figure 2. At the high yield level, plant attrition does not affect yield, while a negative relationship exists for the average and to a greater extent, low yield levels. Therefore, in low yield levels, not only are higher seeding rates required to reach the AOSR, but maintaining this increased plant stand throughout the growing season is critical to maximize yield (Figure 2). The use of seed treatments; appropriate tillage and planting practices; narrow rows; and adequate fertility are all components that can minimize in-season plant attrition in areas of lower productivity.

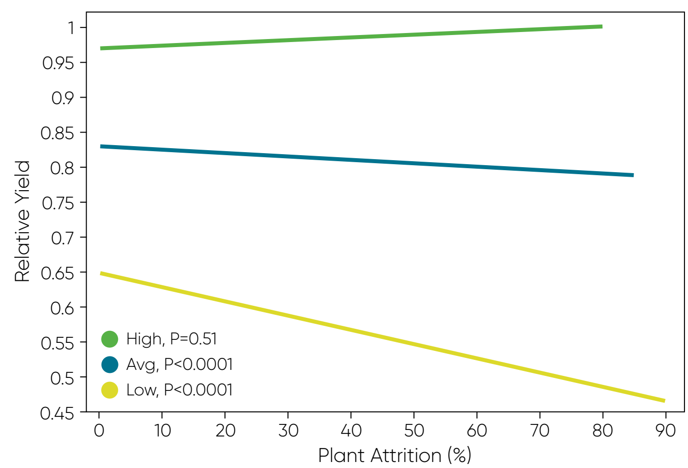


Figure 2. Plant attrition relation to relative yield in three different yield levels.

A key point to remember is that soybean yield is linearly related to light interception, and this relationship is typically more critical in the Northern U.S. versus the Southern U.S. (assuming typical planting dates). Simply put, greater season-long light interception equals greater yield. In highly productive environments, current varieties can maintain yield with slightly reduced plant stands because the individual plant growth rate is not limited, and maximum light interception, and therefore yield, is still achievable. Furthermore, breeding efforts have increased the yield produced per plant, and specifically, this increase is attributed to the branches, not the main stem of the plant (Suhre et al., 2014). This complements lower plant stands. This complements lower plant stands by increasing the plant's compensatory ability where plant stands are lower within highly productive areas (Carpenter and Board, 1997). However, in the inverse direction, breeding efforts have also made current soybean varieties more responsive to higher seeding rates. This complements the increased seeding rate required in areas of lower productivity, where plant growth rate and branching can be limited due to many potential factors, such as precipitation amount, soil water-holding capacity, nutrient supply, rooting depth, etc. These factors, most commonly limiting in low productivity areas, can challenge the ability of soybean plants to maximize season-long light interception. Increased plant density is therefore required to maximize light interception and yield in these lower yield levels. In the same line, total season-long light interception is typically limited in northern latitudes, and this explains why the increase in seeding rate to reach the AOSR within the low yield level is relatively greater in northern versus southern latitudes (Gaspar et al., 2018). These aforementioned factors all contribute to the true physiological basis driving this soybean VRS strategy.

Building Soybean VRS with Encirca® Stand Service

Encirca® Stand service provides the technology and science in one platform to combine multiple sources of data to define and quantify the relative productivity across each individual field and subsequently implement the soybean VRS strategy outlined above. Three general steps to implement Encirca Stand service soybean VRS include:

1. Establishing accurate and representative Encirca services Decision Zones
2. Applying the science-based soybean VRS model
3. Refining VRS prescriptions based upon additional grower knowledge of individual fields

1.) Decision Zones: What Factors to Consider?

The first step in successful implementation of soybean VRS is using sound data to understand the range in productivity across a field. The amount of information that can be collected on any acre is immense and sometimes overwhelming to sort through. What is important in defining management zones?

Use of unpredictable factors like soil crusting or seedling disease incidence make the success of decision zones just that, unpredictable. In comparison, Encirca® Stand service combines the more pertinent and predictable information listed below to partition a field into individual Decision Zones, which consistently vary in productivity. Different seeding rates can then confidently be applied to each decision zone (Jeschke et al., 2015).

- EnClass® services soil types driven by Environmental Response Units (ERU)
  - » Soil type, topography, landscape, slope, drainage
- Yield history or NCCPI when yield history is not available
- Delineation of irrigated and dryland areas of the field, if applicable (i.e., pivot corners)
- Incorporation of electrical conductivity (Veris) or vegetative indices (NDVI)

2.) Applying the Soybean VRS Model

A local standard seeding rate must first be entered for an entire operation or each individual field within Encirca Stand service. The local standard seeding rate, represented by the blue line in Figure 3, is best described as the seeding rate recommended for your local area that would traditionally be used as the single flat rate across the whole field. This local standard rate will vary across the U.S. and therefore, allows local customization. A weighted average productivity of an individual field will be calculated and associated with the local standard seeding rate assigned to each individual field. The soybean VRS model will then increase the seeding rate as the productivity decreases and decrease the seeding rate as productivity increases in each decision zone relative to the weighted average productivity of that individual field. The increase in seeding rate will be greater than the decrease per unit of productivity. Furthermore, the seeding rate range of the prescription for an individual field, which is represented by the green lines in Figure 3, will be dependent upon how variable the field is but will not surpass the seeding rate boundaries. Seeding rate boundaries are represented by the yellow lines in Figure 3. Based upon the local standard seeding rate entered, the range in field productivity, and the soybean VRS model, a seeding rate will be applied to each individual Decision Zone (Figure 3). The seeding rate applied to each individual zone will subsequently be increased or decreased based upon seed treatment use and variety specific attributes. This provides a highly-tailored soybean VRS prescription that considers genetic, environment, and management components.

3.) Refining with Additional Grower Knowledge

Many growers have gained firsthand knowledge of areas within a field that require further consideration and unique management. Adjusting seeding rates can be a key factor to manage these situations. For example, increased seeding rates will help mediate soybean iron chlorosis deficiency and improve weed control. In the inverse direction, decreasing seeding rates is an effective management practice for white mold control. While these situations are not the norm across every operation, some fields will require management of these situations annually. Therefore, the seeding rate in each Decision Zone can be manually edited, when required, to manage unique situations like these.

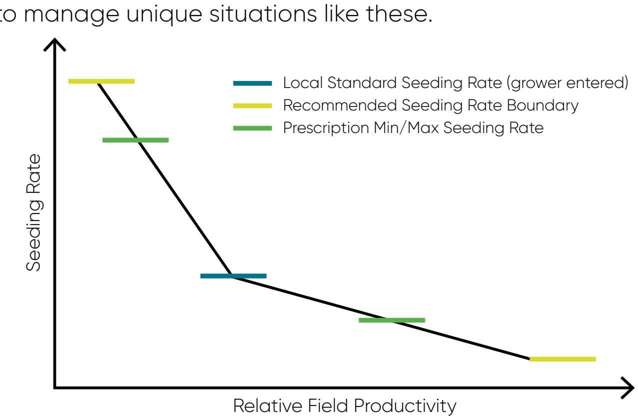


Figure 3. Example of soybean VRS model output for an individual field.

Conclusions

There is an opportunity for growers to fully utilize current planter technology and better manage their soybean seed investment by implementing VRS technology, particularly in more northern latitudes. Ultimately, the specific seeding rates for the varying levels of productivity across an individual field will be based upon local and regional recommendations; grower risk tolerance; economics; variety characteristics; seed treatment use; and other agronomic factors but should follow the trend of increasing seeding rates in areas of lower productivity and decreasing seeding rates in areas of higher productivity. Encirca Stand service, coupled with Encirca certified services agents and Pioneer sales representatives, provides the necessary platform, agronomic science, and technology to develop successful soybean VRS prescriptions that consider genetic, environment, and other management components.

Gall Midge in Soybeans

by **Mark Jeschke, Ph.D.,** Agronomy Manager, with contributions from **Curt Hoffbeck,** Field Agronomist, **Matt Essick,** Agronomy Manager, **Jessie Alt, Ph.D.,** Research Scientist, and **Ryan Rusk,** Pioneer Sales Professional

Gall Midge – A New Pest of Soybean

- Gall midge (also referred to as *soybean gall midge* or *orange gall midge*) is a relatively new pest of soybean.
- Gall midge has been observed in soybeans for several years, but infestation levels and damage to soybeans have increased recently.
- Little is currently known about this pest. It has been identified as belonging to the genus *Resseliella*, which includes 15 species in the U.S., none of which are known to infest soybeans. Genetic and morphological analyses conducted thus far suggest soybean gall midge is a likely new species (McMechan, 2018).
- Research is ongoing to characterize the biology and life cycle of this pest and develop management recommendations.

Gall Midge Species

Hessian fly (Mayetiola de-structtor), an agricultural pest in the Cecidomyiidae family. *Photo courtesy of Scott Bauer, USDA-ARS.*

- The term *midge* is used to refer to a broad group of small fly species encompassing several taxonomic families.
- *Gall midge* refers to a species of flies in the family *Cecidomyiidae.* Gall midges are characterized by larvae that feed inside plant tissue, resulting in abnormal plant growth (galls).
- Over 6,000 species of gall midge have been described world-wide, although the total number of species in existence is believed to be much larger. Over 1,100 species have been described in North America.
- The gall midge family includes numerous species that are economically important pests of agricultural crops, including Hessian fly (*Mayetiola destructor*), wheat blossom midge (*Sitodiplosis mosellana)*, and sunflower midge (*Contarinia schulzi*).
- Some species of gall midge are known to feed primarily on decaying organic matter, fungi, and molds; therefore, they tend to be attracted to damaged or diseased areas on plants.

Field Observations in Soybeans

- Gall midge damage in soybeans was first reported in Nebraska in 2011 in isolated cases mostly associated with damaged or diseased stems. Sporadic infestations were observed in subsequent years, but damage generally was not severe enough to impact yield.
- Gall midge injury was first reported in South Dakota in 2015 and in western Iowa in 2016.
- Pioneer agronomists and scientists at the University of Nebraska, Iowa State University, and South Dakota State University all noted increased infestation in 2018 with infestations occurring earlier in the season and causing higher levels of damage to soybeans.
- Numerous infestations were observed in 2018 by Pioneer agronomists on otherwise healthy soybean plants, indicating that damaged or diseased tissue is not a necessary prerequisite for gall midge infestation.

Characteristics and Plant Injury

- It is currently assumed that gall midge can overwinter in the Corn Belt as a pupa in the soil or crop residue and can complete at least two generations per year.
- Adult midges are small (2-3 mm in length) and have long antennae and hairy wings.
- Larvae are very small and start out white, turning bright red or orange as they mature (Figure 1-4).
- Gall midge injury in soybean is a result of larval feeding, which occurs near the base of the plant. Multiple larvae can infest a plant.
- Larvae feed inside the stem, causing swelling and abnormal growth (galls). Infested portions of the stem will appear swollen and brown (Figure 5-6).
- Discolorations of the stem often begin near the soil surface and can extend up to the unifoliate node.
- Prolonged feeding can cause the stem to eventually break off, resulting in plant death.

Figure 1. Gall midge larvae feeding in a soybean stem near the base of the plant, Nebraska, August 8, 2018. *Photo courtesy of Jessie Alt, Pioneer Research Scientist.*

Figure 2. Gall midge larvae feeding in a soybean stem at the soil surface, South Dakota, August 8, 2018. *Photo courtesy of Curt Hoffbeck, Pioneer Field Agronomist.*

Figure 3. Gall midge larvae feeding in soybean stems. Larvae turn bright red or orange as they mature, Iowa, August 3, 2018. *Photo courtesy of Jessie Alt, Pioneer Research Scientist.*

Figure 4. Gall midge larvae feeding in soybean stems. *Photo courtesy of Ryan Rusk, Pioneer Sales Professional.*

Injury Patterns in Soybeans

- Infestation can occur during vegetative and reproductive stages.
- Injury is generally most severe at field edges (Figure 7-8). Injury on field margins suggests fly movement from previous crop residue to new crop.
- Injury has also been observed next to CRP (Conservation Reserve Program) land, and pastures, tree-lines, and groves.
- In severe cases, infestation can extend into the interior of the field (Figure 9).
- Depending on the severity of gall midge infestation, some soybean plants may wilt, die, or simply show signs of poor pod development and small seed size, especially in the upper ⅓ of the canopy on "healthy-appearing" green plants. Yield loss reports have ranged from one to two bushels per acre to nearly total yield loss depending on how early injury occurs and the severity of the infestation in certain areas of a field.

Figure 5. Galls on a soybean stem due to gall midge infestation (left). Stem girdling resulting from prolonged feeding (right). *Photos courtesy of Jessie Alt, Pioneer Research Scientist.*

Figure 6. Galls on a soybean stem near the soil surface due to gall midge infestation, Nebraska, August 8, 2018. *Photo courtesy of Jessie Alt, Pioneer Research Scientist.*

Figure 7. Dead soybean plants due to gall midge injury along the edge of a soybean field, South Dakota, August 8, 2018. *Photo courtesy of Curt Hoffbeck, Pioneer Field Agronomist.*

Figure 8. Dead soybean plants due to gall midge injury near the edge of a soybean field. Approximately 95% of plants in this area were dead, Iowa, August 3, 2018. *Photo courtesy of Jessie Alt, Pioneer Research Scientist.*

Figure 9. Gall midge injury several hundred feet into the interior of a soybean field. Approximately 50% of plants were dead; all live plants were infested with gall midge larvae, Iowa, August 3, 2018. *Photo courtesy ofJessie Alt, Pioneer Research Scientist.*

Figure 10. Injured and dying plants in a field infested with gall midge, Nebraska, August 8, 2018. *Photo courtesy of Jessie Alt, Pioneer Research Scientist.*

Management Considerations

- Little is currently known about this pest and management recommendations are still in the process of being developed.
- Preliminary investigations into foliar insecticide treatments have shown some promise for suppressing gall midge populations when applied at the time of pre- or early post-emergence herbicide applications to control egg-laying adults.
- However, these types of insecticide applications still need more thorough evaluation, and careful consideration is needed to avoid insect resistance issues with midge or other insects as well as potential harm to beneficial insects.
- Foliar treatments later in the season when larvae feeding in the stems is already underway are not likely to be effective.
- More insecticide treatment timings, active ingredients, and rates need to be fully evaluated to determine what options are effective.
- Cultural practices and insecticide seed treatments do not appear to have an effect on the extent or severity of infestation.
- Scouting recommendations for adult flies have not yet been developed. Scouting is likely to be challenging due to the small size of adult midges.

