agronomy research summary

2023

contents

*Research was supported in part by 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, sales professionals, and customers.

return to table of contents

2022 Growing Season in Review

At this point it's getting difficult to remember what a "normal" year in agriculture even looks like. With the widespread weather impacts of 2019 and early 2020 followed immediately by the pandemic-related supply chain constraints of 2020 and 2021, one would have to go back to 2018 for the last time we had a growing season that was not impacted by some major, widespread disruption. 2022 started right where 2021 left off, with short supplies and high prices for fertilizer, parts, and other farm inputs as a primary concern on the minds of many growers. The Russian invasion of Ukraine in February dashed any hope for a return to normalcy in 2022 and added a whole new dimension of disruption and uncertainty in agricultural and energy markets. Fertilizer and diesel prices would remain elevated throughout the rest of the year.

As the growing season got underway, however, it was often much more familiar challenges, such as weather, insects, and disease pressure that ended up shaping the 2022 season. Planting got off to a relatively slow start in 2022. Below normal temperatures throughout much of the Corn Belt during the month of April caused widespread delays (Figure 1). Planting was able to proceed relatively quickly in many areas once temperatures warmed up, but U.S. corn planting progress overall was about two weeks behind the 2020 and 2021 seasons (Figure 2).

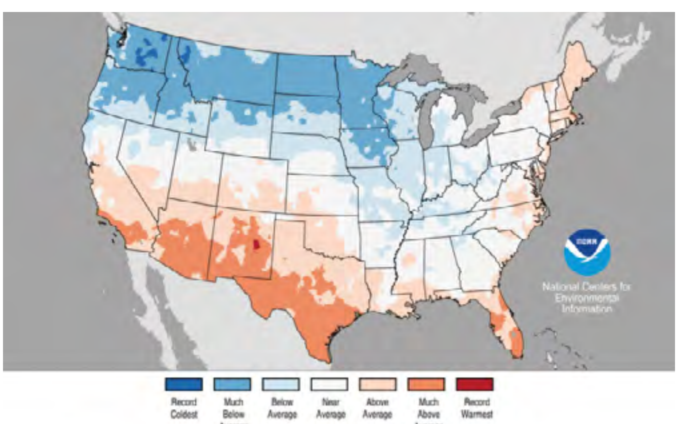

Figure 1. Average temperature percentiles for April 2022 (NOAA).

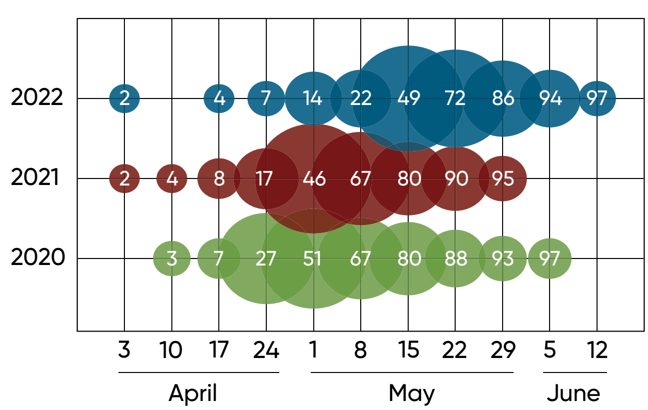

Figure 2. U.S. corn planting progress for 2020, 2021, and 2022 (USDA-NASS).

Planting corn in northern Illinois, May 8, 2022.

Above-average temperatures in May got the crop off to a good start in many areas, although a late-spring freeze in Nebraska and some early-summer hail events led to some replanting of corn in parts of the western Corn Belt.

2022 saw another summer of record high temperatures in the contiguous U.S. The month of July was the 3rd warmest on record (with 2021 being the #1 warmest). As in 2021, the high temperatures were not driven by extreme daytime highs as much as high nighttime temperatures. Both July and August set new all-time records for daily minimum temperatures, with nearly all of the contiguous U.S. experiencing warmer-than-average-nights (Figure 3).

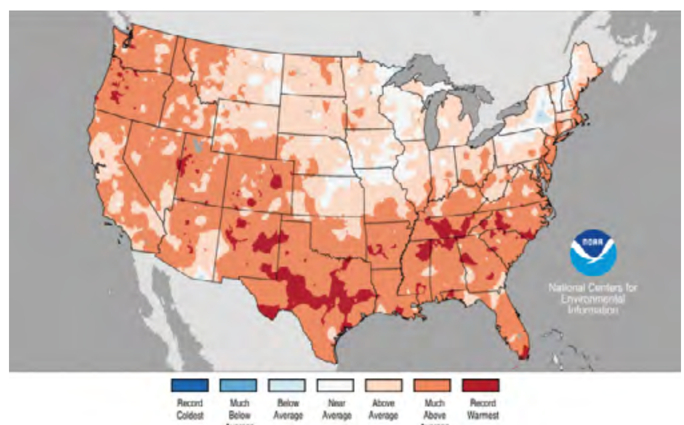

Figure 3. Minimum temperature percentiles, July 2022 (NOAA).

The warm temperatures helped move crop development along and, by the time corn reached silking, it was able to catch up somewhat from its delayed start. Things seemed to lag in the latter half of the season though, with stubbornly slow maturity and dry down in corn throughout much of the northern and eastern Corn Belt. However, a relatively dry October allowed the combines to keep rolling once harvest got started.

The 2022 season brought a mixed bag of insect, weed, and disease issues. Dry conditions early in the summer led to poor efficacy of soil residual herbicides in the western Corn Belt. Corn rootworm pressure remained relatively high in many areas following an above average corn rootworm season in 2021. Populations of northern corn rootworm with extended diapause continued to show up in rotated corn, with parts of Iowa and northwestern Illinois increasingly affected. Dry conditions kept foliar diseases largely in check in many areas. Tar spot continued its westward expansion into Nebraska and Kansas but was generally not severe outside of parts of southern Wisconsin, southeast Minnesota, and northeast Iowa. The slow dry down of corn in some areas led to widespread occurrence of ear molds.

Tar spot in corn, Sept. 2022.

Ultimately it was water – often too much or too little – that determined the fate the 2022 crop, and some of the extremes that occurred at both ends of the spectrum were dramatic. The summer months were generally drier than normal west of the Mississippi, but the situation was much more severe for large parts of Nebraska and Kansas that experienced well below average precipitation. Lack of moisture coupled with high temperatures led to some of the most extreme drought conditions in years for both states. East of the Mississippi, summer precipitation was generally more favorable, but portions of Illinois and Indiana experienced drought stress severe enough to significantly impact yield.

On the other end of the spectrum were numerous instances of extreme rainfall events, including six 1,000-year rain events in the contiguous U.S. that occurred within the span of a month in July and August. On July 26, the St. Louis area received up to nine inches of rain within 24 hours. Two days later a 10-inch rain led to deadly flash flooding in eastern Kentucky. Portions of eastern Illinois were hit with 10-13 inches of rain on August 1-2. By the end of August, the Dallas-Ft. Worth area, southern California, and central Mississippi also experienced 1,000-year events.

Despite these intense rainfall events, very few crop-producing areas experienced sustained periods of excess moisture in 2022. Rather, it was the dry conditions for a longer duration and over a much larger area that had the broader impact. By October, water levels in the Mississippi River had dropped to the point that barge traffic was restricted, with many points on the river hitting their lowest levels in decades. The U.S. Drought Monitor map for October showed that most of the U.S., including nearly all of the Mississippi River watershed, was experiencing some degree of drought (Figure 4).

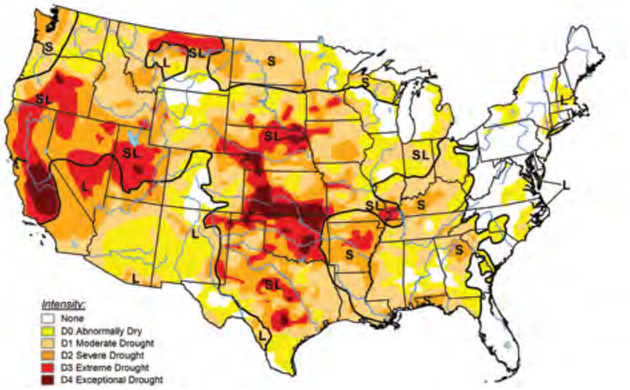

Figure 4. U.S. Drought Monitor map, October 25, 2022.

Successful crop management under constantly evolving conditions requires smart and efficient use of resources, driven by sound agronomic knowledge. A commitment to improved crop management is a core component of the Pioneer brand, exemplified by our industry-leading network of agronomists across North America. The mission of this team is to help maximize grower productivity by delivering useful insights built on rigorous, innovative research. Pioneer agronomists work to help crop producers manage factors within their control and maximize productivity within the environmental constraints unique to a given growing season, be they favorable or not.

This Agronomy Research Summary is the latest edition of an annual compilation of Pioneer agronomy information and research results. Highlights of the 2023 edition include updates on two emerging diseases: tar spot in corn and red crown rot in soybeans; field research results for Lumiscend™ Pro fungicide seed treatment; an overview of nitrogen fertilizer and stabilizer products; new research on fertility management in strip-till systems; and Pioneer on-farm research studies on corn seed orientation in the furrow at planting, phantom yield loss in corn, and corn kernel weight differences by hybrid. The final section of this book takes a look at the science of anthropogenic climate change and how it intersects with crop production. As carbon sequestration, greenhouse gas reduction, and climate change adaptation become more prominent issues for crop management, having a basic understanding of the underlying science will be increasingly important to make sense of it all.

This Agronomy 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 at www.pioneer.com. We hope that resources available in this book and online will help you drive productivity, efficiency, and profitability in 2023.

Mark Jeschke, Ph.D.
Agronomy Manager

return to table of contents

Forward—thinking Farming

a webinar series powered by Pioneer® Agronomy

The Forward-thinking Farming webinar series launched in early 2020 featuring the cutting-edge agronomic knowledge and expertise of the Pioneer® agronomy team. Each episode is led by a Pioneer Agronomy Manager and industry experts, and is focused on the innovative tools, technology, and agronomic practices of Pioneer to help farmers be successful and evolve into the future.

Forward-Thinking Farming Webinar

Listen in on the cutting-edge insights of the Pioneer Agronomy team!
Watch our recent *Forward-Thinking Farming* webinars at **pioneer.com/webinars.**

Pioneer Agronomy

Pioneer Agronomists and others take to the screen to share insights on topics important to you.
Scan the QR codes in text to watch videos from your Pioneer team.

return to table of contents

2022 Webinar Series

Listen in on the cutting-edge insights of the Pioneer Agronomy team!

Watch our recent ***Forward-thinking Farming*** webinars at **pioneer.com/webinars**

Managing for Improved Nitrogen Utilization in Corn

One of the top management decisions for farmers is how to improve the uptake and utilization of nitrogen in their corn crop.

Listen to Dr. Daniel J. Quinn, *Purdue University*, and Dr. Jason DeBruin, *Corteva Agriscience*, discuss hybrid interaction with nitrogen uptake, application methods, nitrogen sources, and insights on environmental interactions that can influence nitrogen management strategies to optimize return on nitrogen investment.

Driving Nitrogen Uptake in Corn – *New Ways to Get Nitrogen into Your Corn Crop*

High nitrogen fertilizer costs have farmers across the U.S. rethinking how to get the most out of their current nitrogen investment and considering alternative options.

Join Mike Koenigs, *Corteva Crop Protection*, and Dr. Michael Moechnig, *Corteva Research & Development*, as we cover opportunities to get the most out of your current fertilizer investment, as well as novel nitrogen sources – including biological products – that can supplement traditional fertilizers.

Getting the Most from Your Fertilizer Using the Pioneer® Yield Pyramid™ decision tool

The 2022 crop may see the highest fertilizer prices in history. The "Law of the Minimum" states that crop yield is limited by the least available crop-essential nutrient. With all of the emphasis on nitrogen, what can farmers do to make sure they get the maximum benefit from phosphorus, potassium and sulfur?

Join Dr. Eric Miller, *Pioneer Field Agronomist*, and Dr. Matt Clover, *Pioneer Agronomy Manager*, to discuss how to use the Pioneer® Yield Pyramid™ decision tool to prioritize secondary nutrient applications and maximize profitability

Planting with Precision - *Adjustments, Tips, and Watchouts*

Planters have come a long way in a short time, and today, they are sophisticated pieces of technology capable of planting seed with incredible accuracy and uniformity. But these planters can only achieve the correct seed placement if adjusted and maintained properly.

Join Mike Gronski, Jason Kienast, and John Mick, *Pioneer Field Agronomists,* as they discuss top planter adjustment tips and watchouts to keep in mind during planting to give your seedlings the best possible start to the growing season.

How Hot is Too Hot? – *Understanding How Heat Stress Affects Corn*

Corn growers know that excessive heat can be detrimental to yield, but how hot is too hot? And what is the risk of yield loss due to excessive heat? Heat stress effects on corn are complex and often difficult to quantify.

Join Dr. Mark Jeschke, *Pioneer Agronomy Manager,* as he covers how the intensity, duration, and timing of heat stress factor into corn growth and yield, how high temperatures can intensify drought stress, and what management options exist to improve corn resiliency against the effects of high heat.

How Pioneer Maximizes Corn and Soybean Seed Quality

Having a uniform stand of soybeans and corn is important to the foundation of yield. Pioneer takes great pride and effort in the quality of seed we produce. Please join this webinar to learn some of the key steps Pioneer takes to create the highest quality of seed for your operation.

Join Kevin Dillion, and Aaron Schwarte, *Corteva Seed Production Research Scientists,* for an overview of the production process that creates the highest quality seed, and a review of the quality testing process that we use to make sure the highest quality seed ends up in every Pioneer bag.

Crop Check-ins and Adapting to the Season

Interested in how major crops are doing across the nation? Tune-in for boots-on-the-ground field updates from Pioneer's expert team of field agronomists. Each season has its unique challenges, and we'll talk through what's happened so far and hear how some farmers are adapting.

Join Pioneer Field Agronomists to discuss the unique challenges that growers are facing this year in their regions, and what new management practices and tools are being adopted to best adapt to them.

June 24th Featured Speakers:

- Clyde Tiffany, *Pioneer Field Agronomist – West-Central Minnesota*
- Gabe Bathen, *Pioneer Field Agronomist – Southeast Nebraska*
- Tony Zerrusen, *Pioneer Field Agronomist – Southern Illinois*
- William Johnson, *Pioneer and PhytoGen District Field Agronomist – Louisiana/ Southern Arkansas*

July 17th Featured Speakers:

- John Schoenhals, *Pioneer Field Agronomist – Northern Ohio*
- Ron Gehl, *Pioneer Field Agronomist – Northeast Kansas*
- Marc Cartwright, *Pioneer Field Agronomist – Northeast North Dakota/ Northwest Minnesota*
- Kyle Holmberg, *Pioneer and PhytoGen District Field Agronomist – Tennessee/ Kentucky*

August 19th Featured Speakers:

- Ryan Clayton, *Pioneer Field Agronomist – Central Iowa*
- Nick Schimek, *Pioneer Field Agronomist – North Central Minnesota*
- Kevin Fry, *Pioneer Field Agronomist – Western Pennsylvania*
- Luke Spainhour, *Pioneer and PhytoGen District Field Agronomist – North Carolina/Virginia*

agronomy team

return to table of contents

Dan Berning, *Agronomy Manager*

Dan earned his B.S. in Agriculture at Kansas State University. In the fall of 1989, he started his career with Pioneer as an Area Agronomist supporting the sales team and their customers in western Kansas and southern Colorado. He became the Pioneer Field Sales Agronomist in northeast and north-central Nebraska in 1994. In 1998, he was promoted to Field Sales Agronomy Manager for the Plains Sales Area. Dan has had the privilege of supporting the Pioneer sales team and customers across the Western Corn Belt in the roles of Technical Information Manager, Technical Services Manager, and now as the Agronomy Manager.

Danny Brummel, M.S., *Agronomy Systems Manager*

Danny leads the Pioneer UAS/Drone Program and supports the execution, analysis and delivery of on-farm research trials that drive Pioneer Agronomy innovation. He earned his B.S and M.S. degrees in Agronomy from Iowa State University and holds CCA and PASp certifications. Danny started his career with Corteva Agriscience in 2019, where he managed disease screening trials and supported precision phenotyping efforts for corn, soybean, and wheat breeding programs. He also serves as chair to the Corteva Grows Science program in Iowa, promoting STEM Outreach in our local communities.