Dectes Stem Borer in Soybeans

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Pest Facts

- Common names: Dectes stem borer, soybean stem borer
- Latin name: *Dectes texanus,* family *Cerambycidae*
- The Dectes stem borer is a small, long-horned beetle whose larvae attack soybeans. It is a native insect species in North America east of the Rocky Mountains.
- Cultivated sunflowers were historically the preferred host plant for Dectes stem borer, and it was not considered a major pest of soybean. Damage to soybeans has been reported since the 1970s, but it has generally been sporadic.
- In recent years, however, reports of damage in soybeans have increased, both in frequency and in geographic range in the U.S.
- Instances of Dectes stem borer damage to soybeans have spread northward in the last several years, likely due to increasing temperatures.

Identification

- Larva: creamy white to dull yellow in color, without legs, ½-inch long with "accordion-style" segments (Figure 1)
- Adult: gray-colored beetle with long black-and-gray banded antennae; length is ½ inch (13 mm) (Figure 2)
- Egg: very small, white-colored egg laid inside soybean petiole where female cuts a scar

Figure 1. Dectes stem borer larvae.

Figure 2. Adult dectes stem borer.

Figure 3. Egg scars on a soybean stem.

Injury and Pest Symptoms

- Larvae damage soybeans by: 1) tunneling inside the stem as well as reducing yield production capacity and 2) girdling, which causes plants to lodge.
- Larvae girdle stem one to two inches above soil line.
- Girdling, and subsequent lodging, tend to be most severe in early planted, short-season soybean varieties.

Figure 4. Dectes stem borer larva tunneling inside a soybean stem.

Pest Status and Economic Importance

- Dectes stem borer has increased in importance as a soybean pest in recent years. Increased infestation may be due to:
  - » Increased adoption of no-till, which leaves the habitat of overwintering larvae undisturbed
  - » Warmer winter temperatures, which may allow greater numbers of larvae to survive the winter
- Yield losses of 7 to 12% caused by larval tunneling have been reported.
- Greater yield losses can result from lodging caused by the girdling of stems prior to harvest.
- Dectes stem borers are also a pest of sunflowers, in which they cause similar damage by tunneling and girdling the stems.

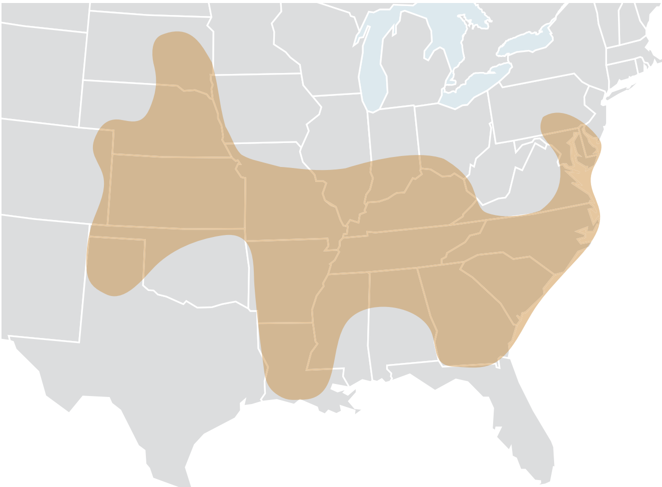


Figure 5. Approximate area of Dectes stem borer infestation in soybean based on Pioneer field agronomist observations, October 2018.

- The geographic range in which Dectes stem borer damage to soybean has been observed has expanded over the past several years (Figure 5).
- Populations infesting sunflowers have been documented further north in the Great Plains, extending into North Dakota.

Life Cycle

- Dectes stem borers go through one generation per year.
- Adults emerge over an extended period during mid-summer.
- Sunflower is the preferred host; soybean is a secondary host. Weed species, such as cocklebur and giant ragweed, can also serve as larval hosts.
- Adults live an average of 23 days on soybean but 53 (males) and 76 (females) days on sunflowers.
- Adults mate and feed on stems and petioles of host plants, leaving longitudinal feeding scars.
- Adults are not strong fliers and will not travel any further than necessary to find a host plant.
- Females lay eggs primarily in leaf petioles. A female will chew a hole in the petiole and then deposit a single egg.
- Larvae tunnel down the leaf petiole and into the main stem, feeding on the pith.
- Multiple eggs can be laid in a plant, but larvae are cannibalistic and typically only one will remain at the end of the season.

Figure 6. Soybean stems girdled and tunnels plugged with frass.

- By the time a soybean plant reaches maturity, the larva will have tunneled down to the base of the plant, where it will overwinter as a mature larva.
- To create a protective cell for overwintering, the larva girdles the interior of the stem at a point near or just above the soil line and plugs the stem with its frass (Figure 6).

Figure 7. Lodging due to stem girdling by Dectes stem borer larvae.

Scouting

- Adults can be found in the soybean canopy throughout most of the summer with peak emergence often occurring in late June or early July and beetle activity extending as late as September.
- As newly hatched larvae tunnel through the petiole toward the main stem, the affected trifoliate will die but remain hanging in the canopy for some time. A dead trifoliate surrounded by healthy leaves is a telltale sign that Dectes stem borer is present (Figure 8).

Figure 8. Dead trifoliate from Dectes stem borer larva tunneling.

Management

Cultural Practices

- Harvest: the best method of reducing yield losses from Dectes stem borer is to harvest heavily-infested fields as soon as possible to minimize lodging loss.
- Planting time: avoid early planting with short-season varieties in areas with known problems.
- Plant resistance: no known resistant soybeans.
- Cropping pattern: avoid crop rotation into commercial sunflowers infested the previous year.
- Tillage: disking or burying infested soybean stems after harvest can reduce subsequent populations.

Insecticides

- Insecticide applications targeted at controlling adults have often had limited effect due to the extended adult emergence period.
- More favorable results have been achieved with applications made prior to egg laying that provide control of the young larvae within the petioles.
- Proper timing of insecticide application is critical for best results:
  - » Use GDUs to determine application date (Base 50, starting January 1st.
  - » Spray within 7 to 10 days of accumulating 1,250 GDUs.
- Consider an insecticide application in soybean fields that will be harvested last or late, which will have a higher risk of yield losses due to girdling/lodging.
- Always read and follow insecticide label guidelines.

Refocusing on Soybean Cyst Nematode Management

by **Mark Jeschke, Ph.D.,** *Agronomy Manager, and* **Pat Arthur,** *Category Leader - Soybeans*

Soybean Cyst Nematode in North America

- Soybean cyst nematode (SCN; *Heterodera glycines*) is a major yield-reducing pathogen of soybean production in North America.
- SCN was likely introduced to the U.S. from Japan. The first report of SCN in the U.S. was in North Carolina in 1954.
- This tiny worm-like parasite has now spread to practically all important soybean production areas of the U.S. and Canada (Figure 1) and is reaching economic levels in more areas.
- SCN may decrease yields substantially without inducing obvious symptoms. Studies have shown that in SCN-infested fields, yields can be reduced by over 30% without visible above-ground symptoms.

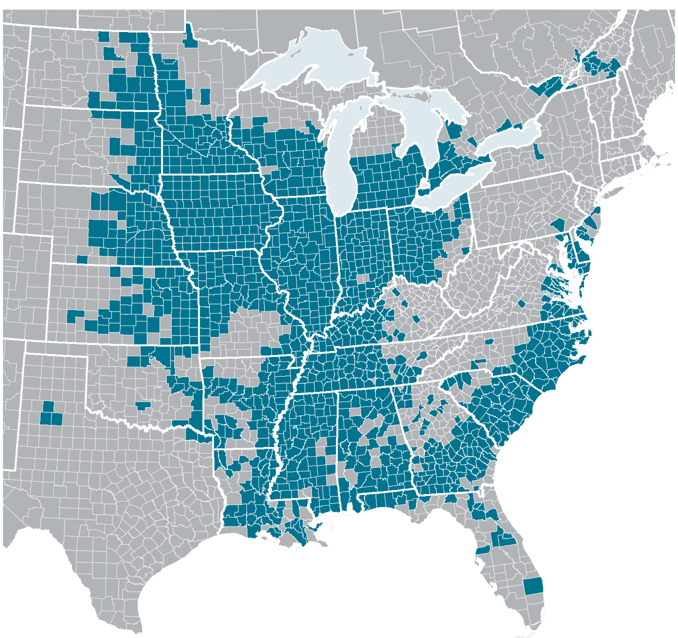


Figure 1. Known distribution of soybean cyst nematode in the U.S. and Canada as of 2017 (from Tylke and Marett, 2017).

Genetic Resistance to SCN

- The most important management tactic for SCN during the years since its establishment as a yield-limiting pest in North America has been selection of soybean varieties with genetic resistance to SCN (Figure 2).
- Researchers have identified a number of soybean lines that have the ability to resist nematode reproduction on their roots.
- Currently, there are three main sources for genetic resistance to SCN in commercially-available soybean varieties: PI 88788, PI 548402 (Peking), and PI 437654 (Hartwig and CystX).
- The PI 88788 source is used in the vast majority of existing SCN-resistant varieties marketed in the U.S.
- Only a small number of varieties currently use the PI 548402 (Peking) source, and even fewer use the PI 437654 source.

Figure 2. Strips of SCN-resistant and non-resistant soybean varieties in a SCN-infested field, showing damage to the non-resistant varieties.

SCN HG Types

- SCN populations are genetically diverse and have historically been separated into races by their ability to reproduce on soybean tester lines.
- The most commonly used system separated SCN into 16 races.
- More recently, a new classification system called the *HG Type test* has been widely adopted. The HG Type test is similar to a SCN race test but includes only the seven sources of resistance in available SCN-resistant soybean varieties.
- Results are shown as a percentage, indicating how much the nematode population from a soil sample increased on each of the seven lines.
- The HG Type test indicates which sources of resistance would be suited for the field being tested. For example, if an HG type contains the number 2, this indicates that PI 88788 would not be an effective source of SCN resistance (Table 1).

Table 1. Indicator lines for HG Type classification of SCN.

	Indicator Line		Indicator Line
1	PI 548402 (Peking)	5	PI 209332
2	PI 88788	6	PI 89772
3	PI 90763	7	PI 548316
4	PI 437654 (Hartwig)		

Decreased Efficacy of PI 88788 Resistance

- Beginning in the 1990s, the widespread availability of soybean varieties with PI 88788 SCN resistance provided a largely effective management tool for SCN in North America.
- In recent years, however, PI 88788 has been losing its effectiveness as a SCN management tool.
  - A recent survey in Nebraska showed almost half (47%) of the fields tested had SCN populations that reproduced on PI 88788 (HG type 2) (Wilson, 2018).
  - A recent University of Missouri study of 28 SCN populations representing different regions of the state found that all of them showed reproduction on PI 88788 varieties (Mitchum and Howland, 2018).
  - Studies in other states have found similar results, showing that SCN populations able to reproduce on PI 88788 varieties have become widespread in many areas.
- The PI 88788 source of SCN resistance no longer provides effective control in many fields, meaning that SCN once again poses a significant threat to soybean yield that requires grower attention and management.

SCN Management Recommendations

- The SCN Coalition provides the following recommendations for developing a plan to manage SCN (www.thescncoalition.com):
  - Test your fields to know your numbers.
  - Rotate resistant varieties.
  - Rotate to non-host crops.
- Consider using a nematode protectant seed treatment.
- Consult your university soybean extension specialist for specific management recommendations for your state.

Test Your Fields

- The first step in developing a SCN management plan is testing fields to determine the presence of SCN and/or the HG type of the population. Soybean specialists now recommend retesting infested fields every six years.
  - Sample at the same time of year and following the same crop each time: SCN populations vary during the growing season and in response to host and non-host crops.
  - Limit the area represented in a single sample to 10 to 20 acres to increase accuracy of results.
  - Use a soil probe, a small shovel, or a trowel to collect samples. Collect soil to a depth of six to eight inches in the root zone of plants.
  - Collect 10 to 20 cores with the probe or 10 to 20 ¼-cup samples with the shovel or trowel. Representative sampling is best achieved by collecting subsamples in a zigzag pattern across the entire sample area.
  - Some universities recommend sampling markedly different soil textures separately. Also, areas with different cropping histories should be sampled separately.
  - Deposit subsamples in a bucket, and mix thoroughly. Place about two cups of soil in a plastic bag, and label with a permanent marker. Paper bags allow soil to dry excessively and are not recommended for SCN.
  - Do not store samples in direct sun or allow them to overheat. Ship as soon as possible to the lab you choose.

Rotate Resistant Varieties

- If your SCN populations are found to be increasing, select varieties with sources of resistance other than PI 88788.
- The most common source of resistance other than PI 88788 is PI 548402 (Peking) resistance.
  - The Peking source of SCN resistance was identified from an older soybean cultivar and has been associated with yield drag.
  - Pioneer has been using precision molecular breeding methods to isolate the Peking genes and eliminate yield drag associated with the trait.
- Pioneer is currently offering 17 high-yield potential soybean varieties with the Peking source of resistance.
- As a leader in SCN breeding, we continue to breed with Peking and Hartwig sources of resistance to provide additional modes of action for a variety of SCN races.
  - The complexity of the Hartwig trait makes it more challenging to bring into high yield potential varieties, but Pioneer anticipates introducing new varieties with the Hartwig source in the next few years.

Rotate to Non-Host Crops

- Rotate to a non-host crop to reduce SCN pressure.
- Corn, alfalfa, and small grains are the most common non-crop choices for reducing SCN numbers.
- Since SCN persists in the soil for many years, however, it cannot be totally eradicated by rotation.

Seed Treatments

- Several nematicide seed treatments with activity against SCN are currently available and can provide added protection when used with a SCN-resistant soybean variety.
- Nematicide seed treatments are intended to supplement current SCN management strategies, not replace them. Seed treatments should, therefore, be used in coordination with SCN-resistant varieties and rotation to non-host crops (Bissonnette and Tylka, 2017).
- The LumiGEN™ system offering includes ILeVO® fungicide/nematicide seed treatment, which has activity against SCN.
- A Pioneer study including 193 on-farm trial locations found an average yield response of 4.9 bu/acre in high SCN fields when ILeVO fungicide/nematicide seed treatment was added to the standard fungicide and insecticide seed treatment package (O'Bryan and Burnison, 2016).

Distribution, Levels, and HG Types of SCN Populations in Missouri

*by **Melissa G. Mitchum Ph.D.,** and **Amanda Howland,** University of Missouri*

Background

- Soybean cyst nematode (SCN) continues to spread throughout soybean-producing regions of the United States.
- Heavy reliance on soybean varieties with SCN resistance from the plant introduction (PI) 88788 is driving changes in the approach to SCN management in Missouri.
- Further exacerbating this problem is the increasing prevalence of virulent SCN populations that are able to reproduce on soybean varieties with PI 88788 resistance, thereby reducing its effectiveness.