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. 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 nine-year career in the fertilizer industry with various roles in agronomy and research and development.

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.

Grant Groene, M.S., *Global Seed Agronomy Lead*

Grant has been with the Corteva organization since 2010 when he began as a Field Agronomist in Eastern Kansas. He spent the next several years working as a Territory Manager and Product Life Cycle Manager, supporting teams in Texas and across the High Plains. Grant relocated to Iowa and began leading the Global Agronomy efforts in 2018. His primary responsibility is to plan strategic agronomy initiatives, facilitate agronomy trainings, and share best agronomic practices with colleagues across the global Corteva business. Grant graduated from Kansas State University with B.S. in Agronomy and an M.S. in Crop Physiology and Plant Breeding, and holds an M.B.A. from West Texas A&M.

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.

return to table of contents

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. Mark is originally from northern Illinois and is actively involved in the family corn and soybean farm near Rock City, Illinois.

Darrin Malone, M.S., *Agronomy Leader - Midsouth*

Darrin holds B.S. and M.S. degrees in agronomy from the University of Arkansas and is a Certified Crop Adviser and Certified Professional Agronomist. Darrin started his career as a Territory Manager for DuPont Crop Protection in Indiana and has subsequently served in a diverse array of roles, including Field Agronomist, Six Sigma Project Manager, Insecticide Portfolio Manager, Field Development Technical Consultant, Market Development Specialist, and Crop Protection District Sales Leader for the Midsouth. Darrin currently serves as the Agronomy Leader for the Midsouth district.

Luke Northway, *Agronomy Systems Manager*

Luke double majored in Management Information Systems and Agricultural Business at Iowa State University and received 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.

Ken O'Brien, M.S., *Agronomy Science Leader*

Ken serves as the Agronomy Sciences Leader for Corteva's U.S. seed businesses. In his 16-plus years with the organization he has held various roles in sales and marketing leadership across both seed and digital/software product lines. His current role supports the field agronomy teams for our seed businesses to provide them with the systems, processes, and information they need in order to provide our customers with successful crop management and product placement information. Ken holds B.S degrees in Agronomy and Plant Health & Protection from Iowa State University and M.S. in Agronomy from Iowa State University.

Todd Rowe, M.S., *Agronomy Leader - Southeast*

Todd is a native of eastern North Carolina and earned his B.S. in Agronomy from North Carolina State University and M.S. in Seed Technology and Business from Iowa State University. Todd held Agronomist positions with other companies prior to joining Pioneer in 2010 as Area IMPACT Lead at the Kinston, North Carolina Research Station. He is now the Agronomy Leader for the Southeast sales area.

April Battani, *Senior Graphic Designer*

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 Senior Graphic Designer for the Creative Services team supporting Agronomy Sciences. 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.

Cori Lee, *Agronomy Sciences Intern*

Cori is a senior at the Ohio State University majoring in Sustainable Plant Systems Agronomy with a minor in Agribusiness. Following graduation, Cori plans to pursue a master's degree and continue helping on her family's farm.

return to table of contents

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A Brief History of Corn

Danny Brummel, M.S., *Pioneer Agronomy Systems Manager,*
and ***Lance Gibson, Ph.D.,*** *Agronomy Training Manager*

Summary

- Modern corn is descended from teosinte, a wild grass native to southern Mexico that was domesticated around 9,000 years ago.
- Cultivation of ancient corn quickly spread and was practiced throughout the Americas by 2500 BCE.
- The two dominant types of corn grown by indigenous peoples of North America were the northern flints and southern dents.
- The bulk of commercial corn varieties worldwide are made up of Corn Belt dent genetics derived from crosses between northern flints and southern dents.
- The advent of hybrid corn in the early 1900s put corn on a trajectory of increasing yields that continues today.
- During the early hybrid corn era, Pioneer took a different approach than many of its competitors by heavily investing in its own inbred line development; an effort that paid off greatly in subsequent decades.
- The adoption of hybrid corn combined with improved breeding techniques and agronomic practices resulted in a steady increase of the average U.S. yield from around 26 bu/acre before the 1930s to 125 bu/acre in 1995.

Corn – A Globally Important Crop

Corn *(Zea mays)*, also known as maize, is an essential crop to a rapidly growing world population, with major uses being feed for livestock, fuel ethanol production, and ingredients for hundreds of foods and industrial products. Globally, corn is grown across six of the seven continents, occupying more than 20% of the land devoted to crop production. Total annual corn production is 50% greater than that of wheat or rice and nearly three times greater than soybean. The history of corn is a 9,000-year journey of significant breakthroughs from early domestication to modern advancements that have occurred over the last decade. For a century, Pioneer has played a significant role in producing key innovations to the modern corn crop. This article reviews the history of corn from domestication until 1995, when the current biotechnology era of corn production began.

Origin, Domestication, And Spread

The journey of modern-day corn started around 7000 BCE in southern Mexico with the domestication of a wild grass plant called teosinte (Figure 1). In the early 20th Century, the ancestry of corn was unknown. Research conducted in the early 1930s pointed to teosinte as corn's wild progenitor, due to similarities in chromosomes and the ability of the two species to produce fertile hybrids. Subsequent research using more advanced genetic tools confirmed this hypothesis. Phylogenetic analysis has placed the timing of genetic divergence between wild teosinte and domesticated corn at around 9,000 years ago. Archaeological research in Mexico has shown evidence of corn cultivation dating back at least 8,700 years.

The physical appearance of corn and its ancestor differs considerably. Whereas corn typically has a tall single stalk and produces an ear up to 12 inches in length with hundreds of kernels, teosinte has many short tillers that produce seeds on a thin axis that is 3 inches in length and contains a dozen seeds encased in hard capsules. Despite the significant differences in physical appearance, corn and teosinte are quite similar genetically.

The domestication of corn from teosinte was accomplished by the inhabitants of the area. These ancient corn breeders practiced selective breeding techniques by saving seed from the plants that had desired traits and replanting the seeds for the next harvest season. Dramatic changes in plant appearance were quickly accomplished and what would be considered recognizable corn was widely present across the Americas by 2500 BCE.

When Christopher Columbus arrived on the eastern shores of the Americas in 1492 CE, corn was already being cultivated throughout both North and South America. While essential to the diet of Native Americans, the annual acreage of corn in North America around the time of early European settlement was thought to be no more than 50,000 acres (compared to around 110 million acres now.) On Columbus's return voyage to Spain, the explorer brought back corn seed to be cultivated in Europe and Northern Africa. The vast expansion of corn across the globe was extremely swift and like that of no other agricultural crop.

Figure 1. Teosinte (*Zea mays* subsp. *Mexicana*), the ancestor of modern corn, native to Mexico and Central America.

Early Breeders and Improvements

The domestication of corn from the tropics to northern temperate areas has shown how adaptable corn can be to various growing environments. Significant modifications have been made by farmers and plant breeders that have made corn a successful agricultural crop around the globe. Different varieties of corn can grow at sea level or at altitudes as high as 12,000 ft; and it can reach harvest maturity within as little as six weeks or up to thirteen months.

return to table of contents

From its domestication until the 1800s, improvements were made to corn through mass selection and geographical isolation. In mass selection, seed is selected and planted based on visual characteristics of the plant, such as size of the ear, plant height or kernel color. These practices resulted in distinct landraces, which are collections of related individuals with enough characteristics in common to permit their recognition as a discrete grouping. Much of this work was done by natives of the Americas as they identified and planted seeds of corn plants that fit their local climate, soil, production practices, and food preferences. Over a hundred distinct landraces of corn have been identified. The various landraces can often be distinguished by ear and kernel characteristics (ear length and width, kernel size and color, hard or soft starch, etc.). The two primary groups of corn when European colonization occurred along the Atlantic Coast of what today is the United States were the northern flints and the southern dents.

In the later part of the 19th century and the early 20th century, ***seed selection*** by farmers was visually based on the **size** and **consistency** of corn ears.

Figure 2. Ears from a northern flint (Longfellow), southern dent (Gourdseed), and Corn Belt dent (Reid Yellow Dent) variety.

With further selection and refinement, varieties with improvements in important traits and reduced variability were developed within landraces. Common varieties of northern flint corn include Longfellow and Tama Flint. These varieties are well adapted to northern climates due to early crop maturity and seedling tolerance to cold soils. Gourdseed, a common variety of southern dent was grown along the southeastern U.S. coastline, reaching as far north as Virginia. In the 19th century, farmers discovered that when crossbreeding occurred between the northern flints and southern dents, it resulted in superior yielding corn with traits desirable for animal feeding. The combination of northern flints and southern dents resulted in the formation of the Corn Belt dents (Figure 2). The creation of the Corn Belt dents is extremely significant to modern corn production as the bulk of commercial corn varieties worldwide are derived from Corn Belt Dent genetics.

New open-pollinated corn varieties can be created by crossing two varieties and saving the seed of the plants that have certain desired traits. (Corn plants have separate male and female flowers, which naturally leads to open, or cross, pollination when wind blows the pollen from one plant to the silks of another.) Farmers continued the practice of crossing varieties of northern flints and southern dents as they settled the Midwestern U.S., developing many Corn Belt open-pollinated varieties. By the early 1900s, it is estimated that around 1,000 different open-pollinated varieties had been created by farmers.

James Reid was a renowned farmer breeder located in central Illinois in the mid-1800s. Reid planted a Gourdseed variety that went through many years of cross breeding with a local northern flint variety known as "Little Yellow Corn." Careful selection of each generation over many years eventually led to the development of the Reid Yellow Dent corn variety. Reid gave seed to his neighbors to ensure the genetic purity of his corn by limiting pollen contamination from other strains of corn. The resulting variety was an overwhelming success, winning corn shows at the Illinois State Fair in 1891 and the World Columbian Exposition in 1893. Reid Yellow Dent became exceedingly popular very quickly, being adapted to nearly every corn producing state and comprising around 75% of all corn acres at its peak. By the early 1900s, hundreds of strains of Reid Yellow Dent had been developed by farmer-breeders.

Advent Of Hybrid Corn

Even with the use of improved breeding techniques beginning in the mid to late 1800s, average U.S. corn yields remained relatively unchanged, averaging between 20 to 30 bu/acre from 1860 through the 1930s. In the later part of the 19th century and the early 20th century, seed selection by farmers was visually based on the size and consistency of corn ears

This practice was widely promoted by corn shows, competitive events that were common at the time and reached their peak popularity in the early 1900s. At corn shows, judges awarded large trophies to entries of 10 ears deemed most 'beautiful' based on ear and kernel uniformity (Figure 3).

After attending a corn show at the age of sixteen, Henry A. Wallace (who would later found the hybrid seed company that became Pioneer Hi-Bred) walked up to a judge and asked how the judge would know that the blue-ribbon winner, if planted the following year, would produce a higher yield than the ears that did not win a ribbon. Challenging the response of the judge, Wallace began his first corn experiment by planting seed from 25 award winning ears and 25 ears that were marked the poorest at the corn show. After collecting yield data from the three-acre plot located in his backyard, the results showed that the highest yielding corn did not come from an award-winning ear but an ear that was near the bottom of the rankings. In fact, the average yield of the lowest ranking ears was greater than the average of the highest-ranking ears. These results challenged conventional thinking at the time by demonstrating there was no relationship between appearance of the ears and yield.

Figure 3. The A.E Cook Corn trophy was commissioned in 1904 to inspire corn development and improvement. The trophy was awarded to the winning collegiate team in the annual corn-judging contest held in Chicago between 1904 and 1907. The trophy is presumed to hold the winning ears from the competition and displays a Native American chief and an early 20th Century corn breeder. Today, the trophy resides in Curtiss Hall at Iowa State University. *Photo Credit: Meyer Bohn Ph.D., Iowa State University.*

While the breeding techniques used by farmers were effective at improving easily observed traits, such as plant height, maturity, ear size, and kernel color, they were not suited to improving yield. A lack of pollen control within fields used for seed was also a factor limiting yield improvement. It was the advent of hybrid corn in the early 1900s that put corn on a trajectory of ever-increasing yields that continues today (Figure 4).

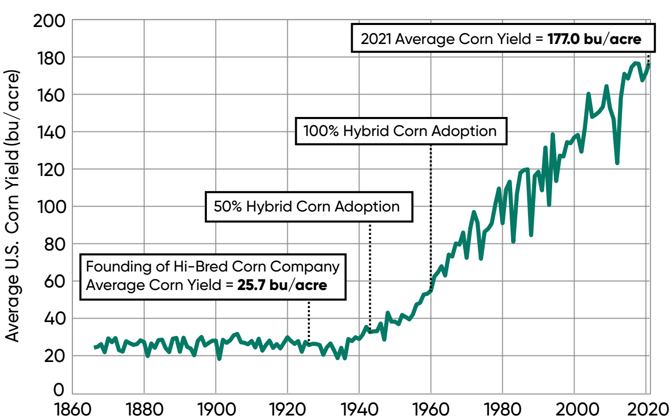


Figure 4. United States average corn yield, 1866-2021. (USDA NASS)

Scientific research by academics Edward East and George Shull were key to the development of hybrid corn. East and Shull individually initiated research on self-pollinating individual corn plants to produce purified lines – East at Connecticut State College and Shull at Cold Spring Harbor Laboratory in New York. Their pursuits did not turn out as planned as they quickly discovered that just a couple generations of inbreeding resulted in plants with significantly less yield and vigor than the original parent. However, Shull crossed inbred lines he had created and made an interesting discovery – the hybrid offspring had growth superior to the inbred parents and had comparable or better yields and greater uniformity than the varieties from which the inbreds were derived. He published a scientific paper on these results in 1908. Shull had observed the effects of heterosis (also called hybrid vigor) in corn and began immediately applying it in further breeding investigations. In a paper published the next year, he outlined procedures that later became standard in hybrid corn breeding programs (Figure 5).

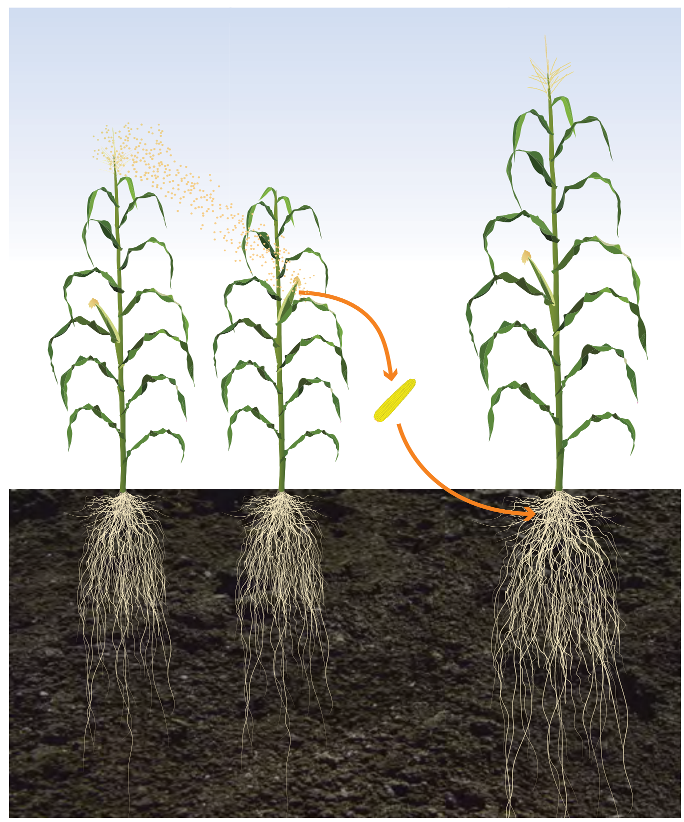


Figure 5. Cross pollination of two corn inbreds to produce a hybrid with agronomic characteristics and yield superior to those of either of the parent lines.

Henry A. Wallace attended Iowa State College, graduating in 1910. While in college, he became fascinated with the relatively new science of genetics. After graduation, Wallace began working on corn-breeding experiments and started breeding hybrid corn in 1920 after visiting Edward East at the Connecticut Agricultural Experiment Station. These early breeding efforts were begun in Johnston, Iowa, on 40 acres of farmland purchased with money from the inheritance of Wallace's wife, Ilo.

return to table of contents

The mathematically inclined Wallace taught himself statistics and applied it to his experiments. In 1923, Wallace entered his newest hybrid "Copper Cross" into the Iowa State Yield Test, which it won. The Copper Cross hybrid was created by crossing an inbred created from Leaming corn and an inbred developed from Bloody Butcher corn (Figure 6).

Figure 6. Ears of Leaming (left) and Bloody Butcher (right) varieties, the parent lines of Copper Cross, the first hybrid produced and sold by Henry A. Wallace.

This cross resulted in an ear that had a distinctive copper color. Convinced that hybrid corn had a bright future, Wallace continued to produce and market small quantities of hybrid seed. He also promoted hybrid corn through frequent writings in his family's magazine, Wallaces' Farmer, a top agriculture periodical.

The continued success of his hybrids convinced Wallace to expand operations and bring new human and financial resources into the business. With the help of several friends, the Hi-Bred Corn Company was organized and incorporated in Iowa on April 20, 1926. This was the first company devoted solely to the production of hybrid seed and the predecessor of Pioneer Hi-Bred. No person was more important to commercialization and farmer acceptance of hybrid corn than Henry A. Wallace. He was one of a handful of people in the world who initially recognized the immense potential for significant gains in productivity with hybrid corn. Wallace was selected as U.S. Secretary of Agriculture by Franklin D. Roosevelt in 1932 and elected Vice President of the United States in 1940.

Hybrid Adoption by Farmers

Adoption of hybrid corn was slow during the first decade after its commercial introduction in the mid-1920s. By 1935, only around 6% of Iowa corn acreage was planted to hybrids. Farmers were not accustomed to purchasing new seed each year, the seed was expensive to produce, and it was in short supply. The situation began to quickly change in the mid-1930s. Yield tests and farmer experience during the "Dust Bowl" years from 1934 to 1940 demonstrated hybrids to be vastly superior to open-pollinated varieties under severe drought. Once farmers had solid evidence of the benefits of hybrid corn, the transition away from open-pollinated varieties was astonishingly rapid.

In 1936, the Pioneer Hi-Bred company released hybrid 307 (Figure 7). Pioneer 307 was selected based on its strong hybrid vigor and drought tolerance observed on sandy soils. It immediately showed its value in its first year when a catastrophic

Figure 7. A plot of Pioneer® hybrid 307 in the History of Corn demonstration at the Corteva Agriscience Johnston Global Business Center (June 26, 2020).

drought resulted in widespread loss of corn acres in Iowa. Hybrids produced double the yield of open-pollinated varieties under these extreme conditions. Rapid adoption of hybrid corn in Iowa soon followed. Ten percent of acres in Iowa were planted with hybrid corn in 1936; two years later, in 1938, it was more than half. By 1942, virtually all corn planted in Iowa was hybrid seed. Within another 20 years, hybrid corn would achieve essentially 100% adoption across all U.S. corn acres. In addition to being more stress tolerant and higher yielding, hybrids were less variable, stood up better, and were easier to harvest than open-pollinated corn varieties.

The significance of hybrid corn adoption was recognized by academics such that it was the basis for the classical model of technology diffusion taught in many economics graduate programs in the 1950s to 1970s. Development of hybrid corn also promoted the advancement of statistics and its establishment as an important field of study. Hybridization of other agricultural crops followed suit, including canola, rice, sorghum, sunflowers, and wheat. Soybean remains an exception because its pollen shed occurs within a closed flower, making outcrossing difficult to achieve on a large enough scale for economical hybrid seed production.

No person was ***more important*** to commercialization and farmer acceptance of hybrid corn than Henry A. Wallace. He was one of a handful of people in the world who initially **recognized the immense potential** for significant gains in productivity with hybrid corn.

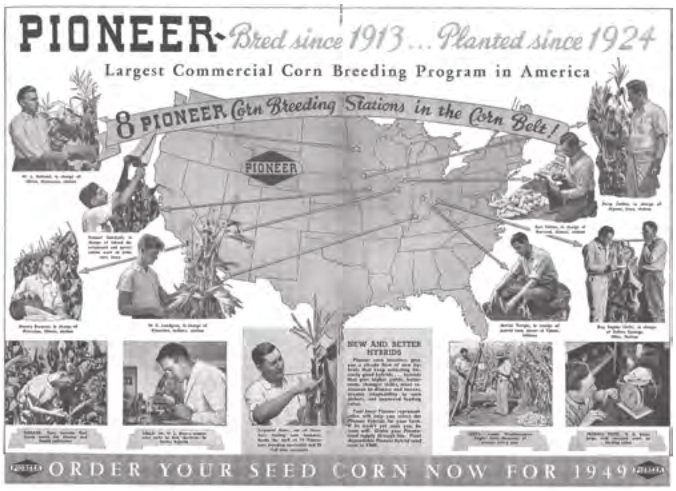


Figure 8. Pioneer advertisement from 1949.

Adoption of Single Cross Hybrids

The next significant innovation in corn production was the wide-scale availability of seed for single-cross hybrids. A single cross hybrid results from the controlled crossing of two distinctly different inbred parents. In the early days of hybrid corn, the creation of an inbred required self-pollinating plants for 7 or more generations until they were nearly genetically pure (each successive generation is genetically identical to the previous generation if no outside pollen is introduced.) As documented by Shull, the inbreeding process results in a loss of vigor and seed number per plant. The production of inbred seed was too inefficient when hybrid corn commercialization initially began making the cost of hybrid seed out of reach for most farmers.

The problem of too little seed produced by corn inbreds was overcome using double-cross hybrids. Creation of a double-cross requires successive stages of crossing with two pairs of inbreds. In the first stage, inbreds A and B are crossed to create a single-cross hybrid and inbreds C and D are crossed to produce a second single-cross hybrid. In the second step, the two single-cross hybrids created in step 1 are crossed to produce the double-cross hybrid. Production of a double-cross requires an extra step compared to single-cross hybrids, but results in more salable seed at a lower cost. While the plants produced from double-cross hybrid seed are not as uniform and high-yielding as those for a single-cross, they exhibited greater vigor and performance than the open-pollinated corn varieties that preceded them.

Double-cross hybrids were primarily grown across the United States from the 1930s through the 1960s. Plant breeders steadily improved the seed production of inbred lines over time to where single-cross corn hybrids became available for purchase by farmers in the 1960s. By the early 1970s, the changeover from double-cross to single-cross corn hybrids was mostly complete. It was shortly after this transition to single-cross hybrids when Pioneer underwent a rapid expansion in the hybrid corn marketplace.

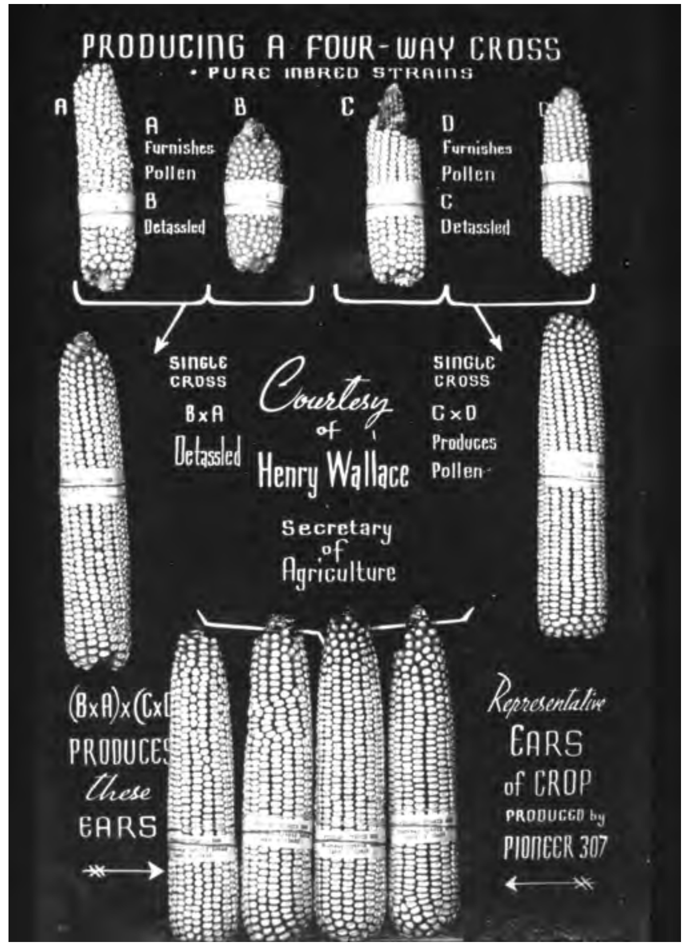


Figure 9. Diagram produced by the U.S. Department of Agriculture showing crosses involved in creating a double-cross, or four-way cross, hybrid.

Pioneer's Rise To Industry Leader

The structure of the seed corn marketplace during the first five decades after hybrid corn was introduced consisted of four main players: land grant universities, private foundation seed companies, farmer seed companies, and larger commercial seed companies like Pioneer. The private foundation seed companies and the universities focused their efforts on population improvement, inbred line development, inbred seed increase, and hybrid testing. The farmer seed companies produced hybrid seed from university or private foundation inbred lines and sold these hybrids in their local area and sometimes in neighboring counties and states. The larger commercial seed companies developed their own proprietary inbreds and combined them with public lines to create hybrids. They sold seed more widely than farmer seed companies, typically across many states and countries.

Crosses between university-derived inbreds were prevalent in the seed corn industry into the 1970s. The B lines (B17, B37, B73), also known as Iowa Stiff Stalk Synthetics, developed by Iowa State University were of particular importance. A hybrid cross of B73 x Mo17 (an inbred from the University of Missouri), released in 1973, was particularly dominant for several years following its introduction. It was sold by most every Corn Belt seed company, with Pioneer being an exception.

Since its inception, Pioneer took a different approach by heavily investing in its own inbred line development. These efforts paid off greatly in the 1970s, as the strong performance of Pioneer hybrids led to a rapid expansion in corn market share. Much of this rapid growth can be contributed to a breeding project started in 1942 by Raymond Baker (Baker was the second employee hired by Henry A. Wallace in 1928. He spent over four decades managing Pioneer corn breeding programs, retiring in 1971.) Baker obtained seed of "Iodent" corn, a Reid Yellow Dent, from Iowa State University. Through many selection cycles, Pioneer plant breeders optimized the performance of Iodent inbred lines. These lines, as well as other Pioneer-developed inbreds, produced industry-leading corn hybrids that outperformed other popular products like B73 x Mo17.

The unique Pioneer germplasm became a differentiator in the market with the introduction of Pioneer brand hybrids 3780 and 3732 in the 1970s. By the early 1980s, the era of university-derived corn inbreds had passed. Continued investment in breeding superior inbreds allowed Pioneer market share to continue to expand with the introduction of Pioneer brand hybrid 3394 in the early 1990s. This hybrid became so dominant by the mid-90s that, by itself, it outsold the entire hybrid lineups of all competitor seed companies.

The **structure of the seed corn marketplace** during the first five decades after hybrid corn was introduced consisted of four main players: ***land grant universities, private foundation seed companies, farmer seed companies, and larger commercial seed companies like Pioneer.***

Changes In Agronomic Practices

Much of this article has focused on genetic improvements to the corn plant since its domestication. However, the history of corn is not complete without a discussion of the adoption of other technologies and agronomic practices by farmers and their contribution to improving corn production. Before the introduction of hybrids, corn was typically planted at a density of 8,000 to 12,000 plants per acre and grown in rows 36 to 42 inches apart. Plant densities above this level would result in smaller ears, plants without harvestable ears, greater root lodging, stalk breakage, and dropped ears. Plant breeding has increased the stress tolerance of corn to where it can be planted at much higher plant densities while maintaining a roughly half-pound ear on each plant. Corn is now typically planted at 32,000 to 35,000 plants per acre in higher-yielding environments in rows 30 inches apart, which allows more efficient light capture.

Figure 10. Corn harvest with a tractor-drawn corn picker.

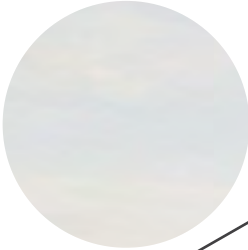
Other important innovations in corn production include synthetic fertilizers, chemical weed control, and mechanization of planting and harvesting. A corn field at the beginning of the hybrid era would typically have been sparsely fertilized with animal manures, mechanically weeded, and harvested by hand. The increased availability of nitrogen fertilizers made most tillable land suitable for corn production and allowed higher-yielding hybrids to reach their full potential. The development of effective herbicides allowed farmers to remove nearly all weeds from corn fields and eliminated the need to use tillage as a weed control tool. Mechanization of corn production has allowed farmers to plant and harvest more quickly, as well as gather yields that are nearly seven times greater than when hybrids were introduced.

Conclusions

The adoption of hybrid corn combined with improved breeding techniques and agronomic practices resulted in a steady increase of the average U.S. yield from around 26 bushels per acre before the 1930s to 125 bushels per acre in 1995. This rate of gain continued in subsequent years with the introduction of several key technologies, including insect and herbicide resistance traits as well as molecular-assisted breeding, adding another 2 bushels per acre per year since 1995. There is little evidence to suggest the rate of gain for corn yield will level off anytime soon.

After 9,000 years of human manipulation to domesticate, adapt, and develop, corn has become essential to the success of humankind. After becoming U.S. Secretary of Agriculture, Henry A. Wallace, founder of Pioneer, said "Of all the annual crops, corn is one of the most efficient in transforming sun energy, soil fertility, and man labor into a maximum of food suitable for animals and human beings. It is to be regretted that so few of the millions whose prosperity rests on the corn plant should have so little appreciation or knowledge of it…." As authors of this article, we hope you have gained a deeper appreciation of where corn originated and how it came to be of such high importance to feeding, fueling, and sustaining modern civilization. Since its founding in 1926, Pioneer has been a leader in making corn into the powerhouse crop that it is today.

return to table of contents



Managing Corn for Greater Yield Potential

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- 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.
- NCGA winners in the non-irrigated yield contest classes have increased their yields at more than double the rate of the national average. What are they doing differently?
- The NCGA National Corn Yield Contest provides a benchmark for yields that are attainable when conditions and management are optimized.
- The 2021 contest had 418 entries that exceeded 300 bu/acre, more than double the number from 2020 and easily surpassing the previous record high of 224 entries in 2017.

4 Lessons for Increasing Corn Yield

1. Selecting the right hybrid can affect yield by over 30 bu/acre, making this decision among the most critical of all controllable factors.
2. High-yielding contest plots are usually planted as early as practical for their geography. Early planting lengthens the growing season and moves pollination earlier.
3. Rotating corn with another crop generally reduces its susceptibility to yield-limiting stresses.
4. Maintaining adequate nitrogen fertility levels is critical in achieving highest yields. In-season applications can help supply nitrogen when plant uptake is high.

Pioneer® brand **P1185** and **P1563** families of products were ***top performers*** in both the 2020 and 2021 yield contests.

Benchmarking Your Corn Yield

Since the introduction of hybrid corn nearly a century ago, corn productivity improvements 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.

2021 NCGA National Corn Yield Contest Trends

The 2021 growing season was a good, but not necessarily exceptional, year for corn yields. The USDA estimated average yield was 177.0 bu/acre, which was the highest ever but was not above the long term trendline. Regional variation in yield was largely driven by rainfall. Corn yields were up over 2020 in most of the eastern U.S. where rainfall was generally adequate, while hot and dry conditions pushed yields down slightly in Minnesota and Wisconsin and down sharply in the Dakotas.

However, 2021 was a big year for big yields in the NCGA National Corn Yield Contest. The number of high-yield entries – defined for the purposes of this discussion as all entries yielding over 300 bu/acre – set a new record in 2021 with 418 in total (Figure 1). This was more than double the number of 300 bu/acre entries from the 2020 yield contest and easily surpassed the previous record high of 224 set in 2017.

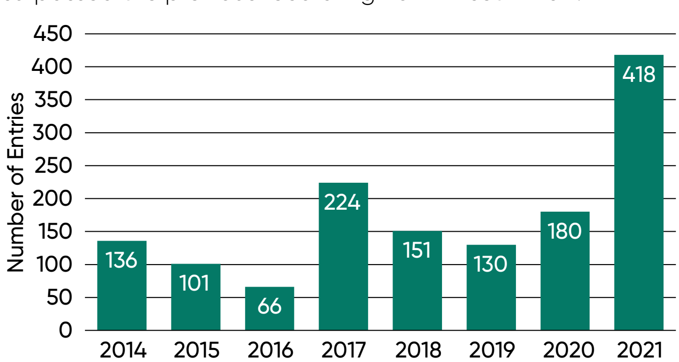


Figure 1. Total entries in the NCGA National Corn Yield Contest exceeding 300 bu/acre by year from 2014 to 2021.