Objectives

- A survey was conducted of grower-submitted soil samples from across Missouri to evaluate the distribution, levels, and HG types of SCN.
- Objectives of this study were to:
  - » Increase awareness among farmers of the presence and level of SCN within their fields
  - » Confirm the existence of virulent SCN populations in grower fields and the need for alternative SCN management strategies

Study Description

- Soil samples were solicited from Missouri growers.
- 293 soil samples were received from different Missouri fields in 2016.
- Cysts were extracted from each sample, and a SCN egg count was determined for each sample.
- HG type tests were conducted for 28 SCN populations representing different regions of Missouri.

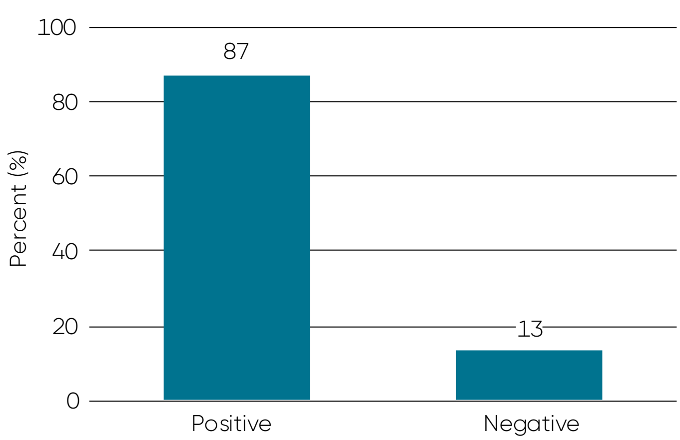


Figure 1. Percentage of soil samples that tested positive for SCN.

Results

- This study determined that 87% of soil samples tested were positive for SCN (Figure 1).
- Samples from 293 fields evaluated showed that 74% of samples had egg counts > 500 eggs/250cc (Figure 2).
- All of the SCN populations evaluated for HG type showed reproduction on PI 88788 (HG type 2). Some populations (43%) showed reproduction on both Peking and PI 88788 (HG type 1.2) (Figure 3).
- 68% of SCN populations had a female index (FI) > 50% on PI 88788 (Table 1).

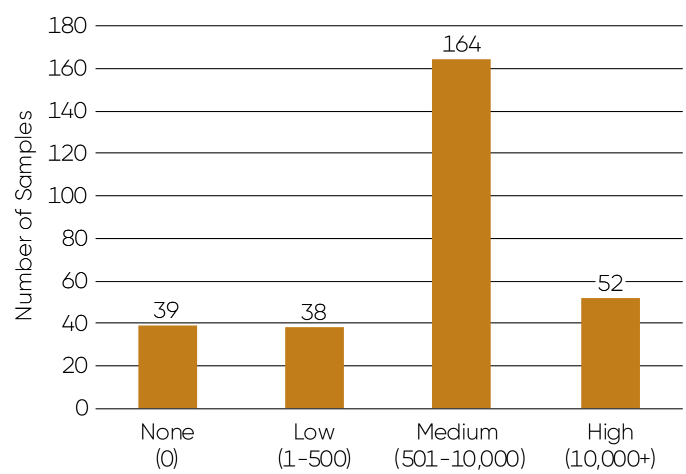


Figure 2. Number of soil samples at the various SCN egg count threshold values (250cc).

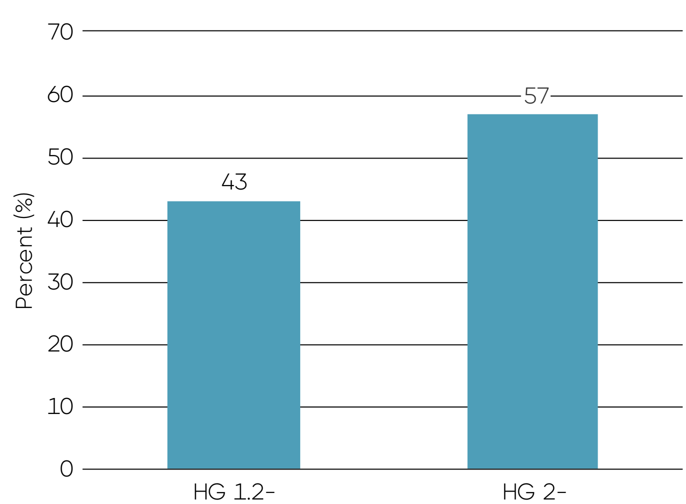


Figure 3. HG types of SCN populations (n=28).

Results (Continued)

Table 1. HG type test results of SCN populations.

Region	County	Egg Count (250 cc)	Avg # Cysts Lee74	Female Index (%) (1) PI 548402	(2) PI 88788	(3) PI 90763	(4) PI 437654	Pickett	HG Type	Race
C	Boone	4,500	280	0	39	0	0	0	2-	1
C	Calloway	750	140	1	49	0	0	1	2-	1
C	Howard	11,625	136	13	80	0	0	46	1.2-	2
C	Pettis	750	184	21	52	1	0	67	1.2-	2
EC	Franklin	7,125	154	9	93	0	0	21	2-	5
EC	Lincoln	25,500	192	28	69	0	0	59	1.2-	2
EC	Montgomery	938	62	2	36	0	0	4	2-	1
EC	St. Charles	17,625	243	1	59	0	0	5	2-	1
NC	Chariton	750	178	14	87	0	0	30	1.2-	2
NC	Livingston	2,250	207	1	55	0	0	6	2-	1
NC	Macon	8,250	166	5	64	0	0	13	2-	5
NC	Randolph	938	123	0	49	0	0	2	2-	1
NE	Audrain	61,500	213	20	45	1	0	83	1.2-	2
NE	Audrain	60,375	193	21	68	0	0	54	1.2-	2
NE	Audrain	23,250	115	0	27	1	0	2	2-	1
NE	Knox	36,750	183	18	36	1	0	35	1.2-	2
NE	Knox	34,875	237	37	58	4	0	80	1.2-	2
NE	Shelby	29,250	200	33	61	2	0	86	1.2-	2
NE	Shelby	12,375	213	8	63	0	0	74	2-	5
NW	Andrew	938	165	17	69	0	0	46	1.2-	2
NW	Buchanan	24,000	146	41	90	0	0	72	1.2-	2
NW	Gentry	48,000	242	1	37	0	0	5	2-	1
NW	Nodaway	375	52	1	61	0	0	6	2-	1
NW	Ray	15,750	210	1	52	0	0	1	2-	1
WC	Bates	6,000	88	66	61	3	0	71	1.2-	2
WC	Jackson	4,125	359	0	66	0	0	3	2-	1
WC	Lafayette	4,500	226	0	40	0	0	0	2-	1
WC	Lafayette	1,125	158	3	74	0	0	8	2-	1

Soybean White Mold Management with DuPont™ Aproach® Fungicide

*by **Nate LeVan,** Field Agronomist, and **Sandy Endicott, M.S.,** Agronomy Manager*

Background and Rationale

- Sclerotinia stem rot *(Sclerotinia sclerotiorum)*, or white mold, is an annual threat to soybeans in most soybean-growing regions in the U.S.
- White mold infections take place starting at the beginning bloom (R1) stage and continue while flowers are present.
- Cultural practices along with fungicides applied during reproductive stages have been shown to help manage white mold.

Objective

- Evaluate DuPont™ Aproach® fungicide to help manage white mold in soybean in northern Iowa.

Study Description

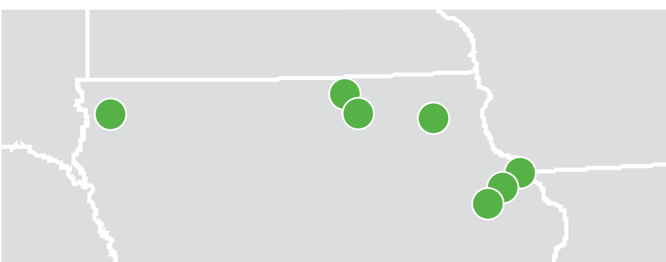


Figure 1. Locations of seven white mold fungicide trials conducted in northern Iowa in 2018.

- Seven locations with a history of white mold were selected for the trial work with three in Delaware County, one in Winneshiek (NE Iowa), two in Floyd County (NC Iowa), and one in Lyon County (NW Iowa) (Figure 1).
- Two of the locations were planted in 15-inch rows, and five locations were planted in 30-inch rows.
- Treatments were set up in field length strips:
  - » Untreated check
  - » Single application of DuPont™ Aproach® fungicide (9 oz/acre applied at R1-R3)
  - » Two applications of DuPont™ Aproach® fungicide (9 oz/acre applied at R1 and R3)
- Trial locations were rated for level of infection, and infected plants were counted to determine percentage of plants infected.
- Several different soybean varieties were used among trial locations, including varieties classified as "tolerant" or "susceptible" to white mold.

Figure 2. White mold on soybean stems.

- Planting dates ranged from May 7 to 26, slightly later than normal.
- Temperatures and precipitation were generally above normal through June, July, and August.

Results

- Six of the locations had a low level of infection (less than 5% of plants infected in the check strip), while one of the locations had a moderate level of infection (check strip with 5% or more infected plants).
- Many locations showed visual differences in foliar health and leaf drop timing. Fungicide treated strips dropped leaves later.

Figure 3. Aerial photo of a trial location in northern Iowa taken August 2018, showing a visual difference in green leaf tissue between the treated strips and the non-treated strip.

- Across the seven locations, the two-pass DuPont™ Aproach® fungicide treatment (one pass at R1 and one pass again at R3) yielded 2 bu/acre more than the untreated check (Figure 4).
- Average late-season white mold infection across the seven locations was 0.7% with the two-pass DuPont™ Aproach® fungicide treatment compared to 3.0% in the untreated check (Figure 5).

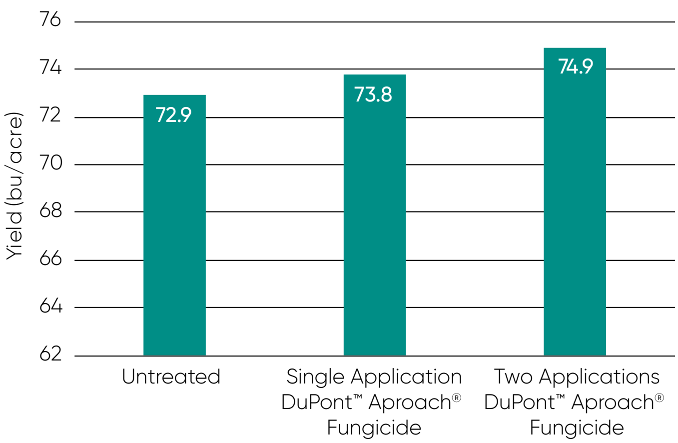


Figure 4. Average soybean yield by fungicide treatments across northern Iowa on-farm trials in 2018.

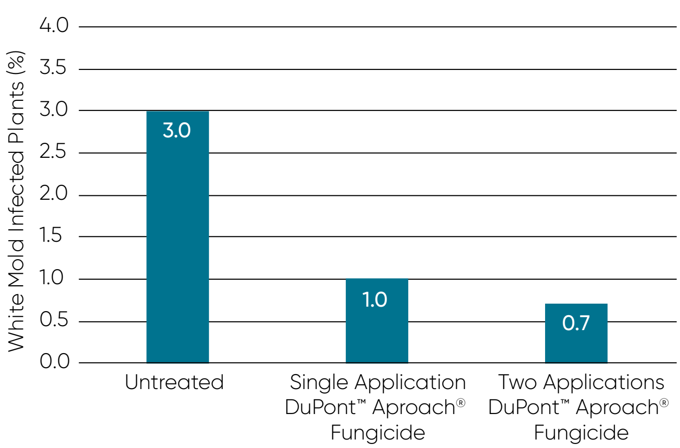


Figure 5. Average percent white mold infection by fungicide treatments across northern Iowa on-farm trials in 2018.

Row Spacing

- Historically, narrow-row soybeans (row spacings of 15 inches or less) have shown an average yield advantage of approximately 4 bu/acre over soybeans in 30-inch rows (Jeschke and Lutt, 2016).
- While narrow-row soybeans are becoming more popular, the denser canopy may provide a more favorable environment for white mold infection.
- Results were similar in this study between locations planted in 30-inch rows and those in 15-inch rows. In both row widths, the two pass fungicide treatment had greater yield and lower rate of white mold infection versus the one-pass treatment and untreated check (Tables 1 and 2).

- The one-pass treatment yielded an average of 1.5 bu/acre more than the untreated check and reduced infection from 3.0 to 1.1% across locations planted in 30-inch rows (Table 1).
- While the one-pass treatment had a similar rate of white mold infection as the two-pass treatment across locations planted in 15-inch rows, the average yield was 3.9 bu/acre less compared to the two-pass treatment (Table 2).

Table 1. Average soybean yield and percent white mold infection by fungicide treatment across locations planted in 30-inch rows.

Treatment	White Mold Infection %	Soybean Yield bu/acre
Untreated	3.0	73.1
Single application of DuPont™ Aproach® fungicide (R1-R3)	1.1	74.6
Two applications of DuPont™ Aproach® fungicide (R1 and R3)	0.7	74.9

Table 2. Average soybean yield and percent white mold infection by fungicide treatment across locations planted in 15-inch rows.

Treatment	White Mold Infection %	Soybean Yield bu/acre
Untreated	2.8	72.3
Single application of DuPont™ Aproach® fungicide (R1-R3)	0.6	71.1
Two applications of DuPont™ Aproach® fungicide (R1 and R3)	0.6	75.0

Conclusions

- Soybean yield was increased and white mold infection was reduced with sequential applications of DuPont™ Aproach® fungicide at 9 oz/acre at beginning bloom (R1) and beginning pod (R3) versus untreated checks.
- Management of white mold in soybeans is complex and can be difficult to target year-over-year treatment plans with only cultural and varietal practices.
- Future management plans need to include tactics like increasing row width, reducing planting populations, and targeted applications of labeled fungicides.

Frogeye Leaf Spot of Soybeans

by ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Frogeye Leaf Spot Facts

- Caused by *Cercospora sojina,* a fungus found throughout the world
- In the U.S., frogeye leaf spot is most common in the Mid-South, Mississippi Delta, and southeastern soybean growing areas.
    - » Development of resistant varieties by Pioneer soybean breeders has limited disease impact in these areas.
- In the past decade, it has been detected in soybean fields in the Midwestern U.S.
- Infects leaves, stems, and pods of soybeans.
- Disease development is favored by warm, humid conditions, and frequent rains following disease onset can lead to serious epidemics.
- Dry weather severely limits disease development.