Contest yields exceeding 300 bu/acre were achieved in 33 different states, which was also a record. The majority of high yield entries were right in the heart of the Corn Belt. Nebraska alone accounted for nearly 100 high yield entries, most of which were irrigated. Iowa, Illinois, and Indiana accounted for another 104 high yield entries, and Kentucky and Ohio added another 49 (Table 1).

Table 1. Number of NCGA National Corn Yield Contest entries over 300 bu/acre by state, 2017-2021.

State	2017	2018	2019	2020	2021
	number of entries				
AL	3	3	5	4	2
AR	2	1	0	1	4
CA	0	3	3	2	1
CO	4	1	0	1	13
DE	0	0	6	0	7
FL	0	0	0	0	0
GA	7	0	7	5	7
IA	16	8	3	6	33
ID	0	8	1	3	5
IL	25	18	6	19	37
IN	26	17	8	23	34
KS	2	3	2	6	13
KY	17	4	3	3	24
MA	1	2	4	1	0
MD	4	2	5	3	8
MI	7	1	4	3	14
MN	1	0	0	5	3
MO	12	4	3	11	15
NC	0	1	3	0	4
NE	41	39	7	37	96
NJ	1	1	9	9	10
NM	2	0	1	0	0
NY	4	0	0	0	1
OH	1	2	2	6	25
OK	2	2	0	2	7
OR	3	4	7	0	0
PA	0	0	15	0	2
SC	9	0	4	3	5
SD	2	0	0	2	3
TN	9	2	3	3	8
TX	3	7	1	2	5
UT	7	6	0	2	6
VA	5	2	9	0	12
WA	2	9	7	3	4
WI	6	1	1	13	8
WV	0	0	1	2	1
WY	0	0	0	0	1
Total	**224**	**151**	**130**	**180**	**418**

Select the Right Hybrid

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 and intensity; maturity zone, residue cover; and even seedbed temperature. To achieve the highest possible yields, growers should select a hybrid with:

1. **Top-end yield potential.** Examine yield data from multiple, diverse environments to identify hybrids with highest yield potential.
2. **Full maturity for the field.** Using all of the available growing season is a good strategy for maximizing yield.
3. **Good emergence under stress.** This helps ensure uniform stand establishment and allows earlier planting, which moves pollination earlier to minimize stress during this critical period.
4. **Above-average drought tolerance.** This will provide insurance against periods of drought that most non-irrigated fields experience.
5. **Resistance to local diseases.** Leaf, stalk, and ear diseases disrupt normal plant function, divert plant energy, and reduce standability and yield.
6. **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 and dropped ears.
7. **Good standability** to minimize harvest losses.

Pioneer® brand products were used in 207 state-level winning entries – more than any other seed brand. State-level winners included a total of 92 different Pioneer brand products from 58 different hybrid families ranging from 91 to 120 CRM.

The brands of seed corn used in the highest yielding contest entries in 2017 through 2021 are shown in Figure 2. In all years, Pioneer brand products were used in more entries exceeding 300 bu/acre than any other individual seed brand.

Yields exceeding 300 bu/acre have been achieved using Pioneer® brand products from 65 different hybrid families over the past five years, ranging from 98 to 121 CRM. The top-performing Pioneer hybrid families in the National Corn Yield Contest are shown in Table 2. The Pioneer brand P1197 family of products has been the top performer in the contest over the past five years, topping 300 bu/acre 69 times since 2017. Pioneer brand P1185 and P1563 families of products were top performers in both the 2020 and 2021 yield contests, and the Pioneer brand P0953 family had a strong debut in 2021.

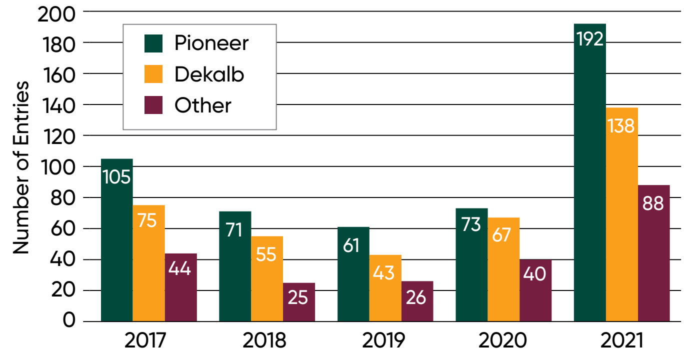


Figure 2. Seed brand planted in National Corn Yield Contest entries exceeding 300 bu/acre from 2017 to 2021.

High-Yield Management Practices

Top performers in the NCGA yield contest not only have produced yields much higher than the current U.S. average, they have also achieved a higher rate of yield gain over time. Over the past 20 years, U.S. corn yields have increased at a rate of 1.9 bu/acre per year while winning yields in the non-irrigated yield contest classes have increased by 5.0 bu/acre per year. Contest fields are planted with the same corn hybrids available to everyone and are subject to the same growing conditions, which suggests that management practices are playing a key role in capturing more yield potential. The following sections will discuss management practices employed in contest entries yielding above 300 bu/acre.

Table 2. Pioneer hybrid families with the most entries over 300 bu/acre in the 2021 NCGA National Corn Yield Contest.

Hybrid Family	2017	2018	2019	2020	2021	2017-2021
	number of entries					
P1185				10	**29**	39
P1563		3	1	11	**22**	37
P0953					**11**	11
P1108			1	3	**10**	14
P1847			4	2	**9**	15
P1197	33	11	11	6	**8**	69
P1572				6	**7**	13
P1082			1	2	**7**	10
P1366	8	10	9	3	**6**	36
P1359				1	**6**	7
P1828		8	4	6	**5**	23
P0801	9	5	1		**5**	20
P1222					**5**	5
P2042					**5**	5
P1506				1	**4**	5
P0924					**4**	4
P1716				10	**4**	4
P1870	4	1	9	1	**3**	18
P1138		4		2	**3**	9
P1464			3	2	**3**	8
P0720				3	**3**	6
P2089				2	**3**	5
P9998		2	3	1	**2**	7

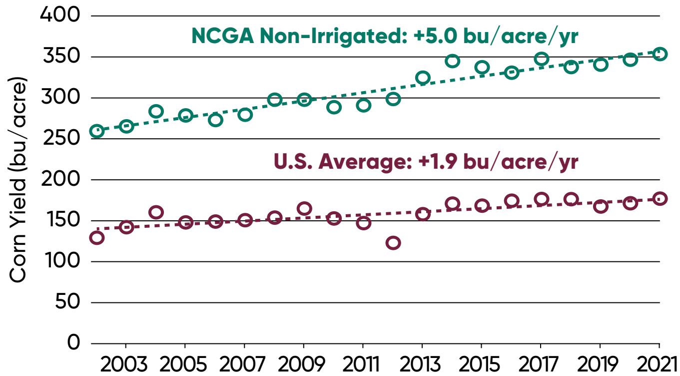


Figure 3. Average yields of NCGA National Corn Yield contest non-irrigated class national winners and U.S. average corn yields, 2002-2021.

Optimize Planting Practices

Establish Sufficient Population Density

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 2017 through 2021 are shown in Figure 4. The average harvest population of non-irrigated entries (36,300 plants/acre) was slightly greater than that of irrigated entries (35,900 plants/acre) over five years. Both are well above the USDA average plant population of 29,000 plants/acre, as would be expected for high-yielding environments. However, yields over 300 bu/acre were achieved over a wide range of populations, from 28,000 to 56,000 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 yield.

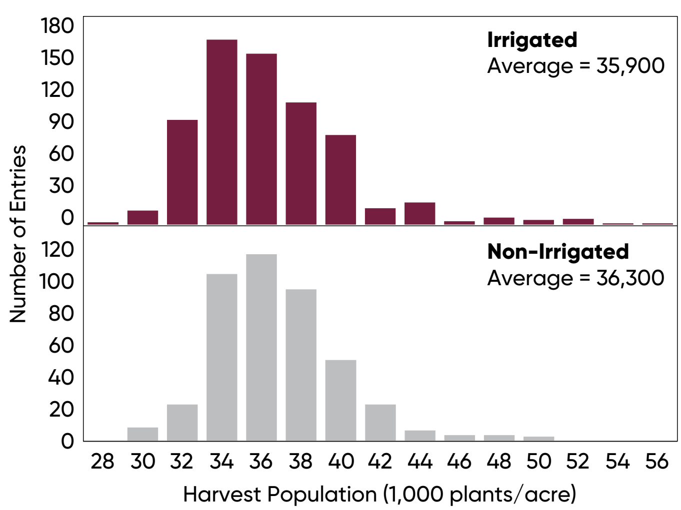


Figure 4. Harvest populations and corn yield of irrigated and non-irrigated NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2017-2021.

Exceptionally **high populations** are not necessarily a prerequisite for ***high yields.***

Plant Early

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 12 to May 30 in 2021 (Figure 5). Mid-April to early-May planting dates have typically been the most common for high-yields in the central Corn Belt. The 2021 contest had several high yield entries planted in mid- to late-May (35 entries over 300 bu/acre were planted after May 15), demonstrating that high yields can still be achieved under favorable conditions if planting is not delayed for too long.

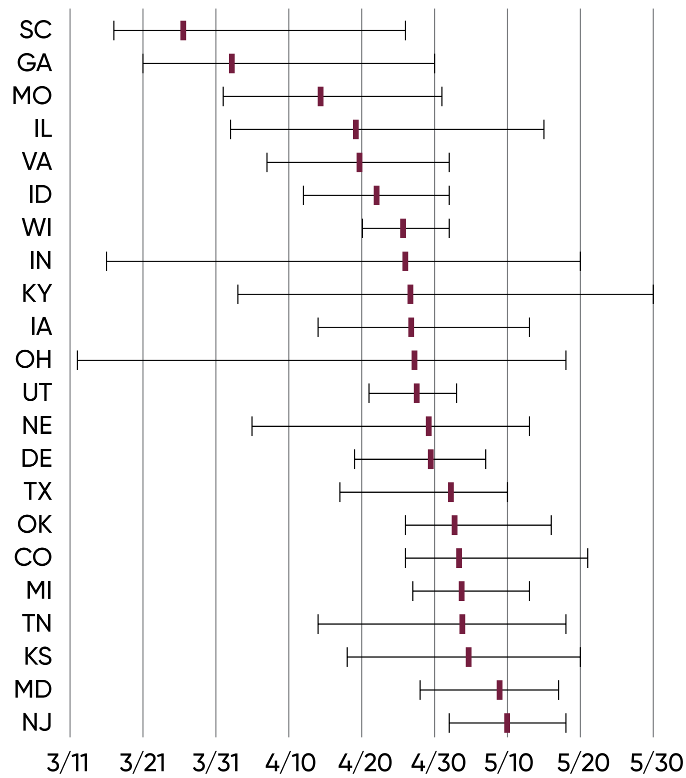


Figure 5. Average planting date and planting date range of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021. (States with 5 or more high-yield entries shown.)

Determine 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 slightly in recent years as wider row configurations (most commonly 36-inch or 38-inch) have remained steady and narrower row configurations (15-inch, 20-inch, 22-inch or 30-inch twin) have declined.

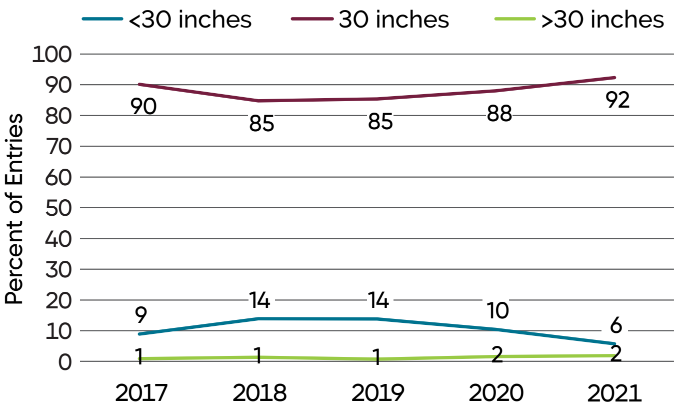


Figure 6. Row width used in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2017-2021.

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, 2018).

Rotate Crops

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 were planted to a crop other than corn the previous growing season (Figure 7).

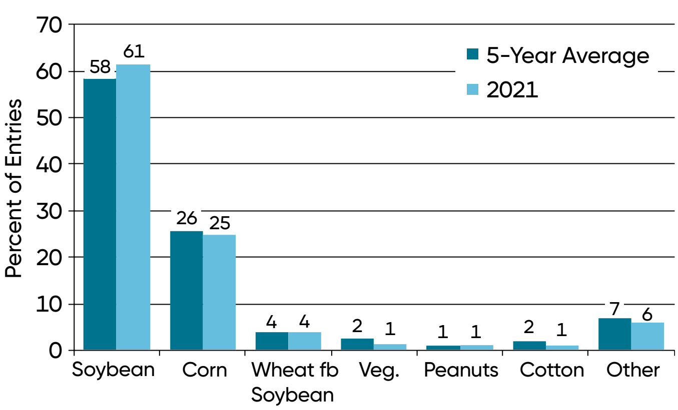


Figure 7. Previous crop in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021 and 5-year averages.

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.

Tillage

Over the past five years, over 40% of the high yield entries in the NCGA contest have used conventional tillage, with the other half using no-tillage or some form of reduced tillage (Figure 8). The proportion of high-yield entries using conventional tillage has declined over time, offset by increases in no-till and strip-till.

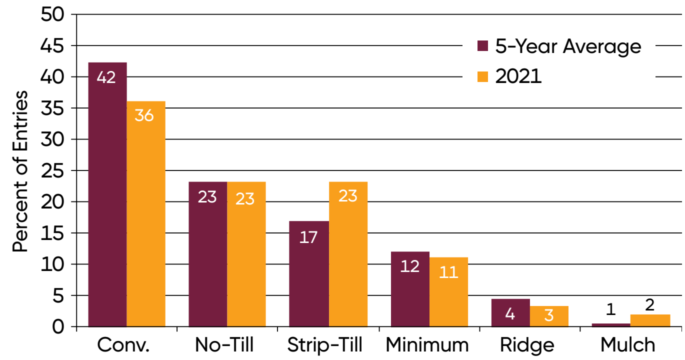


Figure 8. Tillage practices in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021 and 5-year averages.

Optimize Nutrient Management

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 nitrogen per bushel harvested, and stover production requires about 0.45 lbs of nitrogen 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 9.

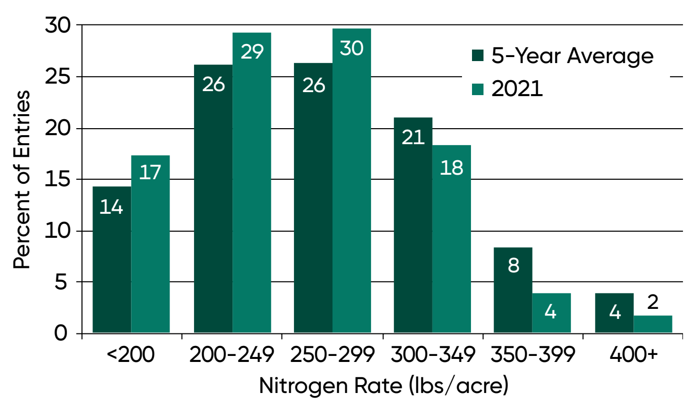


Figure 9. Nitrogen rates (total lbs/acre N applied) of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021 and 5-year averages.

return to table of contents

The N application rates of 300 bu/acre entries varied greatly, but over half were in the range of 200 to 300 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.

Total nitrogen applied in high yield entries has trended downward in recent years. In the 2016 contest, over half of high yield entries had over 300 lbs/acre of N applied, compared to less than a quarter of entries in 2021.

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 10. Very few included fall-applied N. Many applied N before or at planting. Nearly 75% of 300 bu/acre entries included some form of in-season nitrogen, either sidedressed or applied with irrigation. Multiple nitrogen applications were used in around 85% of high-yield entries.

Nearly **75% of 300 bu/acre** entries included some form of ***in-season nitrogen***, either sidedressed or applied with irrigation.

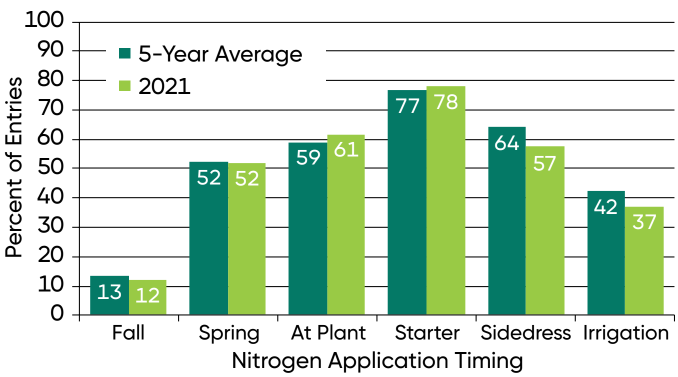


Figure 10. Nitrogen fertilizer application timing of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021 and 5-year averages.

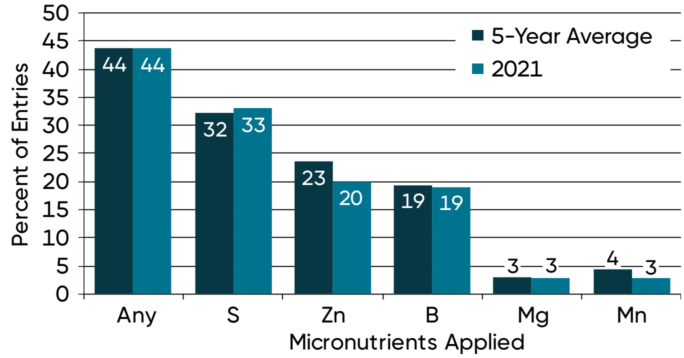
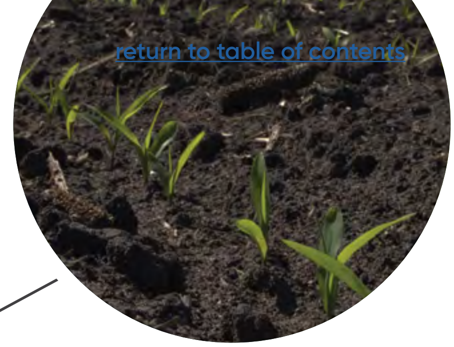


Figure 11. Micronutrients applied in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2021 and 5-year averages.

Micronutrients

Micronutrients were applied on nearly half of the 300 bu/acre entries (Figure 11). 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 many soils to meet crop needs. However, some sandy soils and other low organic matter soils are naturally deficient in micronutrients, and high pH soils may reduce their availability (Butzen, 2010). Additionally, as yields increase, micronutrient removal increases as well, potentially causing deficiencies.

return to table of contents



Critical Period of Weed Control in Corn

Kristin Hacault, Agronomy Information Consultant

Why Control Weeds Early?

- Early season weed control helps protect crop yield potential, as corn is not a very competitive crop.
- Weeds and corn compete for the same resources: water, sunlight, and nutrients.
- Small weeds are easier to control and can absorb and translocate herbicide better.
- Herbicides can be less effective during times of heat and drought stress, which often occur with later applications.
- A sequential weed control program consisting of both pre-plant/emerge (PRE) followed by postemergence (POST) herbicides generally provides the most consistent results.

Figure 1. Field infestation of wild buckwheat and lambsquarters. June 27, 2018. Southern Alberta.

Critical Period of Weed Control

- Defined as the growth stages or time during which weeds must be controlled to maintain maximum yield potential (assumes field is clean at time of planting).
- In Western Canada, weeds can reduce corn yield starting at emergence so controlling weeds from even prior to the VE (emergence) stage of corn to V6 (6 leaf stage) is recommended.
- After this stage, the corn is generally too tall and/or susceptible to glyphosate herbicide injury.
- Controlling weeds is important for minimizing competitive effects and subsequent yield reduction, but also for preventing weed seed production.

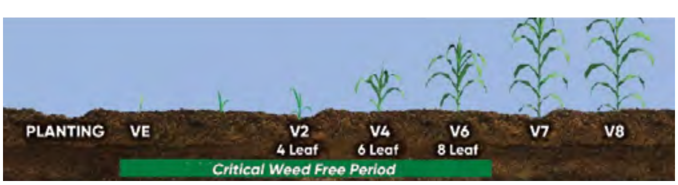


Figure 2. Critical Period of Weed Control in Corn (VE-V6).

Take Time to Apply Preplant/PRE Herbicides

- Weeds that germinate, emerge, and grow with the crop cause the most yield loss.
- Preplant/PRE herbicides provide critical early season weed control when crops are most sensitive to competition.
- Preplant/PRE herbicides can widen the window of application for postemergence herbicide sprays.
- Weed control programs that rely totally on POST applications carry more risk because weather conditions may prevent timely application and weeds may be too large to achieve sufficient efficacy.
- The key is to control weeds before they start to compete.

Postemergence Applications

- Scout fields to determine what weeds are present and what products can be safely used in crop.
- If a preplant/PRE application was not applied, apply postemergence herbicides as soon as possible.
- Always follow labels and guidelines of registered herbicides for maximum efficacy.

Figure 3. Post-emergence sprayer miss. Coaldale, AB. June 14, 2021. Sprayer miss on right hand side of picture.

Figure 4. Same field as shown in figure 3. Sprayer miss was sprayed 7 days after the first application. (Illustrates effect of delaying application and weed/crop competition). July 7, 2021. Coaldale, AB.

return to table of contents

Crop Staging

- Staging a corn crop appropriately to match label recommendations is key to crop safety and herbicide efficacy.
- The leaf collar method is the preferred method of Pioneer agronomists as it leaves no discrepancy in staging.
- This method is utilized to stage corn plants from emergence (VE) to tassel (VT).
- Start with the lowermost short rounded-tip true leaf and end with the uppermost leaf with a visible leaf collar.
- Leaf collar: Is a light collared "band" located at the based of an exposed leaf blade where the leaf contacts the stem of the plant (Abendroth et al., 2011).
- With this method, leaves that are still in the whorl with no visible leaf collar are NOT included in staging. Ex.: V3 = 3 leaves with visible leaf collars.
- Check herbicide labels to determine what staging method is utilized. Contact your local Pioneer representative or agronomist for staging assistance.

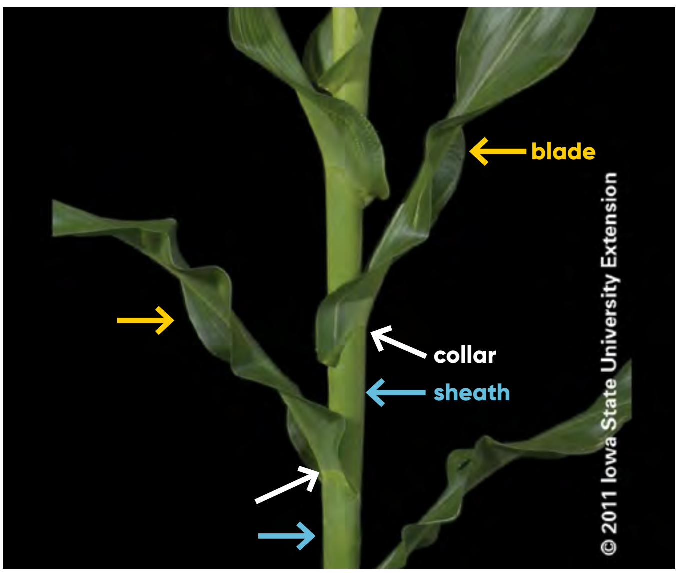


Figure 5. Corn plant showing fully emerged leaves with visible leaf collars. Photo courtesy of Iowa State University Extension.

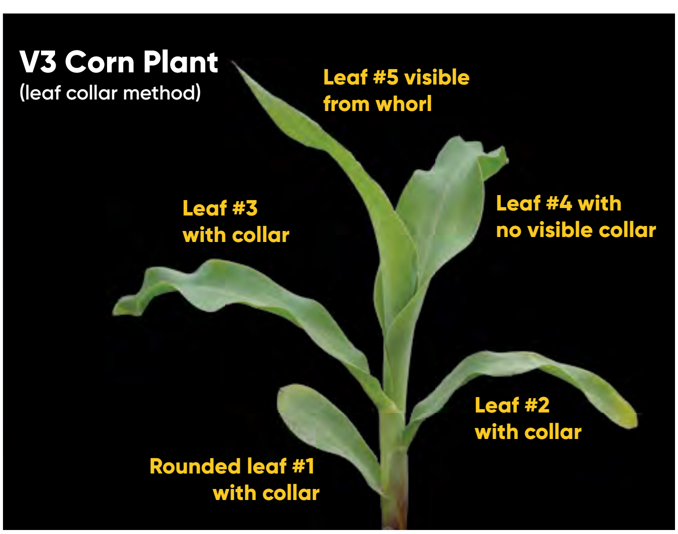


Figure 6. Corn plant staged as V3 according to the leaf collar method.

Pioneer Agronomy

Weed Control Timing in Corn
- Zach Fore, Product Agronomist

Herbicide Injury

- Although many herbicide products are registered on corn, some pose a risk of crop injury under certain environmental conditions, particularly with early maturity corn hybrids.
- Pioneer has developed a Corn Hybrid-Herbicide Management Guide to assist producers in selecting and managing their herbicide programs (Gaspar, 2019). Growers are encouraged to contact their Pioneer sales professional for more information. The current Corn Hybrid-Herbicide Management Guide is available at www.pioneer.com/us/stewardship

Auxin Herbicides (Group 4)

- Ex.: 2,4-D, MCPA, dicamba
- Synthetic auxin herbicides cause tissues to "outgrow" the cells' capacity to maintain function.
- Affected plant tissues can exhibit epinasty – stalks twist, lean and fall over. Leaf rolling and trouble unfurling can also occur.

Figure 7. Group 4 herbicide injury in corn.

Photosystem II Inhibitors (Group 6)

- Ex.: Bromoxynil
- These products can "burn" the cells on the leaves stopping photosynthesis.
- Injury is typically confined to the leaf tissue that has been contacted by the herbicide.

Figure 8. Group 6 herbicide injury in corn.

return to table of contents

Corn Nematode Populations in the Corn Belt

Mary Gumz, Ph.D., Agronomy Manager

Key Findings

- This study found 35% of corn fields sampled throughout the U.S. Corn Belt had medium to high levels of nematode pressure.
- Corn nematodes were present in 99% of the soil samples collected in 2022.
- Nematodes were widely distributed through all sample areas and not confined to sandy soils.

Figure 1. Stunted growth of the corn plant on the left due to corn nematode pressure. Above ground symptoms of nematodes are often non-descript and resemble low fertility, weather stress, or insect and disease pressure.

Rationale and Objectives

- Corn nematodes can cause significant yield loss by damaging corn roots, which impairs water and nutrient uptake and creates entry points for pathogens.
- In 2019, 2020, 2021, and 2022 Pioneer agronomists, territory managers, and sales professionals sampled corn fields across the U.S. Corn Belt to assess nematode population levels and the range of species present
- Over 3,100 samples were collected from fields in 19 states: Texas, Oklahoma, Colorado, Kansas, Nebraska, North Dakota, South Dakota, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York, Maryland, and Delaware.

How We Investigated Nematode Levels

- A total of 3,164 corn fields were sampled for nematode populations from 2019 to 2022.
- Soil samples were taken at approximately the V6 growth stage.
- Soil samples were taken from both within and between the row and contained corn root tissue.
- Samples were submitted to a nematode testing service and analyzed using a sugar-flotation method and a 500 mesh sieve.

Nematode Pressure Levels

- Scientists at Corteva Agriscience have developed high population indicators for major corn nematode species as a relative measure of population levels (Table 1).
- The Corteva Agriscience nematode rating is based on a combination of thresholds from seven labs throughout the Corn Belt. It rates the potential for yield damage due to nematodes based on the population and species of nematodes present.
- Nematode pressure in a field was classified based on the high population indicator level for each species
  - » High: Above indicator level for one or more species
  - » Medium: Above 50% indicator level for one or more species
  - » Low: Less than 50% indicator level for all species.

Table 1. Corteva Agriscience population level indicators for major corn nematode species.

Species	High	Moderate	Low
	nematodes / 100cc soil		
Sting	1	NA	NA
Needle	1	NA	NA
Lance	50	25-49	1-24
Stubby-Root	50	25-49	1-24
Root Knot	50	25-49	1-24
Dagger	100	50-99	1-49
Lesion	150	75-149	1-74
Ring	200	100-199	1-99
Stunt	300	150-299	1-149
Spiral	500	250-499	1-249

Results: Potentially Damaging Nematode Levels

- Nearly all fields sampled had corn nematode species present at some level (Figure 1).
- 35% of corn fields sampled had medium to high levels of nematode pressure (Figure 2).
- Medium and high population levels were found across all regions in the study.
- High nematode population levels were most prevalent in the western Corn Belt states – Nebraska, Kansas, Colorado, and Texas.

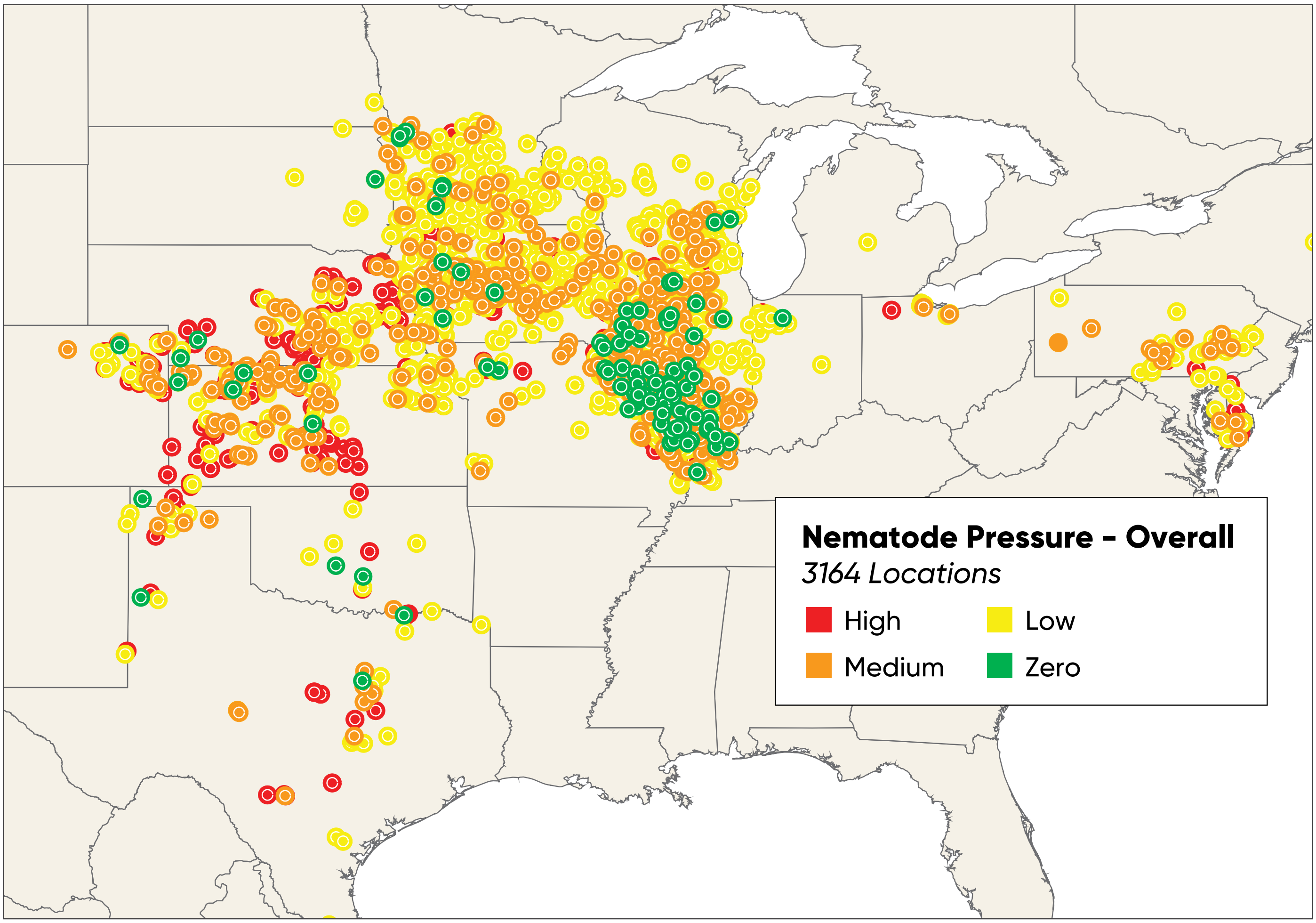


Figure 2. Corn nematode pressure at sites sampled in 2019, 2020, 2021, and 2022.