Disease Cycle

- Disease survives and overwinters in soybean residue and seeds.
- Initial infection occurs as spores produced on infected residues or cotyledons are spread by splashing rain or wind.
- Secondary infection occurs as lesions on the soybean plant produce spores.
- Diseased soybean residue (leaves, stems, and pods) left on soil surface provides inoculum to continue disease cycle in next soybean crop.

Impact on Crop

- Yield losses depend on disease severity and varietal susceptibility.
    - » With severe leaf blighting on susceptible varieties, losses may approach 30%.
    - » Minor symptoms on moderately resistant varieties are unlikely to result in economic losses

Leaf Symptoms

- Symptoms begin as small, circular-to-somewhat-irregular spots on the upper surface of the leaf.
- These dark, water-soaked spots develop into lesions with dark-brown centers surrounded by red or dark reddish-brown margins.
- As lesions age, the center becomes light brown to light gray, and the border remains dark.
- Leaf lesions may coalesce to form larger, irregular spots on the leaf.
- Heavily diseased leaves may wilt and drop prematurely, or dead tissue may weather away, leaving tattered leaflets.

Leaf symptoms of frogeye leaf spot.

Stem, Pod, and Leaf Symptoms

- Stem lesions are reddish brown with a narrow, dark margin.
    - » The centers of the lesions become brown to gray with age.

- Lesion development on pods is similar to that of the leaves.
  - » Symptoms begin as water-soaked spots that progress to dark reddish-brown lesions.
  - » Lesions are circular to elongated in shape and may appear slightly sunken and lighter-colored in the center.
- The fungus can also grow through the pod wall to infect maturing seeds.
  - » These seeds may show cracking of the seed coat and discoloration ranging from small specks to large blotches.

Management – Resistant Varieties

- Plant resistant soybean varieties if fields had frogeye leaf spot in recent years.
- Pioneer rates its varieties and makes ratings available to customers.
- Ratings range from 2 to 9 (9 = resistant), indicating excellent resistance is available in elite soybean varieties.
- Select varieties with resistance to most important diseases first.
  - » Soybean cyst nematode, sudden death syndrome, and Phytophthora root rot may present a greater risk than frogeye leaf spot.
- Select for other key traits required for your fields.
- Your Pioneer sales professional can help you select suitable varieties for your farm.

Other Management Practices

- Consider tillage to reduce infected residue left on soil surface. Reduced inoculum levels can delay the onset and spread of the disease.
- Rotate crops to break the disease cycle and reduce disease inoculum.
- Apply a foliar fungicide if disease levels exceed thresholds established by your state extension soybean disease specialist.
  - » Timely application of a fungicide with multiple modes of action can preserve green leaf material and prevent disease spread by sporulation.
  - » Strobilurin-resistant strains of frogeye leaf spot have been identified in several states, including Arkansas, Kentucky, Illinois, Tennessee, and Missouri.
  - » DuPont™ Aproach® Prima fungicide combines a strobilurin with a triazole for better control of resistant frogeye leaf spot to protect yield and input investments. Apply a full rate (6.8 fluid ounces per acre) of Aproach® Prima to soybeans at R2 to R3.
  - » Be sure to read and follow all label instructions.

Glyphosate-Resistant Weeds in North America

*by **Mark Jeschke, Ph.D.,** Agronomy Manager, and **Samantha Teten,** Agronomy Sciences Intern*

History and Current Status:

- Glyphosate was introduced in the U.S. in 1976.
- The first case of evolved resistance to glyphosate was confirmed in rigid ryegrass in Australia in 1996.
- The first case of glyphosate resistance in the U.S. occurred in 2000 in horseweed (marestail) in Delaware.
- To date, glyphosate resistance has been confirmed in 41 weed species worldwide, including 18 in North America.
- Glyphosate-resistant weed populations have been confirmed in 38 states and 5 provinces (Figure 1).

How Do Weeds Become Herbicide Resistant?

- Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.
- Herbicides do not induce resistance in weed species, rather they simply select for resistant individuals that naturally occur within the weed population.
- Once a resistant plant has been selected, repeated use of a herbicide over multiple generations allows resistant plants to proliferate as susceptible plants are eliminated.

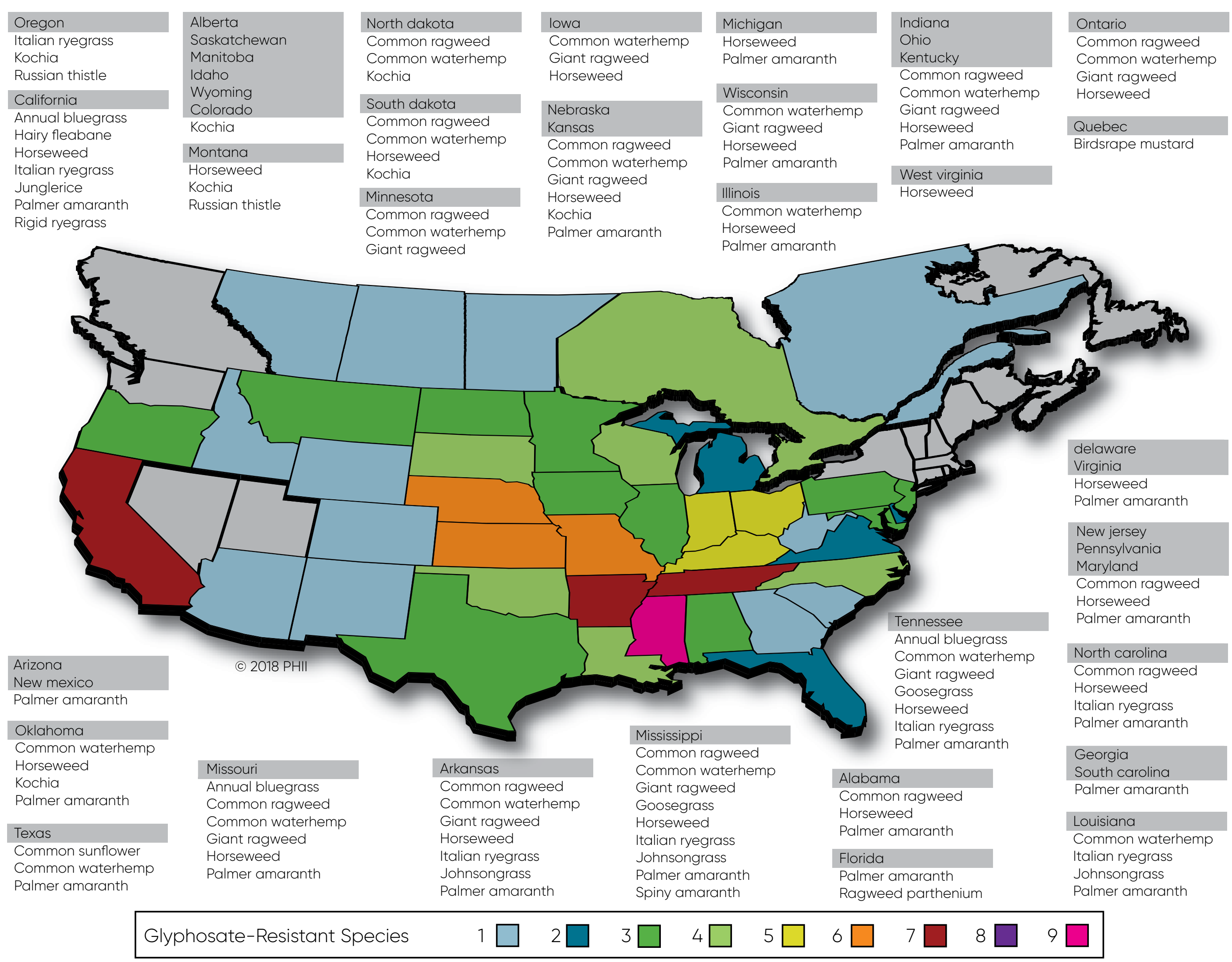


Figure 1. Confirmed cases of glyphosate resistance in North America as of spring 2018.

Herbicide Failure Can Be Rapid

- Weed resistance to continuous use of the same herbicide occurs on a logarithmic rate of seed increase.
- The percentage of weeds in the population that are resistant to the herbicide gradually increases at an imperceptible rate and then makes a logarithmic jump to become more than half the weed population.
- This is why fields typically go from adequate control (>90% control) to failure (<50% control) in 1 year (Table 1).

Table 1. Logarithmic progression of resistance to herbicides.

Treatment Year	% Resistant Weeds in Total Population	Weed Control
0	0.0001	Excellent
1st application	0.00143	Excellent
2nd application	0.0205	Excellent
3rd application	0.294	Excellent
4th application	4.22	Excellent
5th application	**60.5**	**Failure**

Factors Influencing Resistance Risk

- Most factors that influence the risk of herbicide resistance are inherent characteristics of a weed species and cannot be affected by management:
  - Mutation rate for resistance traits
  - Number of genes required to confer resistance
  - Dominance of the resistance allele
  - Inheritance of resistance traits
  - Fitness of resistant plants
- The only risk factor that growers can change is herbicide selection intensity.
  - Herbicide selection intensity is determined by herbicide efficacy, persistence, and frequency of application.
  - Combination or rotation of herbicide modes of action can reduce selection intensity.
  - Agronomic practices, such as crop rotation and tillage, can decrease herbicide selection intensity by reducing weed populations.

Weed Species Vary Widely in Resistance Risk

- Many weed species that have developed resistance to glyphosate already had extensive histories of resistance to other herbicides, indicating that they have an inherently high risk for resistance development.
- Multiple resistance is becoming an increasing problem in species, such as waterhemp, where resistance to alternative herbicides is already common.
- Some of the worst glyphosate-resistant weeds are also highly prolific seed producers, making them exceptionally capable of spreading resistance once it occurs.

Horseweed (left) and waterhemp (right) possess characteristics that make them extremely good at developing and spreading herbicide resistance.

Considerations for Resistance Management

Reduce the Development of Glyphosate Resistance

- Practices that reduce glyphosate selection intensity, such as combination or rotation of herbicides, crop rotation, or tillage, can reduce the risk of resistance.
- A sequential weed management program can reduce selection intensity by using multiple herbicide modes of action as well as provide more consistent weed management.

Reduce the Spread of Glyphosate Resistance

- Movement by field equipment appears to be a major factor in the spread of glyphosate resistant weeds.
- Cleaning tillage and harvest equipment when moving between fields can reduce the movement of weed seeds and slow the spread of resistant populations.

Practice Good Stewardship of All Weed Management Technologies

- Weed management systems using crops resistant to other herbicide modes of action, such as glufosinate, HPPD inhibitors, and synthetic auxins (2,4-D and dicamba), offer additional tools to manage glyphosate-resistant weeds.
- However, weed populations resistant to each of these modes of action already exist in North America.
- Overreliance on any single herbicide to manage glyphosate-resistant weeds can lead to resistance to that herbicide as well.

Soybean Pod and Seed Rots in 2018

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Soybean Seed Quality Problems in 2018

- Extended periods of warm and wet conditions following maturity can negatively affect seed quality and yield in soybeans by causing pod shattering, seed sprouting in the pods, and growth of fungal diseases.
- Many soybean-producing areas experienced excessive rainfall during fall of 2018, which delayed harvest and exposed mature soybeans to weathering and degradation in the field.
- Areas of the Eastern and Northeastern U.S. were particularly affected due to a combination of record rainfall and above-average temperatures that provided an ideal environment for the proliferation of fungal diseases.
- Pioneer field teams worked with soybean growers to determine the extent and severity of seed quality problems and identify any management factors that may have had an impact.

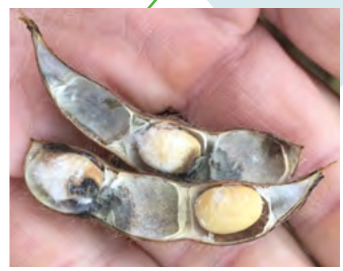
Pod and Seed Diseases Observed in 2018

- Several common pathogens that can affect soybean pods and seed were observed in 2018.
- None of these pathogens are known to produce mycotoxins, but some can reduce yield and seed quality.

Cercospora Leaf Blight and Purple Seed Stain

- Caused by the fungal pathogen *Cercospora kikuchii*, which attacks both the leaves and the seeds of soybeans.
- Seeds are infected through their attachment to the pod, the hilum. Infected seeds may show a pink to pale or dark-purple discoloration, which varies in size from specks to blotches to the entire seed coat.
- Cercospora diminishes seed appearance and quality but usually does not decrease yields significantly.

Cercospora purple seed stain.



Phomposis Seed Decay

- Caused by the fungal pathogen *Phomopsis longicolla*, which forms a complex with *Diaporthe phaseolorum var. sojae* to infect soybeans
- Seeds appear shriveled, cracked, and elongated and may be covered with a thin white layer of mold. Small black specks of pycnidia may occur on the seeds.
- Infection can cause reductions in soybean yield and grade.

Frogeye Leaf Spot

- Caused by *Cercospora sojina*, a fungus that infects leaves, stems, and pods of soybeans.
- Lesion development on pods begins as water-soaked spots that progress to dark reddish-brown lesions.
- The fungus can also grow through the pod wall to infect maturing seeds. These seeds may show cracking of the seed coat and discoloration ranging from small specks to large blotches.

Frogeye leaf spot lesions.

Anthracnose

- Anthracnose in soybean is primarily caused by the fungal species *Colletotrichum truncatum* in the Midwestern U.S.
- Anthracnose can infect stems, leaves, and pods of soybean.
- Infected pods may be completely filled with mycelium and can have no seeds or fewer/smaller seed form. Seed that does form may be discolored, shriveled, and moldy.

Opportunistic Fungi and Bacteria

- Opportunistic pathogens are those that are normally associated with degradation of crop residue.
- Once the plant tissue is dead, it can no longer defend itself against these pathogens and is susceptible to infection.
- Soybean plants that remain in the field for extended periods following maturity can be degraded by opportunistic pathogens when conditions are favorable for diseases.

Weather is the Driving Factor

- Fungal pathogens that commonly infect soybean pods and seed overwinter in crop residue so are present in essentially all soybean fields at some level.
- The severity of infection that actually occurs is, therefore, largely determined by the favorability of weather conditions.
- Soybean seed quality problems in 2018 were the result of an unusual confluence of weather conditions that both delayed harvest and provided a uniquely favorable environment for fungal diseases.
- Many soybean-producing areas of the U.S. experienced above-average rainfall as soybeans were maturing (Figure 1).
- In the Northeastern U.S., above-average rainfall was accompanied by above-average temperatures (Figure 2), producing an environment highly favorable to fungal diseases.
- Rainfall during July, August, and September was double or triple the long-term average in some areas.

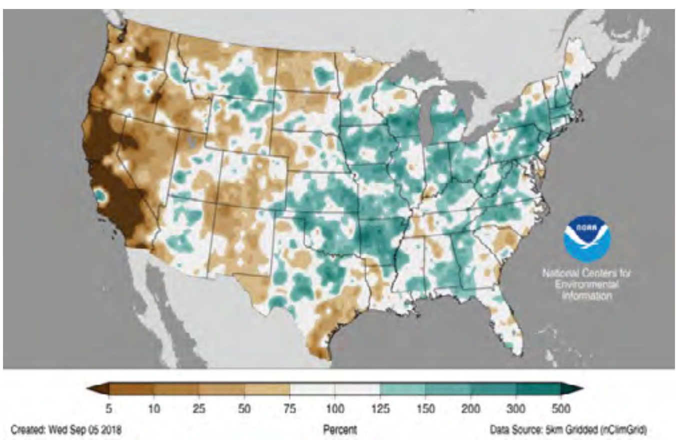


Figure 1. Precipitation (percent of long-term average) in August 2018.

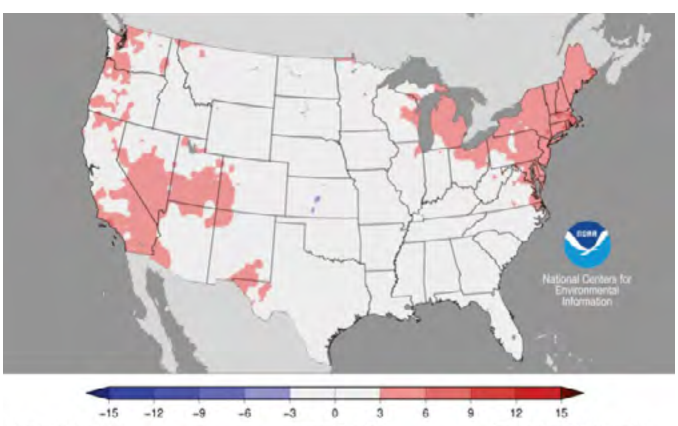


Figure 2. Mean temperature departures from average in August 2018.

Observations

- In general, seed quality issues tended to be more prevalent in earlier-planted soybeans.
- Problems did not appear to be associated with any particular soybean maturity groups or varieties.
- It is likely that the interaction between maturity timing and weather conditions was the primary determinant of seed quality problems in a given field.
  - Soybean plants that are mature and weathering in the field under conditions favorable for disease are highly prone to infection.
  - The longer the soybeans remain in the field before harvest, the more time diseases have to work.
  - Soybeans easily take up water, which can cause seed swelling and pod splitting as well as increase susceptibility to diseases.
  - Warmer temperatures drive faster fungal growth.
- Effects of foliar fungicide applications varied in terms of preventing yield loss from pod and seed diseases in 2018.
  - In many cases, it appears there was no effect. An application made around the typical timing (R3 stage) would not have any activity left to control pathogens invading the mature plant late in the season.
  - In areas with heavy frogeye leaf spot pressure, more consistent yield benefits were observed, particularly on soybean varieties with lower genetic resistance.

Harvest, Handling, and Storage

- Affected fields should be harvested as soon as feasible to prevent further loss of yield and quality.
- If soybean plants have retained green foliage due to wet conditions, a desiccant may be needed.
- Soybeans should be dried down to 11% moisture to inhibit fungal growth, aerated, and delivered as soon as possible.
- Soybeans should be dried at temperatures between 100 and 130 °F. Higher temperatures can cause damage to the seed.
- Damaged soybeans can be blended with good quality soybeans, if possible.
- Growers should open a claim with their crop insurance provider if there is a concern over soybean quality and yield.
- There are no mycotoxins associated with the soybean seed diseases that were observed in 2018.

Management Considerations for the Future

- Seed quality problems in 2018 were largely the product of a highly unusual set of weather conditions that favored disease growth and delayed harvest, so there were no simple management changes that could have prevented problems in 2018 or that will prevent problems in the future.
- In general, anything growers can do to reduce the amount of time mature soybeans remain in the field before harvest will help reduce seed quality issues.
- Pioneer and university researchers will continue to evaluate results from 2018 to look for any genetic or management differences.
- Although 2018 was an unusual year, similar weather patterns are expected to appear more frequently in the future due to climate change.

Soybean Pod Splitting and Seed Sprouting in 2018

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

Weather Conditions During 2018 Harvest

- Many soybean-producing areas experienced prolonged wet conditions during the 2018 harvest season.
- These conditions caused substantial delays in harvest in some areas and led to yield losses due to pod splitting as well as seed germination in the pods.
- Two conditions are necessary for soybeans to germinate in the pods following physiological maturity:
    - Seed moisture raised back above 50%
    - Temperatures greater than 50 °F
- Weather conditions in September of 2018 met both of these requirements in many areas; temperatures were above average through most of the Eastern and Midwestern U.S. (Figure 1), and precipitation was double or even triple the monthly average in many areas (Figure 2).

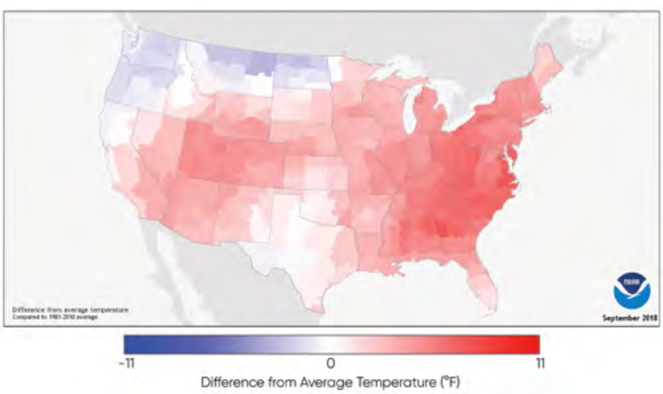


Figure 1. September 2018 temperature deviation from average, 1981-2010, (NOAA).

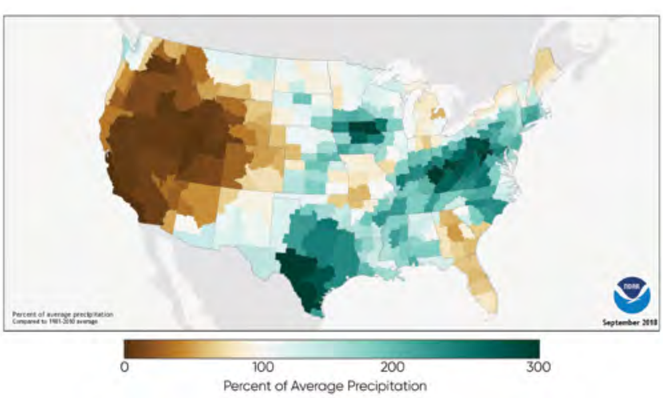


Figure 2. September 2018 precipitation percent of average, 1981-2010, (NOAA).

Figure 3. Soybeans that have swollen and ruptured the pods due to persistent wet conditions in Iowa in 2018. *Photo courtesy of Chris Doud, Pioneer Field Agronomist.*

Seed Swelling and Pod Splitting

- Soybean seed moisture is around 35% at physiological maturity and will decline quickly under dry conditions, drying down much more rapidly than corn.
- However, soybeans will readily re-absorb water and expand when exposed to moisture.
- Frequent rains and persistent wet conditions, such as those experienced in many areas in 2018, can allow water to soak through the pods and cause the seeds to swell inside the pods.
- If the seeds swell enough, they can cause the pod to rupture (Figure 3).
- Soybeans that experienced drought stress earlier in the season can have an elevated risk due to smaller and weaker pods.
- When pods are ruptured, seeds are prone to loss, particularly when they dry back down, either before or during harvest (Figure 4).

Germination in the Pods

- Once the pod has ruptured, the seeds are directly exposed to soaking rainfall. If the seeds swell to above 50% moisture and temperatures are above 50 °F, they may begin to germinate (Figure 5).
- Germination will continue as long as moisture and temperatures remain favorable.

Figure 4. Soybeans that have fallen to the ground after the pods ruptured. *Photo courtesy of Chris Doud, Pioneer Field Agronomist.*

Harvest

- Affected fields should be harvested as soon as feasible to prevent further loss of yield and quality.
- If soybean plants have retained green foliage due to wet conditions, a desiccant may be needed.

Combine Speed and Settings

- Slowing down harvest speed can help reduce gathering losses. Keep forward speed at about three miles per hour for most combines. Slow down for uneven soil surface or other abnormal conditions.
- Equipment must be properly adjusted and carefully operated to minimize losses. Soybeans that never get inside the combine can account for 80 to 85% of harvest losses.
  - » Be sure knife sections as well as ledger plates are sharp and that wear plates, hold-down clips, and guards are properly adjusted. Chains and bearings should be properly lubricated and belts tight.
  - » Proper reel speed in relation to ground speed will reduce gathering losses. Shatter increases if the reel turns too fast; stalks may be dropped if the reel turns too slow. Use a reel speed about 25% faster than ground speed.
  - » The reel axle should be 6 to 12 inches ahead of the sickle in most cases. Operate a bat reel just low enough to tip cut stalks onto the platform. The tips of the fingers on a pickup reel should clear the cutterbar by about two inches.

Handling and Storage

- Swollen and/or germinated seed will negatively affect seed quality.
- Germinated seeds will die and break into pieces during harvest, most of which will likely go out the back of the combine.
- Pieces that remain in the harvested grain can promote spoilage due to the breakdown of carbohydrates, proteins, and fats in the seed that is initiated during the germination process.

Figure 5. Soybeans germinating in the pods due to persistent wet conditions in Iowa in 2018. *Photos courtesy of Chris Doud, Pioneer Field Agronomist.*

- Soybeans subjected to conditions capable of causing germination in the pods will also likely have pod and seed diseases present as well, which can also contribute to grain-quality concerns (Figure 6).
- Soybeans should be dried down to 11% moisture to inhibit fungal growth, aerated, and delivered as soon as possible.
- Soybeans should be dried at temperatures between 100 and 130 °F. Higher temperatures can cause damage to the seed.
- Damaged soybeans can be blended with good quality soybeans, if possible.
- Growers should open a claim with their crop insurance provider if there is a concern over soybean quality and yield.

Figure 6. Swollen seeds and ruptured pods with disease visible on both the pods and seeds. *Photo courtesy of Chris Doud, Pioneer Field Agronomist.*

2018 Corn Silage Yield and Quality Response to Fungicide

*by **Bob Berkevich,** Field Agronomist, and **Scott Rowntree, M.S.,** Field Agronomist*

- In 2018, six Pioneer® GrowingPoint™ agronomy plot locations in Wisconsin were utilized to investigate the yield and quality response to a fungicide application applied at the VT to R1 growth stage.
- DuPont™ Aproach® Prima fungicide was applied at 6.8 oz/acre to BMR and non-BMR hybrids with 2 replications per hybrid. Pioneer® brand corn products included P0157AMXT™ (AMXT, LL, RR2), P0789AMXT™ (AMXT, LL, RR2), P0956AMX™ (AMX, LL, RR2), P1180XR (HXX, LL, RR2), and P1366AMXT™ (AMXT, LL, RR2). Within each plot, 1/1,000 acre was hand-harvested, weighed, and sampled for quality analysis.
- Results show that dry matter content was lower with fungicide treatment, which helps reduce risk of silage getting too dry if delays occur during the critical harvest period. Yield and all quality parameters were improved from the fungicide application in this study. On a milk per acre basis, DuPont™ Aproach® Prima fungicide returned +$501.60/acre to BMR silage and +$158.25 to non-BMR silage, using $15/cwt for the price of milk.
- Returns from fungicide applications to corn silage varies among years and environments but increased yield and quality as well as lower risk from harvest delays are compelling reasons to consider VT to R1 fungicide applications for corn silage production in Wisconsin.