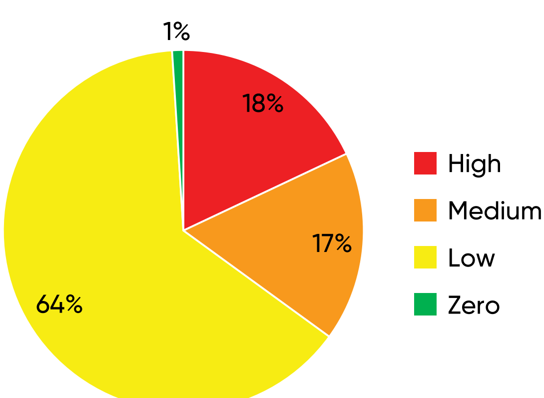


Figure 3. Corn nematode pressure at sites sampled in 2022.

Managing Corn Nematodes

- Results of this study showed that potentially damaging levels of corn nematode populations are prevalent throughout corn production areas in the U.S.
- If damaging levels of corn nematodes are found, implementing control measures such as rotation, sanitation or use of nematicide seed treatments should be considered.
- Nematode species vary in their host range, so rotation can be effective for reducing populations of some, but not all, corn nematode species.
- Pioneer® brand corn products come with Lumialza™ nematicide seed treatment for nematode control:
  - Lumialza nematicide seed treatment is a biological product that contains the active ingredient *Bacillus amyloliquefaciens* – Strain PTA-4838 and has activity against all primary corn nematode species.
  - National trials have shown yield improvements of 3.7 bu/acre under low pressure and up to 9 bu/acre in high pressure fields.
  - Research has shown that nematode protection lasts for over 80 days in the upper, middle, and lower root zones.

return to table of contents

Spider Mite Management in Corn

Grant Groene, M.S., Global Seed Agronomy Lead

Key Points

- The Banks grass mite (BGM) and the two-spotted spider mite (TSM) are problematic pests for corn producers in the High Plains and Western United States, often causing significant economic injury.
- The amount of economic loss that spider mites cause varies from year to year based on several biotic and abiotic factors and has been documented as high as 47% in corn grain.
- Spider mites damage corn by rupturing leaf cells and drinking the contents out; most damage is done when feeding is on leaves at or above ear level.
- Managing for resistance is a key issue that growers should be aware of when controlling spider mites.
- This article discusses spider mite life cycle, plant damage, identification, and management options.

Spider Mites – A Problem in Drought Years

Two-spotted spider mite *(Tetranychus urticae)* is a pest of soybeans that proliferates during extended periods of drought. Drought conditions accelerate spider mite movement and reproduction and inhibit fungal pathogens that normally help keep spider mite populations in check. Economically damaging outbreaks of spider mites are relatively rare, but populations can grow rapidly when conditions are favorable.

What Are Spider Mites?

Spider mites (Family Tetranycidae, Order Acari) are not insects, but are tiny arachnids closely related to ticks and spiders. They can be problematic pests for corn producers, primarily in the High Plains and extending through the western US. While high spider mite numbers frequently cause significant damage to corn (grain, silage, and sweet), the level of economic loss is different from season to season. Temperature, humidity, rainfall, soil type, pesticide applications, host proximity and natural enemies affect population dynamics from year to year. High temperatures and drought stress generally accompany high populations of mites. Higher populations of spider mites are often found in sandy soil types, as these soils typically incur drought stress in western states, even under irrigation.

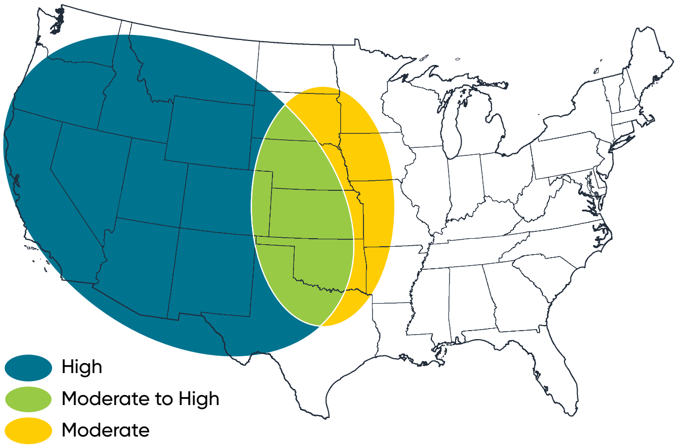
Two Common Mite Species in Corn

The two most common and widespread mite species causing concern for corn producers across the Western U.S. (Bynum et al., 1997) are:

1. The Banks grass mite [*Oligonychus pratensis* (Banks)] (BGM) – predominant earlier in the growing season.
2. The two-spotted spider mite [*Tetranychus urticae* Koch] (TSM) – extends later into the growing season.

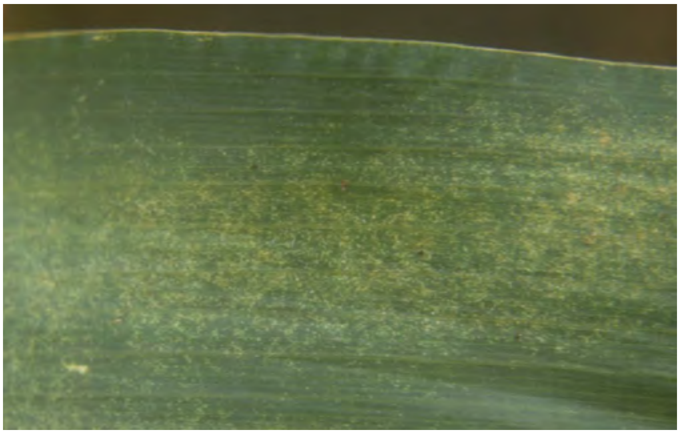
Spider mites can damage corn from the seedling stage all the way to maturity. Both the BGM and TSM feed primarily on grass species. They can differ in their susceptibility and resistance to insecticides, making them difficult to manage.

Risk of Spider Mite Infestation in Corn in the Western U.S.



Spider Mite Damage to Corn

The BGM and TSM damage plants by using needle-like stylets to rupture leaf cells, pushing their mouth into the torn tissue and drinking the leaf contents. This results in clusters of dead cells, leaving a stippled or speckled appearance on the upper leaf surface. Concentrated chlorotic areas begin along the midrib and folded areas of the leaf, spreading to the basal half of the leaf. In instances of severe feeding, leaves will become gray, yellow, bronzed, dry, or bleached. High populations of untreated mites will cause loss of vigor and eventual death.



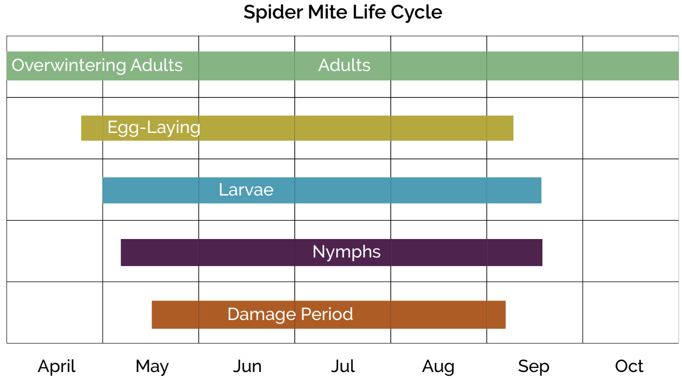
Mottled, discolored corn leaf from spider mite feeding.

Mite activity increases under hot and dry conditions. Crop damage is most severe when feeding occurs on the leaves at or above the ear level between tasseling and hard dough. Yield loss attributed to spider mite feeding may be as high as **40%** (on a dry matter basis) in corn silage, and grain losses may be as high as **47%** (Archer and Bynum, 1993). A long-term university study observed yield losses ranging from **6% to 48%** with an 18-year average of **21%**.

Biology and Life Cycle

Spider mites have four life stages: egg, larva, nymph, and adult. Mites may occasionally overwinter in crop residue, but primarily the BGM will overwinter in crowns of winter wheat and native grasses. The TSM primarily overwinters in alfalfa and other broadleaf species bordering fields. Beyond that, the life cycles of the two mite species are quite similar. When conditions are favorable, overwintering adult females will begin to move into the corn crop by crawling short distances or being carried by the wind.

Spider Mite Life Cycle

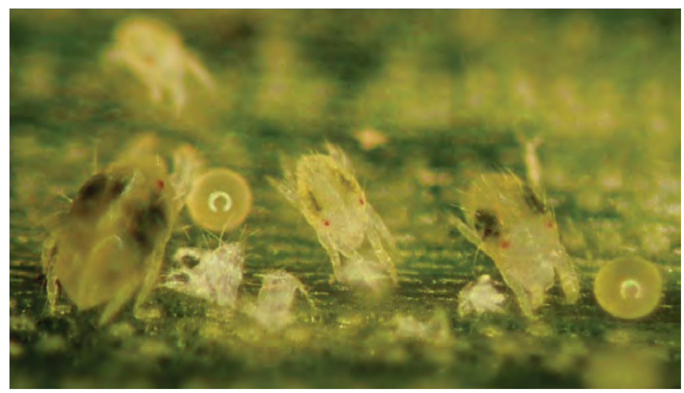


Adapted from Purdue University.[2]

Spherical, pearly white eggs are laid and fastened to the underside of the leaf by webbing produced by the adult females. Eggs will hatch in a range of 3 to 19 days depending on temperature, and will change in color from pearly white to a yellowish-green just prior to hatching. The larvae have six legs, are colorless, and resemble the nymph and adult. Little leaf nutrients are consumed in this stage. The nymph has eight legs, looks like the adult, but is smaller and sexually immature. The nymphs will undergo both a protonymph and deutonymph instar stage. Adults are eight-legged and range in color from bright green to red. Females are $\frac{1}{60}$ inch long and are slightly larger and more robust than males, which are only $\frac{1}{80}$ inch long.

Spider mites are an arrenotochous species, meaning a female will lay both fertilized and unfertilized eggs. The fertilized eggs will turn into diploid females, and the unfertilized eggs will turn into haploid males. The ratio of males to females can vary considerably from one population to the next but is normally female-biased.

A generation usually proceeds from start to finish in as little as 5 to 20 days, depending on temperature. Hot and dry conditions will increase the rate of development. Optimum temperatures differ slightly for the BGM and TSM. BGM are more fecund in climates with lower humidity and 97 to 98°F temperatures. However, the TSM thrives in climates with a higher percent humidity and 86 to 90°F temperatures. BGM populations have been shown to increase 70-fold in one generation. It is typical for both mite species, and all mite stages, to be present with 7 to 10 generations per season overlapping one another.



Two-spotted spider mite eggs, larvae, nymphs, and adult.

Table 1. Developmental time for spider mites on corn.

Stage	77°F	97°F
	number of days	
Egg	4.3	2.1
Larva	1.7	0.8
Protonymph	1.3	0.8
Deutonymph	1.9	1.4
Adult	19.1	5.8
Generation	9.9	5.5

Adapted from Perring et. al., 1983.[3]

Spider Mite Scouting and Identification Tips

- **When:** Scouting for spider mites should begin as soon as wheat, alfalfa, native grasses, and broadleaf weeds bordering fields begin to dry down and continue until corn reaches dent.
- **Where:** Early in the season, scouting plants next to grass waterways, field edges, or stressed areas will give the best indication of whether spider mites are feeding on corn.

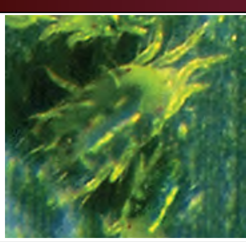
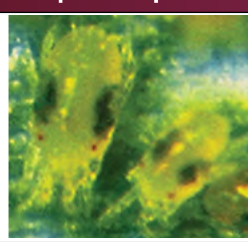
- **How:** Spider mites will produce fine webbing to protect themselves and their eggs. Check the underside of discolored leaves for both the webbing and mites. Mites are small and sometimes hard to see. Taking a white piece of paper and shaking the leaf over it can help to visually identify mite presence.

When scouting, identify which mite species is present. Even though the BGM and TSM are similar in appearance and can appear simultaneously, they have several different biological characteristics and differ in their susceptibility to pesticides (Table 2). The **BGM** will appear earlier in the season from mid-whorl through the early grain-filling stages and feed mostly on the lower leaves before moving to the upper leaves of the plant. The **TSM** will appear mid to late season, usually after flowering, and feed over the entire plant. To identify the type of mite present, use a 10X hand lens, and observe 20 adult females. It is best to do this procedure in 5 to 10 randomly selected areas in the field. Females will be the largest individuals present and have rounded bodies, while males have a more slender, tapered body.

How to Control Spider Mites in Corn

The economic damage spider mites can cause varies from year to year and depends on several biotic and abiotic factors. When deciding how best to manage spider mite infestations in a corn crop, consider biological, cultural, and chemical control methods, individually or in combination.

Table 2. Biological comparison of Banks grass mite and two-spotted spider mite.[4,5]

Banks Grass Mite	Two-Spotted Spider Mite
	
Produce less webbing	Produce more webbing
Generally less robust, smaller	Generally more robust, larger
Pointed rear	Rounded rear
More susceptible to miticides	Less susceptible to miticides
Burn leaves of plant from bottom up	May occur in high numbers without burning leaves
Generalized gut pigmentation*	Concentrated gut pigmentation*

**Visible green markings on spider mites are a result of ingested plant material and differences in gut structure.*

Biological and Cultural Control

In some years, fields may not have to be treated as beneficial predatory insects keep the mite populations below economic injury levels. Beneficial predatory insects include the *Stethorus* lady beetles, minute pirate bugs, lacewing larvae, and thrips. In addition to predatory insects, *Neozygites floridana*, a naturally occurring fungus, is a common pathogen that attacks spider mites and can be beneficial in controlling population numbers. Daily temperatures below 85°F with high relative humidity create favorable conditions for fungal growth on the spider mites.

Hot and dry climates tend to have higher levels of spider mite infestations as natural enemies cannot keep up with increasing spider mite numbers, and the fungal pathogen *Neozygites floridana* is not as active. Avoiding drought stress with properly applied irrigations is a key cultural control component. However, once spider mite populations are established, irrigation will not decrease the density of the population. Other cultural components to consider are later plantings or planting a fuller-season hybrid if these options are feasible.

Chemical Control with Miticides

Biological and cultural control practices can be beneficial but often unreliable. Many growers rely heavily on chemical control. While chemical control can be effective, this method does not come without problems or concerns. The TSM is more tolerant to miticides and is harder to control than the BGM. Additionally, spider mites colonize on the bottom side of the leaves, leading to difficulties in application coverage. It is recommended to use three or more gallons of water per acre to increase effectiveness. Aerial applications are most effective. More scouting and secondary treatments can usually be expected as it is difficult to kill eggs with a miticide application. Reinfestation will likely occur within 7 to 10 days after initial application.

Early season preventative treatments can provide some economic benefit. Growers should carefully consider:

- The amount of plants infested with small colonies of mites
- Temperature and humidity patterns
- Any drought stress the crop may be under
- Predatory insect populations
- Field history of mite infestations

Again, this places a high emphasis on properly scouting for the pest.

A simple guideline in determining treatment thresholds is to treat when damage is visible in the lower third of the plant, colonies are present in the middle third of the plant, and the corn has not yet reached hard dough stage. Once the corn crop has reached the hard dough to dent stage, no economic benefit will be gained from a miticide treatment.

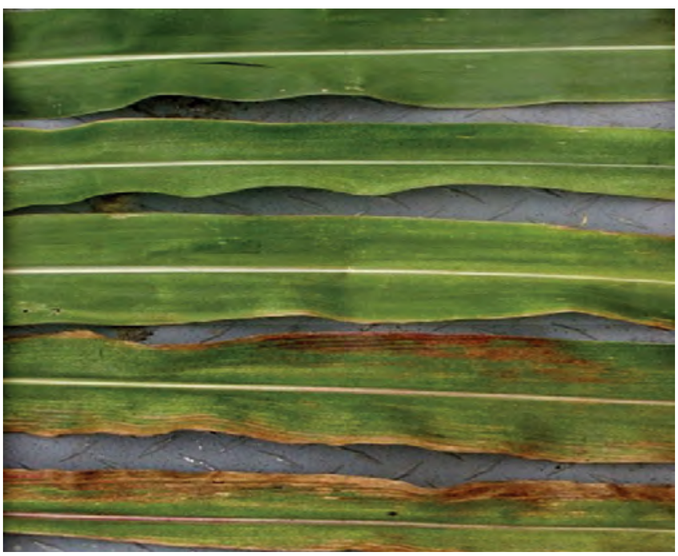
Another more sophisticated guideline takes into account the cost of treatment and expected crop value based on the percent of infested leaves and the amount of leaf area damaged (Table 3). To use this table, the control cost (miticide + application cost) and the expected crop value (grain bu/acre x market price) must be determined. Then a two-step sampling method is used. First, select an individual plant, and check green leaves for presence or absence of mites to calculate the percentage of infested green leaves (first value listed in table). This should be done 10 times in different portions of the field. If the percentage of green leaves infested exceeds that of the control cost and crop value, then the percent of leaf area damaged will need to be determined.

Example: If the estimated control cost is $20/acre, the crop is valued at $300/acre and the percent of green leaves infested exceeds 39, then the percent leaf area damaged needs to be estimated. If the percent leaf area damaged exceeds 21, then it will likely pay to apply a miticide treatment.

Table 3. Economic injury threshold for BGM and TSM in corn.

Cost per Acre	Crop Value per Acre						
	$250	$300	$350	$400	$450	$500	$550
	– % infested leaves per plant / % leaf area damaged –						
$ 5	12/6	10/5	8/5	7/4	7/3	6/3	5/6
$ 10	24/13	20/10	17/9	15/18	13/7	12/6	11/6
$ 15	35/19	29/16	25/13	22/12	20/10	18/9	16/9
$ 20	47/25	39/21	34/18	29/16	26/14	24/13	21/11
$ 25	59/31	49/26	42/22	37/20	33/17	29/16	27/14

Developed by Archer and Bynum, 1993.[6]



Leaves showing progression of no damage (top) to intense damage (bottom) due to spider mite feeding.

Resistance Management

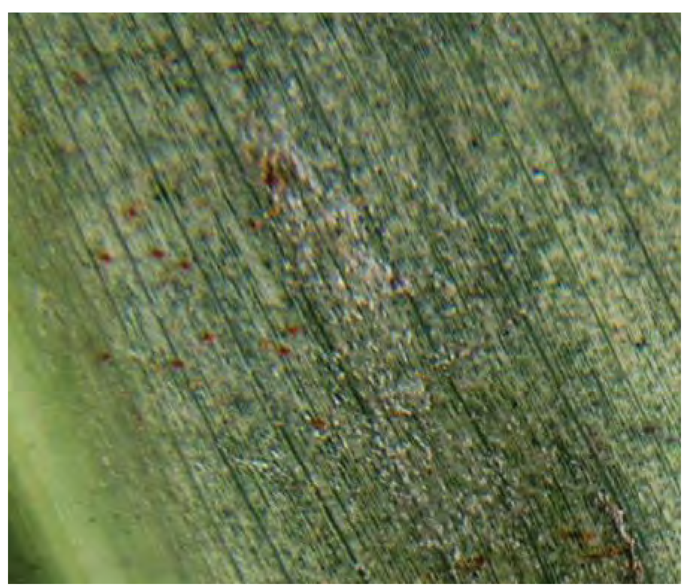
Because spider mites can develop resistance to miticides, resistance management is a key concern for growers. Continued use of any one miticide will naturally select against susceptible mites and increase the number of tolerant mites in each subsequent generation. In areas where spider mites are a consistent problem, the following resistance management strategies can be extremely helpful.

- If able, keep corn well-watered and avoid drought stress.
- Avoid planting corn next to winter wheat and alfalfa fields, particularly if mite infestations are known.
- Use insecticides only when faced with serious yield loss.
- Beneficial insects that are predatory on spider mites are better able to thrive when insecticides are not used on corn. Planting Pioneer® brand hybrids with aboveground insect protection technologies can help preserve yield potential while reducing or eliminating the need for insecticides.
- Only apply miticides when yield is threatened based on treatment thresholds and application guidelines.
- When miticide applications are necessary, be sure to maximize miticidal activity by applying with the proper carrier volumes and appropriate adjuvants (Table 4).
- Do not consistently use the same miticide year after year.

Table 4. Spider mite management options.[7]

Insecticide**	Trade Name	Rate
Bifenthrin	numerous products	0.08 to 0.10 lb. a.i./acre (5.1 to 6.4 fl. oz.)
Etoxazole	Zeal®	4 to 6 oz./acre
Fenpyroximate	Portal®	2 pt./acre
Hexythiazox	Onager®	0.073 to 0.176 lb. a.i./acre (10 to 24 fl. oz.)
Propargite	Comite® II	2.25 pt./acre
Spiromesifen	Oberon® 4 SC	0.09 to 0.25 lb. a.i./acre (2.85 to 8.0 fl. oz.)
Zeta-cypermethrin + Bifenthrin	Hero®	10.3 fl. oz. of product/acre
Dimethoate	Dimethoate, Dimate®	0.33 to 0.5 lb. a.i./acre

***Always read and follow manufacturers label, directions, and recommendations.*



Corn leaf infested by spider mites, showing webbing and damage on underside of leaf.

return to table of contents

Corn Root Lodging

Cori Lee, *Agronomy Sciences Intern, and* ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Key Points

- Root lodging often occurs in late June and early July when severe thunderstorms are common and brace roots on corn plants are not yet fully developed.
- Wind-induced root lodging is not always related to root injury but is more likely to occur when root systems are damaged or restricted.
- Corn plants have more ability to recover from lodging when it occurs during vegetative growth stages.
- Yield impact is greatest when lodging occurs during pollination.

Summer Storms Can Cause Root Lodging

- Root lodging in corn can occur when soils are saturated by heavy rain and the rain is accompanied by high winds.
- Root lodging risk in the Corn Belt is typically greatest in late June and early July when severe thunderstorms are common, and corn is most vulnerable.
- Corn in the mid-vegetative stages of development has sufficient top growth to be impacted by severe winds but brace roots are not yet fully developed.
- Injury to the root system caused by corn rootworm feeding can increase susceptibility to lodging.

Figure 1. A combination of wet soils and strong winds can lead to lodging even if roots systems are healthy; however, plants with damaged or restricted roots are more susceptible to lodging.

Factors That Can Increase Root Lodging Risk

- Compacted soil around the root zone due to wet conditions at planting, resulting in restricted root development.
- Wet soil early in the season, which reduces the need for root expansion.
- Dry soils later in the season that slow down brace root development.
- Water-saturated soils at the time of a wind event.
- Corn rootworm damage.

Impact on Growth and Development

- The impacts of root lodging depend on timing, moisture availability, and root regeneration after lodging.
- The earlier that root lodging occurs, the less of an impact it is likely to have on yield.
- Yield loss will likely be greater if root systems have been damaged by rootworm feeding.
- Lodging in mid-to-late vegetative stages can delay silk emergence by one to two days.
- Root lodging during pollen shed can cause silks to be covered by the leaves of lodged plants, reducing pollination success.
- The later that root lodging occurs in the growing season, the less able corn is to straighten back up afterward without pronounced goose-necking.
- As corn nears its full height, stalk elongation is nearly complete, making recovery after lodging unlikely.

Figure 2. Heavy corn rootworm feeding on unprotected root. Corn rootworm damage reduces a plant's structural support and makes it more susceptible to lodging.

Effect of Root Lodging on Corn Yield

- A three year field study by Ohio State University researchers evaluated effects of root lodging on corn development and grain yield (Lindsey et al., 2021).
- Simulated wind lodging treatments were applied by pushing plants over by hand immediately after irrigation or heavy precipitation events.
- Recovery from lodging was highly dependent on crop growth stage, with plants that lodged during vegetative growth (V10 and V13) able to recover much more than plants that lodged after tasseling (VT-R1 and R3).
- Yield loss resulting from lodging was greatest at VT-R1, stemming from reduced kernel number, poor pollination, and increased barren plants (Figure 3).
- Yield loss from lodging at R3 was mostly attributable to reduced kernel weight, and partially to reduced kernel number.
- Ears close to the ground at VT-R1 and R3 increased incidence of vivipary which could also impact grain marketability.

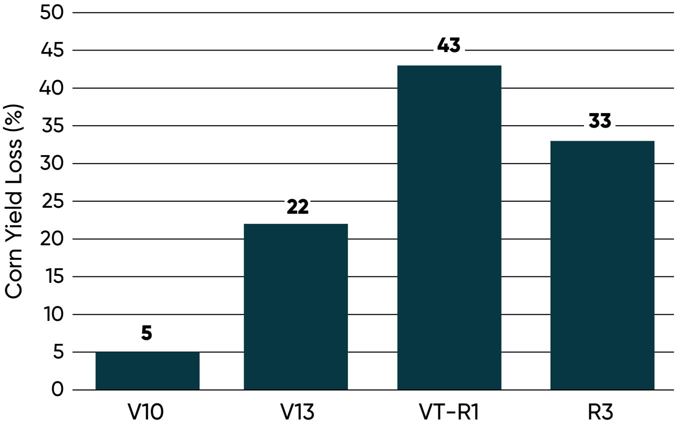


Figure 3. Yield loss associated with root lodging at different corn development stages in a three year Ohio State University study (Lindsey et al., 2021).

Managing Lodged Corn

- Although yield loss due to lodging cannot be recovered, management practices can be used to mitigate additional threats to remaining yield and reduce the risk of lodging in future crops.
- Extension pathologists do not generally recommend rescue applications of fungicide on root lodged corn beyond what a grower would normally do.
  - » Effectiveness of a fungicide application decreases with the severity of lodging because of reduced spray coverage, and the likelihood of an economic return may be lower for corn that already has reduced yield potential.
  - » Diseases favored by injury to plants form wind or hail are primarily bacterial and not controlled by fungicides.
- Goose-necked corn can be challenging to harvest. The use of after-market corn head reels can help guide stalks through the header and minimize harvest loss.
- If lodging was due to rootworm feeding, practices to reduce rootworm population levels should be implemented.

Figure 4. Brace roots are important for stabilizing the plant under high winds and recovery after lodging has occurred. Lodging risk is increased when high winds occur before brace roots have fully developed or brace root development has been inhibited by dry soil conditions.

return to table of contents

Brittle Snap in Corn

Cori Lee, Agronomy Sciences Intern

Key Points

- Brittle snap or green snap refers to breakage of corn stalks by strong winds, most often occurring during periods of rapid vegetative growth.
- There are two periods when corn is most susceptible to brittle snap – V5 to V8, when the growing point is just advancing above the soil line, and V12 to R1, or two weeks prior to tasseling until silking.
- Any conditions which promote rapid growth may also increase susceptibility to brittle snap damage. It is often the most productive fields that incur damage.

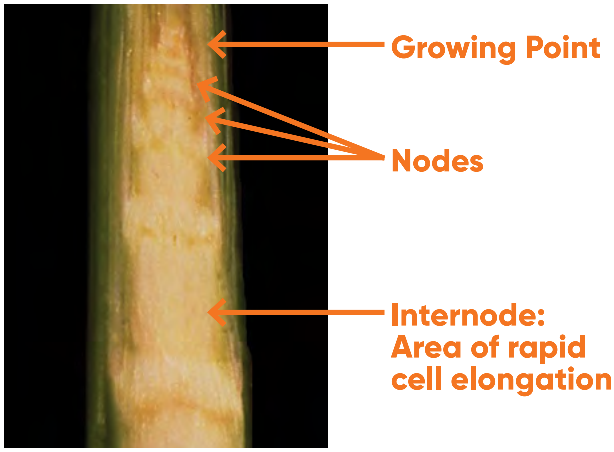


Figure 2. Dissected corn plant showing the developing structures inside the stalk, including the growing point, nodes and internode area.

Contributing Factors

- Brittle snap refers to breakage of corn stalks by violent winds and is reported most frequently in the Plains and Northern Plains areas of the U.S., where high winds are more common.
- During vegetative growth, rapidly elongating internodes can be brittle and susceptible to breakage.
- Many factors affect the severity of brittle snap injury, including growing conditions, field geography, crop management practices, soil type, and hybrid genetics.

Injury at V5 to V8

- A corn plant at V5 is entering a period of rapid growth. Stalk growth occurs by elongation of internode cells, which increases the rigidity of the stalk. Cell walls are very fragile at this stage.
- At the V5 to V8 stage, many nodes and internodes are stacked together in a small area (see image at top right). This dense concentration may make the plants less flexible and more susceptible to breakage.
- Brittle snap breakage at V5 to V8 occurs below the growing point, at a stalk node at or near the soil surface. Snapped plants will not recover, nor contribute appreciably to yield.

Figure 1. Brittle snap observed at V5 to V8 often follows a surge in corn growth and development stimulated by favorable rainfall and temperature.

Injury at V12 to R1

- A key factor which increases the incidence of brittle snap from V12 to tasseling is the enlargement in leaf surface area and plant height, which increases wind resistance during a period of potentially severe storms and wind events.
- Snapped plants often have visible ear shoots on the stalk shortly after the wind damage event. However, the reduced leaf surface area usually results in limited grain production.
- The most common sites for breakage at this stage are at the nodes – immediately below, at or above the primary ear node.
- Upon reaching mature height, the risk of brittle snap diminishes as cell walls are strengthened by the deposition of lignin and other structural materials.

return to table of contents

Planter Preparation for Spring

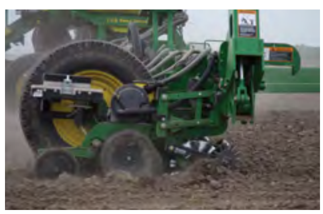
Laura Sharpe, *Agronomy Information Consultant,*
and **Mark Jeschke, Ph.D.**, *Agronomy Manager*

Summary

- Preparing your planter for spring planting is critical for the success of your next crop.
- Start with the basics like tire pressure, planter leveling and parallel linkage arm wear. Then move to seed tubes, double disc openers, meters, and closing wheels.
- Finally, check your technology, including wiring, monitors, and sensors. Store data and prepare for new fields.

Planter Leveling

For proper disc cutting action, seed delivery, planting depth accuracy, and press wheel action, planters need to run slightly uphill, particularly as they age and the parallel linkages become worn. Check your planter for levelness. If the planter is running downhill, it may require adjusting the hitch position.



Parallel Linkages

Parallel linkages wear over time, which can lead to excessive movement of the row unit. Bushing wear will tend to make a row unit plant slightly shallower with more tendency for erratic seed distribution. With your planter raised in the air stand behind each row unit and push up and side to side. If you find that the row unit moves excessively, it is time to replace the parallel linkage bushings.

Opening Discs

Sharp cutting double-disc openers can either make or break a planter. A business card can be used to determine if the discs have the necessary 2 inches of cutting edge contact. The V-trench they form is critical for good seed-to-soil contact and uniform emergence. As disc openers wear, they will no longer form a firm cutting point. This can lead to an irregular furrow, shaped like a "W" instead of a "V" resulting in variable seed depth placement and a lack of seed to soil contact. Discs should be replaced when wear exceeds factory specifications, which is typically when they have lost ½-inch or more of their original diameter. A good visual indicator that discs need to be replaced is when the original bevel on the edge of the discs is gone.

> Discs should be replaced ***when wear exceeds factory specifications,*** which is typically when they have lost **½-inch or more** of their original diameter.

Depth Gauge Wheels

Depth-gauge wheels should be checked to make sure that they turn freely, move up and down easily, and run tightly against the opening discs. This is important to ensure that soil doesn't flow between the wheels and the opening discs and into the seed trench, which can result in irregular seed placement and planting depth variability. Yearly inspections will tell you if the gauge wheel arm bushings are worn and if the wheels need to be shimmed in against the double disc openers.

Seed Tubes

Inspect seed tubes and vacuum for obstructions, leaks, and loose fittings, and continue to do this regularly throughout spring planting season. Clean seed tube sensors routinely, and make sure to adjust vacuum pressure according to seed size and shape.

Check your seed drop tubes to be sure they are free and clear of any obstructions, and make sure that they are not worn by your double disc openers. Rough edges caused by wear can alter your planter's seed drop accuracy. Any hindrance or obstruction that interferes with seed drop can result in erratic seed distribution, even though meters are functioning perfectly. If seed tubes are worn, they should be replaced. If the planter is equipped with seed firmers, they should also be checked for wear and replaced if necessary.