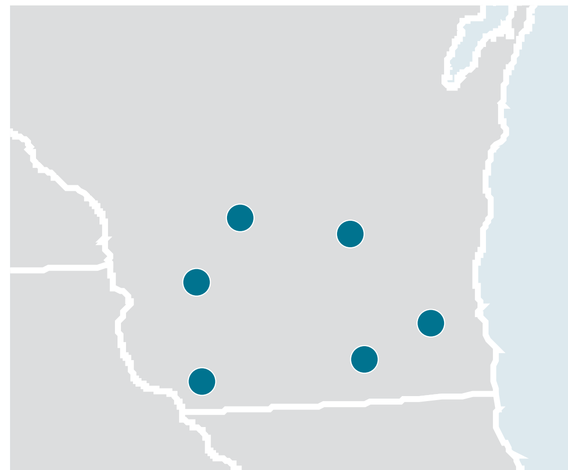
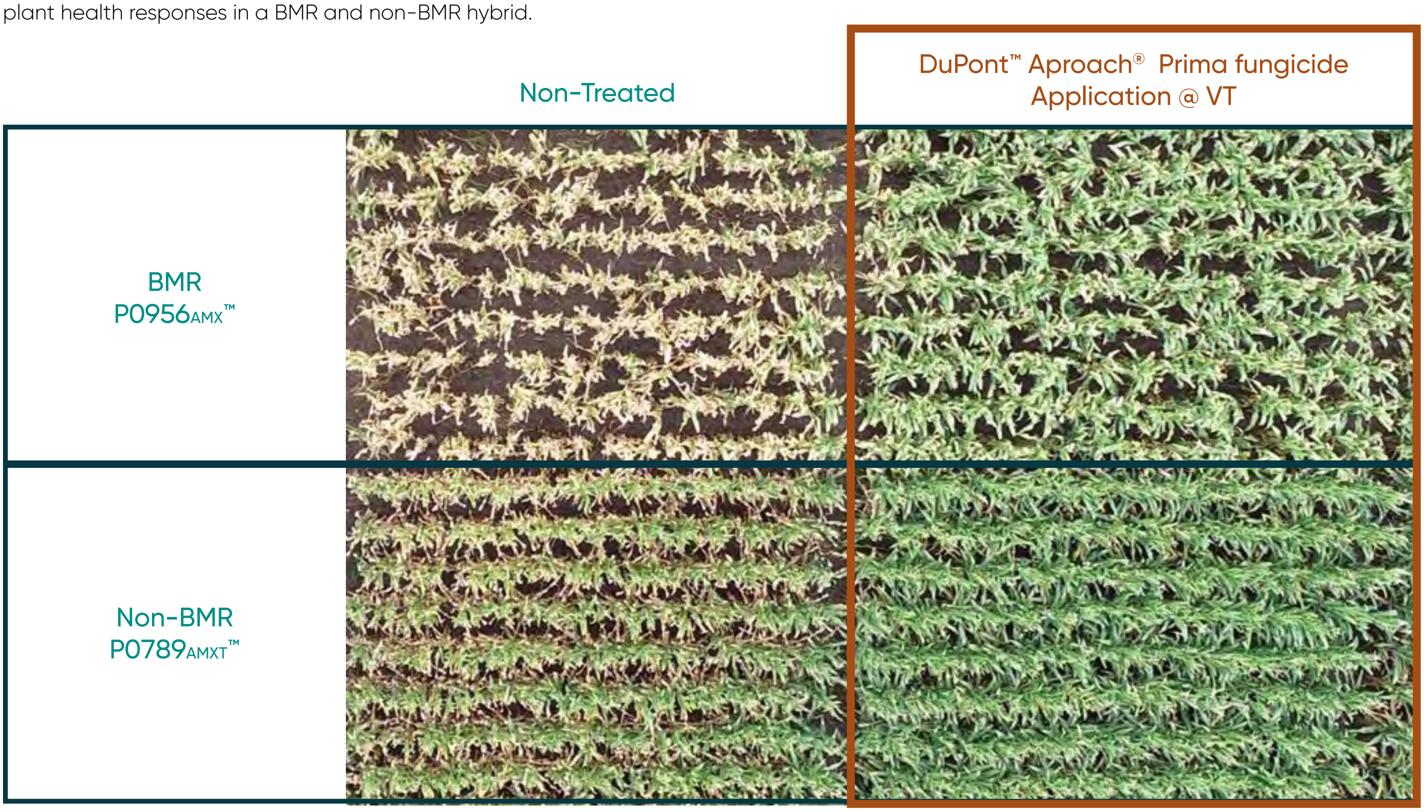


Figure 1. Pioneer® GrowingPoint™ agronomy plot locations with corn silage fungicide studies in 2018.

Figure 2. Photo taken September 6, 2018, near Burlington, WI, showing visual plant health responses in a BMR and non-BMR hybrid.



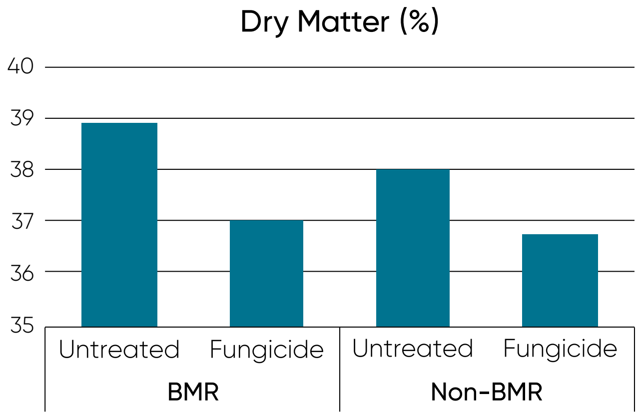


Figure 3. Fungicide application resulted in lower DM content.

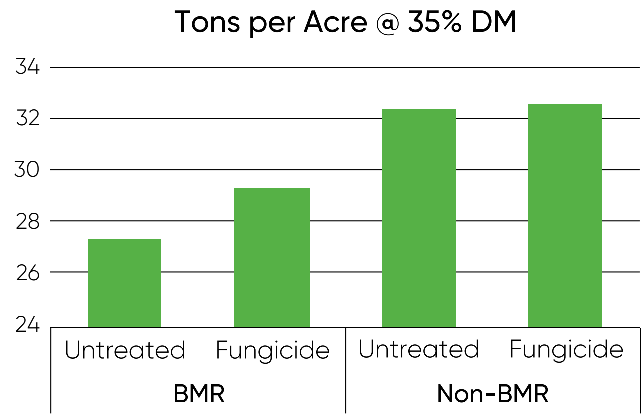


Figure 4. Yield response to fungicide was greater in BMR hybrids, many of which have lower disease ratings and stress tolerance than non-BMR hybrids.

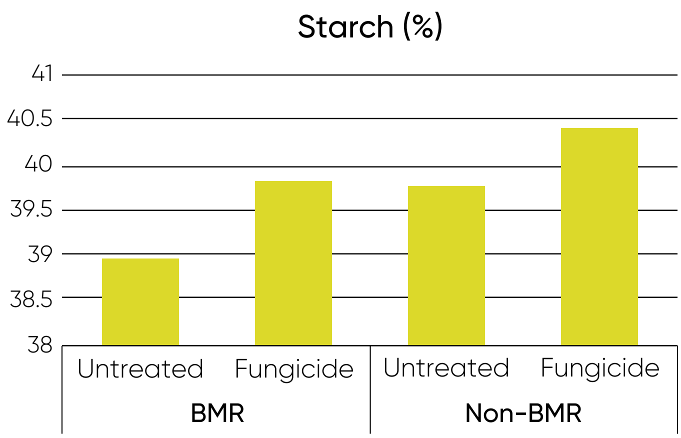


Figure 5. Interestingly, corn silage moisture was higher with fungicide application (Figure 2), and starch levels increased. Healthy leaf tissue is required for full starch accumulation potential.

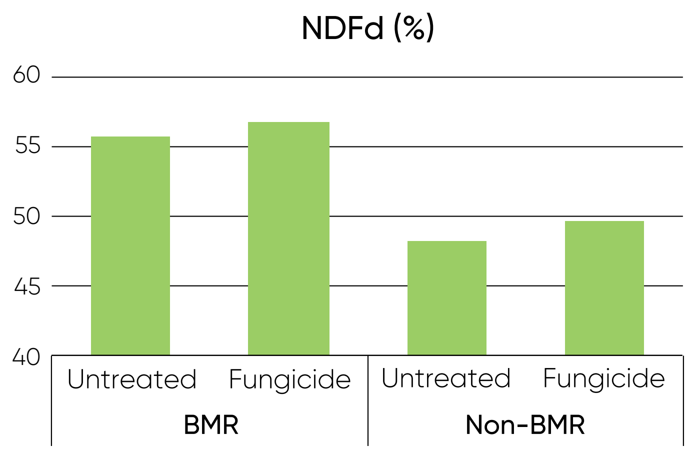


Figure 6. Increases in digestibility occurred for both hybrid types but were larger for non-BMR hybrids.

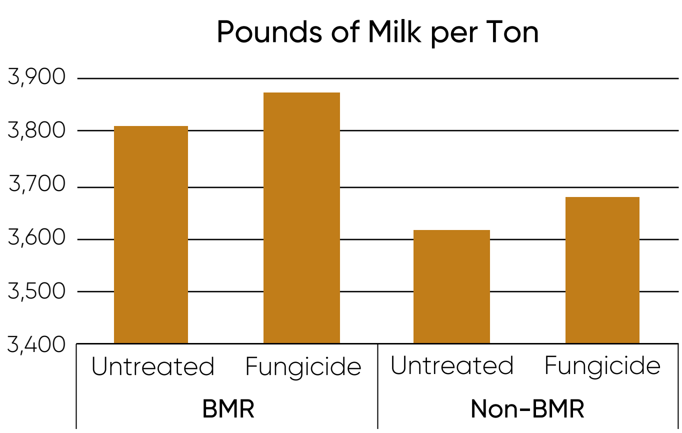


Figure 7. Improvements in starch levels and NDFd provided a consistent overall feed quality increase from fungicide.

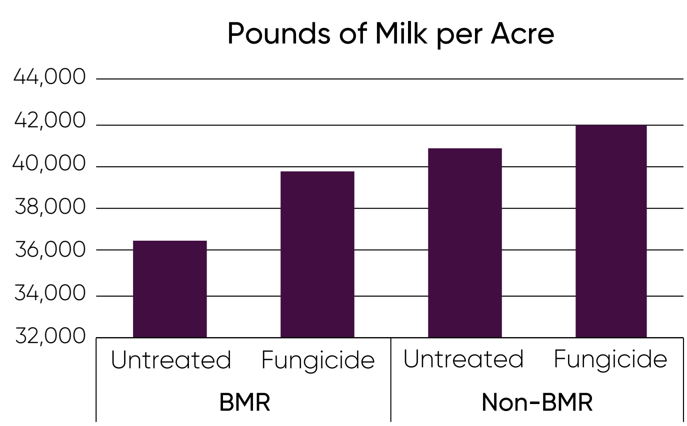


Figure 8. At $15/cwt, fungicide application increased the value of milk per acre by $501.60 for the BMR hybrids and $158.25 for the non-BMR hybrids.

Alfalfa Seed Coat, Seeding Rates, and Establishment Success

by ***Josh Shofner,*** *Consultant,* ***Brian Buck,*** *Consultant,* ***Jim Smith,*** *Strategic Account Manager - Dairy,* ***Bill Powel-Smith,*** *Strategic Account Manager - Dairy, and* ***Daniel Wiersma, M.S.,*** *Business Manager - Alfalfa*

Introduction

- Seed companies sell alfalfa seed with differing levels of seed coating. This can range from raw seed with no coating to heavy-coat seed with up to 34% coating material applied.
- This article will discuss two studies with various seed coats and seeding rates to help better understand how seed coat may impact early stand establishment.

Alfalfa Seed Coat & Seeding Rate Study

- A field-scale study was planted in May 2017 to compare the effects of heavy versus light seed coat on stand establishment success at two seeding rates. Field preparation was identical for each treatment. Seeding equipment was precisely calibrated for each variety and seeding rate treatment as shown in Table 1.
- Following emergence, alfalfa seedlings were counted from 10 random locations and averaged within each treatment. Photos of a representative area were taken to show visual differences.

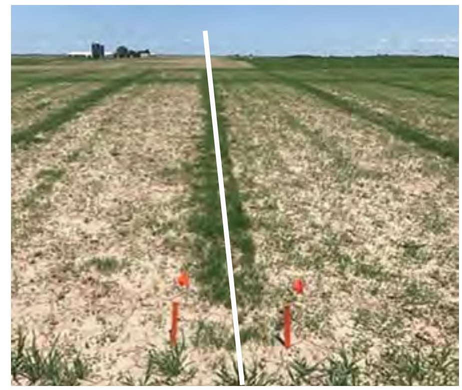


Figure 1 (right). Side by side comparison of heavy coat (left) and 55V50 light coat (right) seeded at 18 lbs/acre.

Table 1. Effect of variety, seed coating, and seeding rates on plants established per square foot.

Variety	Seed Coat* Level	Seed Coating	Seeding Rate (lbs/acre)	Plants (plts/ft^2)
Pioneer® variety 55V50	Light	9%	10	25.5
Competitor	Heavy	34%	10	12.0
Pioneer variety 55V50	Light	9%	18	34.5
Competitor	Heavy	34%	18	18.0

*Both varieties had fungicide and rhizobium inoculant applied in addition to the coating material. The competitor variety may have had additional fungicide or micronutrients applied as part of the seed coating.

Figure 2. 55V50 with light coat seeded at 10 lbs/acre.

Figure 3. Competitor variety with heavy coat seeded at 10 lbs/acre.

Figure 4. 55V50 with light coat seeded at 18 lbs/acre.

Figure 5. Competitor variety with heavy coat seeded at 18 lbs/acre.

Summary

- Heavy-coat seed levels significantly reduced early stand establishment as measured by plants per square foot, resulting in marginal stands for long-term stand life.
- 55V50 with the light-coat Pioneer Premium Seed Treatment offering (PPST - Apron XL® fungicide and Nitragin Gold®) established more plants per square foot than the competitive variety with heavy coat.
- 55V50 seeded at 10 or 18 lbs/acre established an acceptable stand count.

Alfalfa Seed Coat and Residue Study

Observations and data were collected from two fields planted on the same day in early May 2017 near Brownsville, WI. One field was planted with Pioneer® variety 54HVX41 alfalfa (9% light coat) and the other planted with a competitor variety (34% heavy coat). Alfalfa was planted using the same seeder and the same alfalfa seeding rate setting (17 lbs/acre) for all fields and varieties. Both fields had corn residue present from the previous crop. In addition, the field planted to 54HVX41 had two different previous crops and residue levels. In June 2017, stand counts were taken from random locations in each field as well as residue treatment and reported in Table 2.

Figure 6. Stand establishment (left) and plant size (right) of 54HVX41 in differing previous crops and residue levels.

Table 2. Effect of variety, seed coat, previous crop, and residue level on plants emerged.

Variety	Seed Coat*	Previous Crop	Residue Level	Plants Emerged (plts/ft²)
Pioneer variety 54HVX41	Light, 9%	Pea	Light	58
Pioneer variety 54HVX41	Light, 9%	Corn	Light	42
Pioneer variety 54HVX41	Light, 9%	Corn	Heavy	21
Competitor	Heavy, 34%	Corn	Light	23

Figure 7. 54HVX41 with light coat seeded at 17 lbs/acre into pea residue (58 plants/ft²).

Figure 9. 54HVX41 with light coat seeded at 17 lbs/acre into heavy corn residue (21 plants/ft²).

Figure 8. 54HVX41 with light coat seeded at 17 lbs/acre into light corn residue (42 plants/ft²).

Figure 10. Competitor variety with heavy coat seeded at 17 lbs/acre into light corn residue (23 plants/ft²).

Summary

- Previous crop residue type and level can greatly impact early establishment success of alfalfa. Heavy crop residue may decrease early stand establishment by as much as 50%. In addition, early vigor is influenced by previous crop residue.
- Varieties with heavy-coat seed (34%) result in fewer seedlings established compared to a light-coat (9%) variety when planted with the same drill setting.
- Adjust planter settings for each variety to compensate for different seed-coating levels. This results in a greater number of established seedlings, which may lead to higher yields and longer stand life.
- Alfalfa seeding rates are best determined by targeting the number of seeds per square foot (60-80) and then calculating pounds per acre by adjusting for seed coat and germination level.

Achieving Corn Silage Harvest Timing Forgiveness

Late Season Plant Health Leads to Silage Harvest Window Flexibility with Pioneer® Brand Corn

*by **Dann Bolinger, M.S.,** Dairy Specialist*

Data Collection

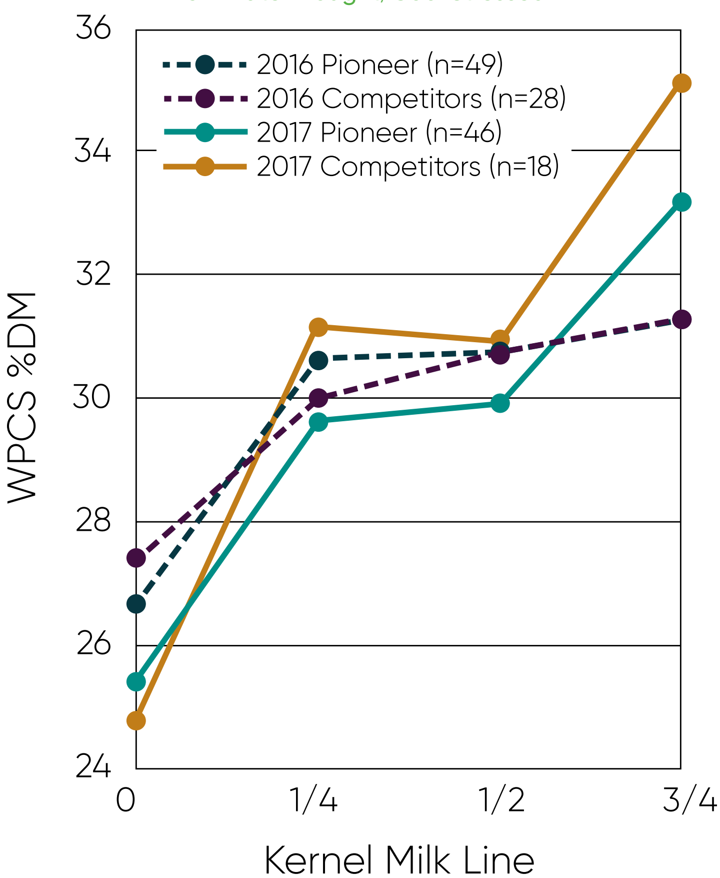
As part of routine efforts to manage corn silage harvest timing, 141 samples of 2 to 3 representative plants each were collected from fields, assessed for milk line, chipped then measured for whole plant corn silage percent dry matter (WPCS%DM). The 2016 and 2017 growing seasons were extremes in late season drought stress in the four county mid-Michigan area represented. While 2016 corn plants were relatively stress-free as silage harvest approached, 2017 experienced six or more continuous weeks of minimal precipitation plus cool, then hot temperature stressors prior to harvest.

Findings

- In the absence of plant stress, Pioneer® brand corn and competitor products dried down similarly in grain maturity relative to WPCS%DM.
- Under stressful conditions, Pioneer® brand corn increased WPCS%DM more slowly than the average of competitor products while continuing to advance grain maturity. Individual comparisons followed through harvest support this conclusion.
- **These data strongly suggest a more forgiving and flexible harvest window under stressful crop conditions.**

Harvest Timing Samples (Normal Hybrids)

2016 Non-Stressed
2017 Late Drought/Cool Stressed



Harvest data collected 19 days after the above photos.

	DKC50-82RIB	P9789AMXT™ (AMXT, LL, RR2)
Relative Maturity	*100d*	*97d*
Harvest %DM	*50.8*	*53.6*
Tons/Acre @ 35%DM	*27.0*	*28.0*
%Starch	*44.4*	*44.3*
%Sugar	*2.3*	*5.1*
%NDFd-24h	*57.5*	*60.7*
%uNDFom-240h	*8.7*	*7.5*

Images imply greater plant health in the shorter relative maturity Pioneer® brand hybrid despite more advanced grain maturity. The observed plant health carried through extreme heat and drought to the harvest of an overly mature crop. Higher %sugar and fiber digestibility plus lower uNDF concur with observations of greater plant health. Harvest %DM relative to visual appearance and quality data strongly suggests moisture was proportionately much greater in the fodder versus grain as compared to competitor product.

High Yield Sorghum Production

*by **Mark Jeschke, Ph.D.,** Agronomy Manager*

National Sorghum Producers Yield Contest

- The National Sorghum Producers (NSP) Yield Contest provides a benchmark for yields that are attainable under optimal conditions and management.
- The NSP Yield Contest recognizes three national winners annually in each of eight production divisions:
  - » Dryland Conventional-Till
  - » Dryland Double Crop
  - » Dryland No-Till
  - » Dryland Reduced-Till
  - » Irrigated Conventional-Till
  - » Irrigated Double Crop
  - » Irrigated No-Till
  - » Irrigated Reduced-Till

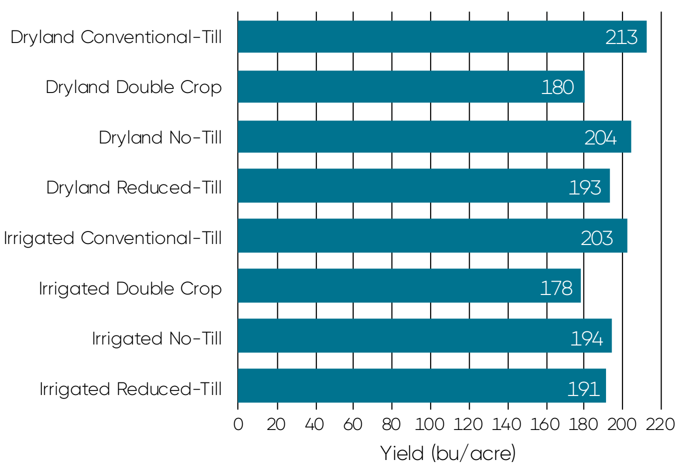


Figure 1. Average yield of 2017 NSP Yield Contest national winners in the eight contest categories.

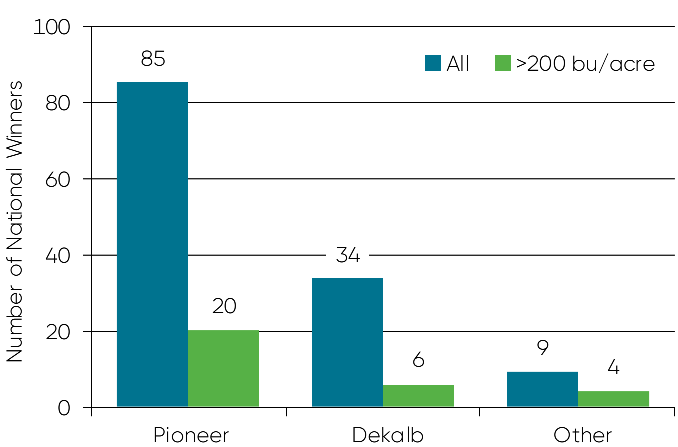


Figure 2. Seed brand planted by NSP Yield Contest national winners and winners yielding above 200 bu/acre, 2012-2017.

Hybrid Selection

- Selecting the right hybrid is likely the most important management decision of all those made by contest winners.
- Maximizing yield requires matching hybrid characteristics with field attributes, such as moisture supplying capacity; insect and disease spectrum and intensity; maturity zone; residue cover; and even seedbed temperature.
- Pioneer® brand products were used in the majority of NSP Yield Contest national winners in 2012 to 2017 (Figure 2).
- Eight different Pioneer® brand sorghum hybrids were national winners from 2012 to 2016 and seven different hybrids in the 2017 contest, showcasing a diversity of product success (Table 1).
- Five Pioneer® brand sorghum hybrids achieved yields above 200 bu/acre in the NSP Yield Contest over the past 6 years (Table 2).

Table 1. Pioneer® brand sorghum hybrids planted by past NSP Yield Contest national winners (2012-2016) and national winners in the 2017 contest.

	NSP National Winners	
Hybrid	2012-2016	2017
84G62	35	8
84P80	16	3
85Y40	8	2
84P72	4	2
83P17	1	
83P99	1	
86G32	1	
87P06	1	1
85G03		1
86P90		1

Table 2. Yields above 200 bu/acre attained with Pioneer® brand sorghum hybrids in the NSP Yield Contest, 2012-2017.

84G62	84P80	85Y40	86P90	87P06
233.4	245.9	237.9	207.8	212.7
229.5	210.1	220.5		209.2
228.1	215.0	209.7		
215.0		208.4		
210.9		205.1		
210.7				
209.1				
208.0				
206.9				

Seeding Rate

- The majority of winning entries in the NSP Yield Contest seeded sorghum at a rate between 90,000 and 140,000 seeds/acre with some variation among categories (Figure 3).
- Among all contest entries, a wide range of sorghum seeding rates were used, but the most common rates were between 40,000 and 120,000 seeds/acre (Figure 4).

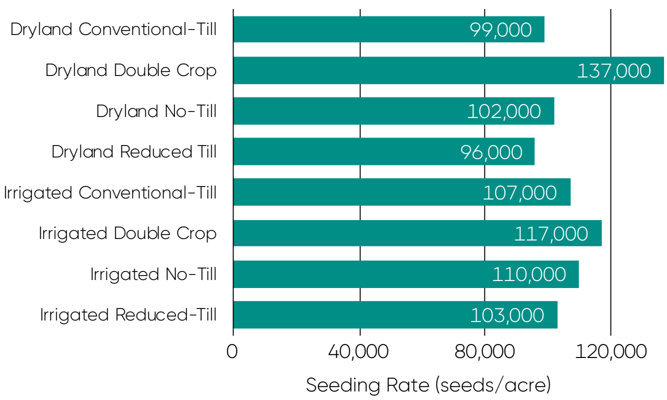


Figure 3. Average seeding rate of NSP Yield Contest national winners from 2017 by division.

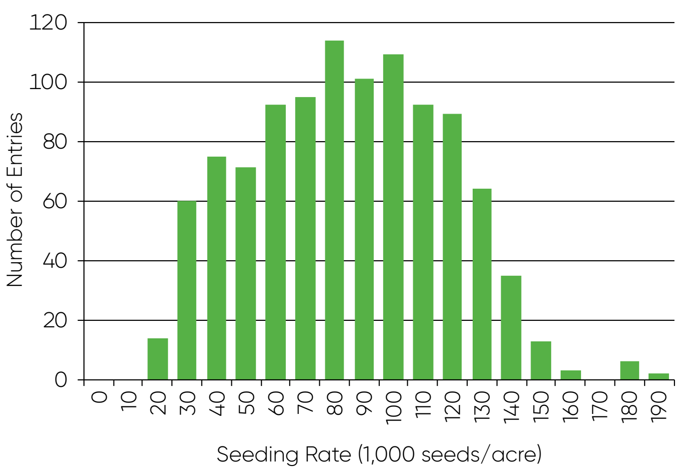


Figure 4. Frequency of seeding rates used among all contest entries in the NSP Yield Contest, 2012-2017.

Row Width

- The most common row width used in the NSP Yield Contest was 30-inch rows, which was used in 62% of contest entries (Figure 5).
- 15-inch rows was the second most popular row width, accounting for 19% of entries.
- Narrower row configurations (<15 inches) comprised 6% of entries, 16 to 29-inch widths were represented at 6%, and 7% of contestants planted sorghum at wider row configurations above 30 inches.

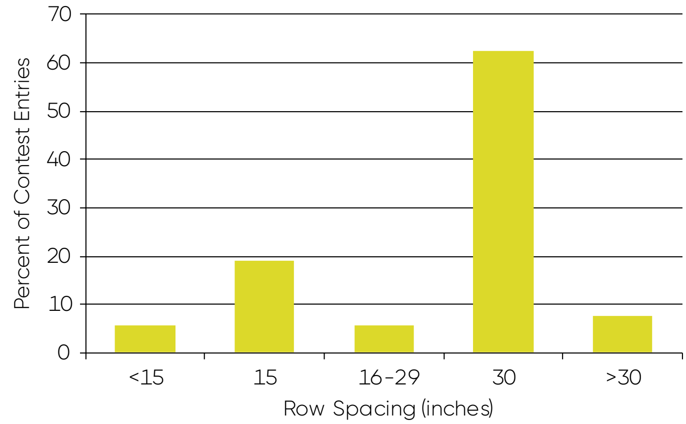


Figure 5. Row spacing of entries in the NSP Yield Contest, 2012-2017.

Nitrogen Fertilizer

- Although sorghum is considered a relatively low-input crop compared to corn, nitrogen is the nutrient that most frequently limits sorghum production.
- Sorghum requires approximately 1.1 to 1.5 lbs of nitrogen per bushel harvested, so a total nitrogen needed for the soil per acre can depend on expected yield.
- Only a portion of this amount needs to be supplied through nitrogen fertilizer; nitrogen is also supplied by the soil through mineralization of soil organic matter.
- The most common nitrogen fertilizer rates among 2017 NSP Yield Contest entries ranged from 101 to 150 lbs/acre with over 30% of entries in this range (Figure 6).
- 18% of entries had a nitrogen fertilization rate less than 100 lbs/acre, while 26% applied nitrogen at a rate from 151 to 200 lbs/acre and 15% above 200 lbs/acre.

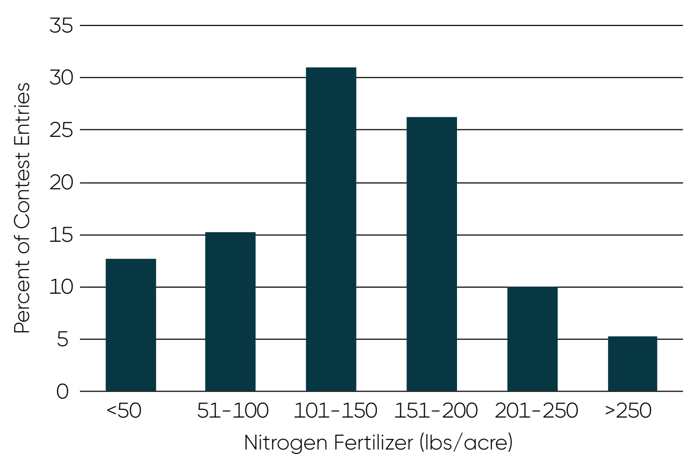


Figure 6. Nitrogen fertilizer rates for all entries in the NSP Yield Contest, 2017.

Breeding for Sugarcane Aphid Tolerance in Sorghum

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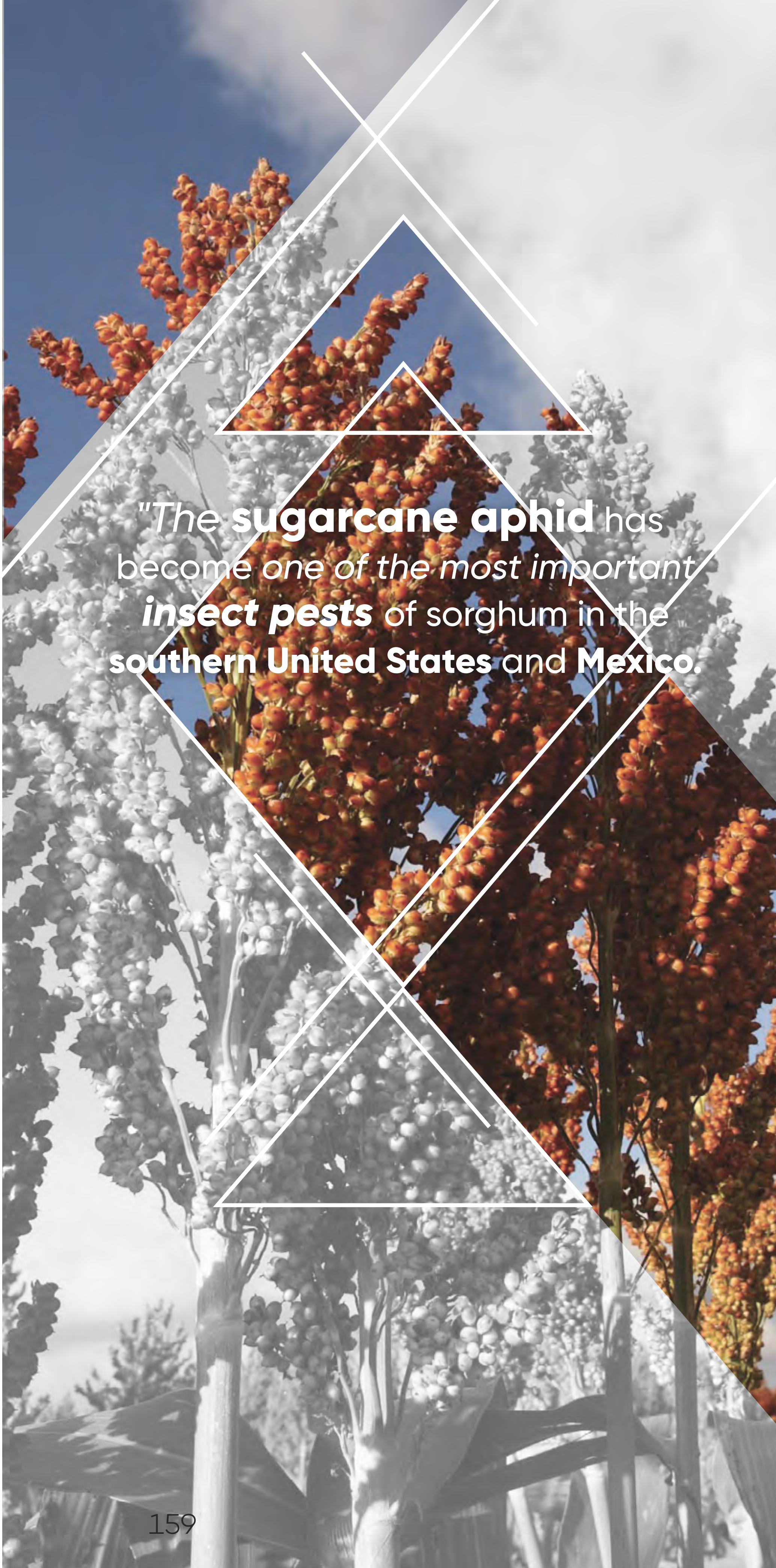
Summary

- Breeding for sugarcane aphid tolerance in sorghum, as with all traits, relies heavily on observational data.
- Sorghum sugarcane aphid tolerance falls somewhere in between a single-gene and multi-gene trait.
- Characterizing sorghum hybrids for sugarcane aphid tolerance utilizes genetic and phenotypic screening approaches that include field observations and laboratory screening.
- Knowing the genetic tolerance to sugarcane aphid is only one tool for management of the pest. This knowledge, along with good field management, offers the best protection against sugarcane aphid.



Introduction

The sugarcane aphid, *Melanaphis sacchari*, also known as the white sugarcane aphid, has become one of the most important insect pests of sorghum in the southern United States and Mexico. Sugarcane aphid is capable of causing significant damage and reductions to yield in sorghum. Its rapid spread has quickly made it a major pest of sorghum production in North America. Research has shown that sugarcane aphid tolerant sorghum hybrids have slower sugarcane aphid reproduction and, in some cases, can withstand higher sugarcane aphid populations than susceptible hybrids without a reduction in yield.

Breeding Strategy

Breeding for sugarcane aphid tolerance in sorghum, as with all traits, relies heavily on observational data. Any measurable characteristic can be referred to as a phenotype. The phenotype is the visual manifestation of the underlying genetics of the plant, the environment in which it grows, and the interaction of the genetics and environment. The genetic component that influences a phenotype can vary drastically from trait to trait. Some traits can be controlled by a single gene. For example, downy mildew and head smut resistance in sorghum are controlled by a single major gene. On the other end of the spectrum are multi-gene traits. These traits are controlled by numerous genes that each have a small effect on the phenotype. Yield is the most commonly cited example of a multi-gene trait, regardless of crop.

Figure 1. Sugarcane aphids: A winged adult, non-winged adults, and nymph.

The nature of a trait has a large influence on the breeding strategy and rate of genetic gain for a given trait. Single-gene traits can be moved around to other genetic backgrounds relatively quickly. Typically, this is done through backcrossing, where germplasm with the desired trait (the donor) is crossed into elite germplasm containing adapted traits for a given geography. The offspring of this cross is then crossed back to the elite germplasm again. By selecting for both the trait of interest and the background genetics of the elite line over a few generations, a converted line with all the elite adapted traits and the trait of interest is created.

In the case of multi-gene traits, the breeding strategy is more complex. The process becomes more akin to shuffling a deck of cards to produce new combinations of many existing genes in the germplasm pool. The goal is to create new lines with the largest number of positive genes for the trait of interest. The primary challenge is that these effects are small, and therefore, the number of positive genes cannot be measured directly. Instead, the phenotype is used to infer the effects of all the positive genes together in the new breeding lines and hybrids lines created.

Sorghum sugarcane aphid tolerance falls somewhere in between a single-gene and multi-gene trait. There is a single genetic region that confers a large improvement in the sugarcane aphid tolerance of a sorghum hybrid. If a hybrid has the tolerant allele at this region of the genome, then aphid reproduction and survival are reduced on these plants compared to a susceptible control. Because this is a large effect gene, it can be moved into elite germplasm via backcrossing in a few generations, especially since the trait can now be tracked using molecular markers. This allows a reduction in the amount of time needed to breed sugarcane aphid tolerance into commercial hybrids. It also provides the least disruption to the other traits of interest, particularly yield gain, standability, and disease tolerance.

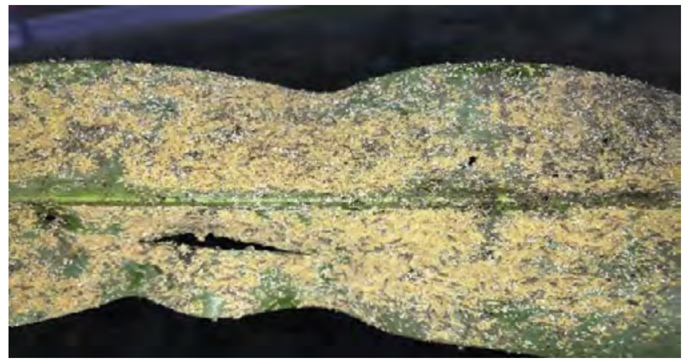


Figure 2. Sorghum leaf covered with sugarcane aphids.

Phenotypic Screening

As the number of factors influencing a given trait increases, it becomes more difficult to make genetic improvements for that trait. It is very difficult to change the number of genes underlying a phenotype so breeders must look elsewhere to increase the efficiency of genetic gain. A key way to improve genetic gain is to improve the accuracy of phenotypic characterization for a given trait. Breeders can leverage lessons learned breeding for other traits to apply to screening for sugarcane aphid tolerance. Phenotypic data are used to guide population and inbred development, advise hybrid advancements, and shape the breeding strategy, so accuracy of this information is paramount.

Figure 3. A typical sorghum sugarcane aphid screening nursery.

Figure 4. An example of a sorghum hybrid highly susceptible to sugarcane aphid feeding.

Figure 5. An example of a hybrid with moderate tolerance to sugarcane aphid feeding.

Figure 6. An example of a sorghum hybrid with a high level of tolerance to sugarcane aphid feeding.

A common way to increase the accuracy of phenotypic data is replication. Replication can take on many forms, including multiple plots within one location, multiple locations, and repetition over multiple years. Pioneer breeders use all three of these replication methods to improve the accuracy of phenotypic estimates for sugarcane aphid tolerance. If sugarcane aphid tolerance is observed in one replication but not the other(s) within a given location, then the confidence level of the information is suspect. Confidence increases as a hybrid or inbred shows tolerance across multiple replications. Every year, Pioneer breeders plant multiple locations dedicated exclusively to sugarcane aphid screening across North America. Additionally, sugarcane aphid data are often collected at nursery and yield trial locations when there are opportunities to do so.

Another way to increase the accuracy of the data is to remove human and experimental bias from the observations. One way this can be done is to use UAV imagery to quantify leaf health instead of estimating it via visual ratings. Another approach that is being taken to remove bias is to remove field variation from the equation. When the sugarcane aphid infests a location, it does not spread evenly throughout the location, making this a very difficult trait to score accurately. This is a major reason why replication is so important for sugarcane aphid scoring. There are many experimental designs that can be used to try to account for and remove field variation. It is also possible to completely remove this variation by moving the assay to the greenhouse as discussed in the native resistance section.

Figure 7. Aerial view from a drone to observe hybrid differences.

Germplasm

Determining what material to screen for sugarcane aphid tolerance is a crucial step in developing tolerant hybrids. Screening millions of sorghum accessions, even by the most precise means available, may not lead to progress in improving the trait if there is not enough genetic variability for sugarcane aphid tolerance. Pioneer breeders screen by separating the germplasm into two categories based on the selection criterion. Characterization of the current commercial and pre-commercial hybrid lineup is essential. This information is used to advise customers and place products in environments that will maximize their performance. In addition, it facilitates improvement of sugarcane aphid tolerance in commercial products, and data collected on hybrids can be leveraged to guide breeding efforts.

The other category of material Pioneer breeders screen for sugarcane aphid tolerance is for discovery and molecular mapping purposes. This is critical to understanding sugarcane aphid tolerance and continuing to drive improvement. In addition to screening current elite germplasm, Pioneer breeders have maintained coded inbred lines from the beginning of their sorghum breeding efforts in the 1960s, have an extensive collection of public germplasm, and maintain an extremely diverse exotic sorghum germplasm collection. This one-of-a-kind collection can be screened in high volume, low replication field trials. Any promising lines can then be re-evaluated with a higher precision method to determine the value of the material as a sugarcane aphid tolerant donor. Pioneer breeders have successfully used this approach to identify several new promising sources of tolerance to sugarcane aphid that are now being incorporated into elite material.

As with any defensive trait, there is always the opportunity for sugarcane aphid to overcome the tolerance currently used. For this reason, discovery efforts continue, in addition to backcrossing sources of resistance already identified to our world class germplasm. Multiple sources of tolerance will help ensure the longevity of sugarcane aphid tolerance in commercial hybrids.

Native Resistance

Corteva Agriscience™, Agricultural Division of DowDuPont has developed a technique for screening sorghum lines for their ability to reduce the survival and reproduction of the sugarcane aphid. The bioassay facility screens germplasm for native resistance to this important pest. Native resistance is an important part of an integrated pest management (IPM) system. The goal of IPM is to keep the number of aphids per plant below the economic threshold level. The identification and introgression of resistance is an important part of hybrid development in sorghum. Sorghum resistance to the sugarcane aphid has been identified and resistant hybrids are currently under development. Sorghum entries are evaluated for sugarcane aphid antixenosis at the bioassay facility. These scores should be used as an aphid management tool along with diligent scouting.

Figure 8. Sugarcane aphid bioassay.

Figure 9. Resistant vs. susceptible entries.

Local Management Information

For specific product information on sugarcane aphid tolerance by hybrid, please consult your local Pioneer sales representative.

For information on chemical control of sugarcane aphid (if needed), consult your local Corteva Agriscience representative.

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Footnotes and Acknowledgments

[1] All Pioneer products are hybrids unless designated with AM1, AM, AMRW, AML, AMT, AMX, AMXT and Q, in which case they are brands.

Harvest photo on page 19 and CaseIH MX 285 and Magnum 380 photos in Figure 1, courtesy of CNH.

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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 products.

AM1 - Optimum® AcreMax® 1 Insect Protection System with an integrated corn rootworm refuge solution includes HXX, LL, RR2. Optimum AcreMax 1 products contain the LibertyLink® gene and can be sprayed with Liberty® herbicide. The required corn borer refuge can be planted up to half a mile away.

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 corn borer refuge must be planted with Optimum AcreMax Xtra products.

AMXT - 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 cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax XTreme products.

AVBL, YGCB, HX1, LL, RR2 (Optimum® Leptra®) - Contains the Agrisure Viptera® trait, the YieldGard Corn Borer gene, the Herculex® I gene, the LibertyLink® gene, and the Roundup Ready® Corn 2 trait.

YGCB, HX1, LL, RR2 - Optimum® Intrasect® contains the Herculex® I gene and the YieldGard® Corn Borer gene for resistance to corn borer.

Components of the LumiGEN™ system for soybeans are applied at a Corteva Agriscience™, Agriculture Division of DowDuPont production facility, or by an independent sales representative of Corteva Agriscience or its affiliates. Not all sales representatives offer treatment services, and costs and other charges may vary. See your sales representative for details. Seed applied technologies exclusive to Corteva Agriscience and its affiliates.

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HX1 - Contains the Herculex® I Insect Protection gene which provides protection against European corn borer, southwestern corn borer, black cutworm, fall armyworm, western bean cutworm, lesser corn stalk borer, southern corn stalk borer, and sugarcane borer; and suppresses corn earworm.

HXX - Herculex® XTRA contains the Herculex I and Herculex RW genes.

HXRW - The Herculex® RW insect protection trait contains proteins that provide enhanced resistance against western corn rootworm, northern corn rootworm and Mexican corn rootworm. Herculex® RW Rootworm Protection technology by Dow AgroSciences and Pioneer Hi-Bred.

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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.

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