Pioneer Agronomy

Planter Setup

- Jonathan Rotz, Field Agronomist

Meters

Meters should be taken apart before each planting season for cleaning and to check parts for wear. Finger pick-up metering units should be recalibrated after 100 acres have been planted per row unit. Confirm that all seals on vacuum meters are in working order and seed discs are flat and not warped. Double check the clearance between the seed disc and the housing to prevent vacuum leaks. Inspect any belt or brush within the meter, and in high-speed delivery systems, for wear and misshapen bristles or paddles. It is also important to check the bowl tension on John Deere ExactEmerge™ planters. If the bowl tension is too loose, seeds may not end up getting to the brush belt for delivery to the seed furrow.

Coulters and Row Cleaners

Coulters and other attachments can impact seed to soil contact, especially with heavy residues. Coulter depth and sharpness are important to allow residues to be cut cleanly rather than crimping and pushing them into the seed furrow. Most coulters should be set to run about 1/4 inch above the depth of the double-disc openers. Be sure that coulters and residue attachments are aligned properly with the double-disc planted too deep and double disc openers not turning properly.

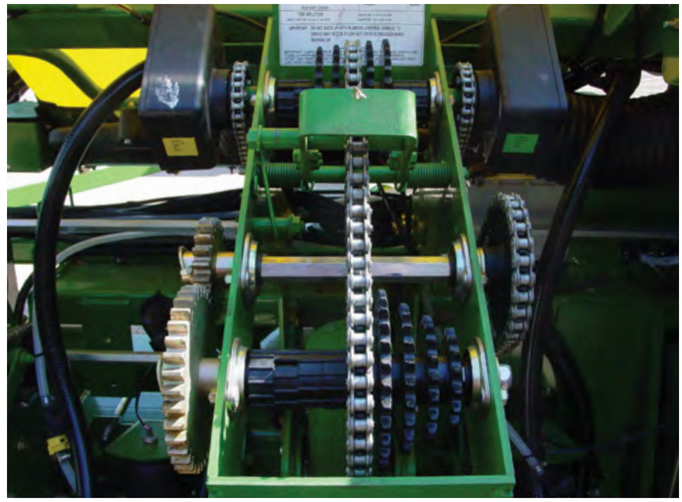
Make sure row cleaners gently sweep residue – you don't want to move soil, just residue. Watch the row cleaners running. Fixed row cleaners shouldn't turn constantly; they should gently turn sporadically, especially through areas of thick residue. Floating row cleaners should maintain constant contact with the ground, flowing the contours and providing a clean and consistent path for the depth gauge wheels to follow.

Closing Wheels

For closing wheels to perform properly, it is important to ensure that they are aligned with the opening discs. To check alignment, set the planter on the ground and pull ahead about 5 feet. Look at the mark left behind the planter by the double disc openers. The mark should run right down the centerline between closing wheels. If a closing wheel is running too close to the seed furrow, adjust the closing wheels to bring it back to the center.

Chains and Sprockets

Check all chains, sprockets, and shear pins for wear and proper tension. If they are worn or chain links are stiff, the chain should be replaced. Make sure chains are lubricated properly.



Technology Check

Check all wiring harnesses, ensure all wiring is connected and in working order. Consider gathering loose cords with zip ties. For all add on equipment, check all electric sensors, down force compressors etc.

Review all monitors, remove old prescriptions. Load VRS planting scripts from Granular Insights prior to planting and ensure planter is accepting the prescription. Utilize agronomic tools from Granular Insights like population charts for hybrids based on seed price, yield environment, and commodity price. Scan corn seed batch tags for final planter settings to optimize seed drop. Have your planting plan pre-loaded into the monitor and onto all employee smart phones for simple stress-free planting.

Safety Check

Perform a safety check on all planting equipment to make sure lights and signals work properly so you don't risk accidents when moving from one farm or field to another. Ensure that all farm equipment has the appropriate slow moving vehicle signage. Clean windows to ensure operators can see clearly. Ensure the hitch pin is secure and safety chain is attached, especially for road travel.

Forward-Thinking Farming Webinar

Planting with Precision - Adjustments, Tips, and Watchouts

Mike Gronski, Jason Kienast, and John Mick, Pioneer Field Agronomists

Pioneer field agronomists discuss top planter adjustment tips and watchouts to keep in mind during planting to give your seedlings the best possible start to the growing season.

return to table of contents

Determining Soil Fitness for Spring Field Work

Laura Sharpe, *Agronomy Information Consultant*

Key Points

- Evaluate every field for soil moisture conditions before starting any field work. Use the simple "ribbon" test to determine soil conditions and fitness.
- Determining when the soil is fit to work or plant in the spring is a key skill to growing high yielding crops.
- Tillage and planting operations are best done when soils are dry enough in the top 3 to 4 inches of soil that they do not form a ribbon with normal compression forces from your hand.

How to Determine if Soil is Fit for Field Work

- The following soil test is a quick method to accurately gauge if soil is ready for spring tillage and seedbed preparation.
- Take your trowel and dig down 3 to 4 inches into the seedbed.
- Grasp a handful of soil from the trowel and squeeze it together with your hands; be firm, the action of a cultivator or disk is not gentle.
- Try to break apart the ball and assess how friable the soil is.
- If the ball is easily broken down to its original crumb structure, the ground is fit to work.
- If any of the following are true, the soil is too wet:
  - The soil smears together
  - The ball of soil sticks together
  - Soil feels tacky
  - A ribbon forms when squeezed between your thumb and forefinger (as shown in Figure 1)
- If water comes out of the ball when you squeeze it, the soil is much too wet to be worked or planted.

Figure 1. (Left) Soil that is too wet to plant, as it forms a ribbon when squeezed between your thumb and forefinger. **(Right)** Soil that is fit for field work when it crumbles when pressed.

What Happens When Soils are Worked or Seeded When They are Too Wet?

- Planting into wet soils or working soils too wet can cause smearing of the seed furrow sidewall, sidewall compaction from the disk openers, and a seed trench that does not close (see Figures 2-4). This can cause uneven crop emergence.
- Compacted soil restricts corn and soybean root systems and causes uneven emergence. Restricted nodal root systems will reduce the plant's ability to uptake water and nutrients, lowering yield potential (see Figure 5).

Figure 2. Soil that was too wet to plant, leaving the seed trench open and the seed exposed.

Figure 3. Wet soils at planting can lead to sidewall smearing that restricts optimum nodal root growth and yield potential. Note that the roots of this corn plant are running horizontally along the seed trench.

return to table of contents

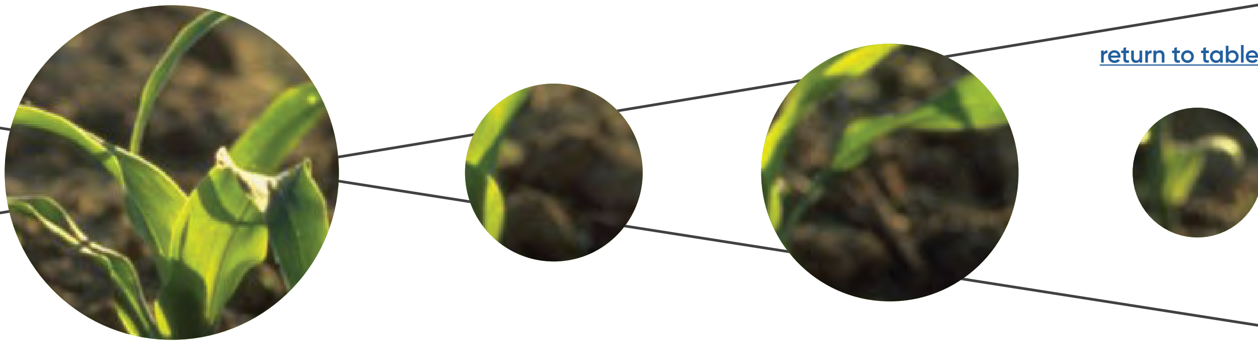


Figure 4. Planting into wet soils caused an open seed trench resulting in uneven emergence and poor stands. Arrows indicate emerged corn plants. Photo from Paul Hermans, Pioneer Agronomist.

What About a Dry Spring?

- Dry soil in the spring is less susceptible to impacts of equipment traffic, such as compaction and ruts in the field.
- However, soil disturbance increases the potential for soil erosion after any rain events and the loss of soil organic matter, topsoil, and nutrients.
- Inspect the top 6 inches for soil moisture status and plan to minimize tillage unless it is absolutely necessary.
- Minimizing tillage passes can save as much as a quarter of an inch of water per pass (Al-Kaisi, 2020).

How to Tell When Soil is Ready for Field Work

- Soil should be dry enough in the top 3 to 4 inches that it does not form a ribbon with normal compression in your hand.
- Soils in proper condition for seedbed preparation should crumble between your fingers and have favorable tilth. These properties will optimize early growth and minimize soil compaction.
- Soil moisture conditions can change between the time the seedbed is prepared and planting begins in the field.
- If soils become wet, be patient and allow them to dry out. Try to work fields as close to planting operations as possible.

How to Tell When Soil is Ready for Planting

- When you walk on a field prior to planting, your boots should not sink into the soil more than an inch.
- The goal of spring tillage is to prepare a seed bed. Ideal seed beds are firm. A very loose seedbed will result in uneven emergence, poor nodal root establishment, potential for root lodging in summer storms, less root mass for periods of drought, and lower yields.

Figure 5. The roots on the left are from a plant that experienced sidewall smearing – notice how the roots are concentrated directly underneath the stalk and do not branch out horizontally. The roots on the right show what normal roots look like. Notice the greater root mass and more even distribution across the area.

return to table of contents

Effects of Seed Orientation at Planting on Corn Growth

Dan Emmert, M.S., Former Pioneer Field Agronomist, and ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Key Findings

- A 2022 field demonstration was conducted to study the effects of seed orientation in the furrow at planting on corn growth.
- Seeds planted with the kernel tip down emerged about 20 GDUs earlier than those planted with the tip pointed up.
- Seeds planted tip down with the germ oriented toward the interrow had greater light capture and lower temperature under the canopy during late vegetative growth stages.

Does Seed Orientation Matter?

- Agronomists and corn producers have long been interested in the potential to improve corn growth and yield by controlling the orientation of the corn seed in the furrow at planting.
- The reason that seed orientation could potentially influence corn growth is because of how the initial growth from the germinating seed occurs (Figure 1):
  - The radicle root emerges near the tip of the kernel.
  - The coleoptile emerges from the embryo (germ) side of the kernel and elongates in the opposite direction toward the dent end of the kernel.
- When a corn kernel planted with the tip pointed downward, the emerging radicle and coleoptile are already pointed in the direction they need to grow, without the need for the seedling to expend additional energy and time to bend their growth downward and upward, respectively (Figure 2).
- Furthermore, the direction of the germ side of the kernel influences the orientation of the plant's leaves, particularly during the early vegetative stages.
- Seeds planted with the germ side perpendicular to the row will tend to have leaves oriented across the row rather than toward adjacent plants in the row.

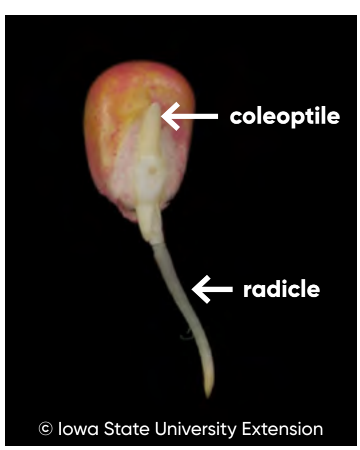


Figure 1. Germinated corn seed showing the emerging coleoptile and radicle.

Figure 2. Corn seedling that was planted with the kernel tip angled upward, showing how both the coleoptile and radicle had to bend as they elongated to grow in the proper direction.

Previous Research on Seed Orientation

- Several previous research studies have investigated the potential for controlled seed orientation to provide:
  - Better stand establishment
  - More uniform emergence
  - More efficient light utilization
  - Quicker canopy closure
- Results of these studies have been mixed, with some studies showing a yield advantage with uniform seed orientation, while others have shown improvements in emergence uniformity and light capture but no significant effect on yield.
- A three-year Pioneer study comparing seeds planted with the germ oriented with the row, across the row, or randomly over a range of plant populations produced different results in each year of the study (Paszkiewicz, et al., 2005).
- Research over the years on corn seed orientation has been limited, however; likely due to the labor-intensive nature of the work and difficulty in mitigating confounding factors.
- The lack of any available planting technology capable of controlling seed orientation in the furrow has likely also limited the amount of interest in researching seed orientation – even it were shown to matter, growers would have no way of doing anything about it.
- However, with the advent of planting technologies such as John Deere's ExactEmerge, that maintain control of the seed from the meter until it is deposited in the furrow, manipulating seed orientation seems like much less of a leap in technology than it would have been 50 years ago when the first research into the question was being conducted.

2022 Seed Orientation Field Demonstration

- A field demonstration was conducted in 2022 near Montgomery Indiana to investigate the effects of corn seed orientation on speed of emergence, canopy closure, and light capture.
- The study compared four different seed orientations:
  1. Tip down, germ across the row
  2. Tip up, germ with the row
  3. Tip down, germ with the row
  4. Seed laying flat in the furrow
- Seed furrows 1.5 inches deep spaced 30 inches apart were created using a planter with the closing wheels tied up.
- Seeds were then planted by hand in the furrows in each of the four different orientations and the seed furrows were closed (Figure 3).
- Time to emergence and canopy closure were recorded, as well as measurements of light capture and temperature under the canopy.
- Light capture was assessed by measuring the amount of light that was able to penetrate the canopy and reach ground level using an Apogee DLI-400 light meter.

Figure 3. Seeds that have been hand planted into the open furrow in the 2022 seed orientation demonstration.

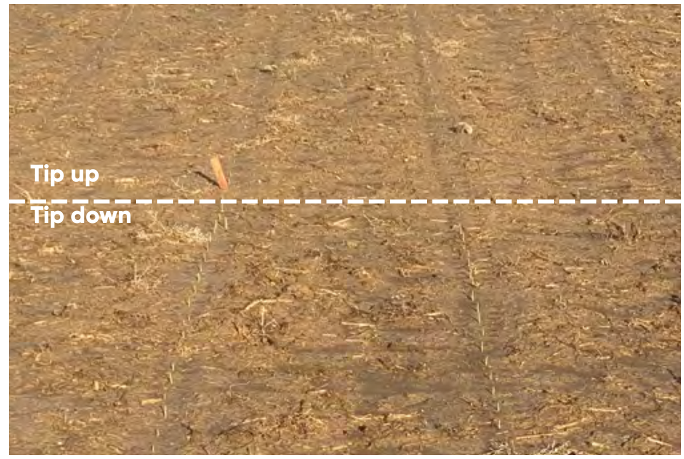


Figure 4. Emerged seedlings from corn seeds planted tip down (foreground) and tip up (background) showing faster emergence with seed planted tip down.

Figure 5. Corn plants from seeds planted tip down with the germ oriented across the row (left) and with the row (right) showing the impact of germ direction of leaf orientation during early vegetative growth.

Results

Emergence

- Seeds planted with the tip down emerged faster than those planted tip up by approximately 20 GDUs (Figure 4).

Leaf Orientation

- The impact of germ direction on leaf orientation for seeds planted tip down was apparent during early vegetative growth.
- Seeds planted with the tip down and germ oriented perpendicular to the row resulted in leaves growing across the row, while seeds planted tip down with the germ parallel to the row resulted in leaves growing with the row (Figure 5).
- Seeds planted with the tip up did not result in uniform leaf orientation, even though the germ orientation was uniform. This is due to the circuitous path the coleoptile had to take around the kernel as it emerged.

Canopy Closure and Light Capture

- Seeds planted with the tip down and germ perpendicular to the row resulted in leaves growing across the row which closed the canopy quicker than seeds planted tip down with the germ parallel to the row or seeds planted tip up (Figure 6).
- Light penetration through the canopy was measured from July 3 to July 13. Plots with seeds planted tip down and the germ oriented across the row captured an average of 40% more light than those with the germ oriented with the row (Figure 7).
- A period of high temperatures and drought stress occurred during late vegetative growth stages. The greater light interception in plots with leaves oriented across the row was able to reduce daytime soil surface temperatures by around 14° F.

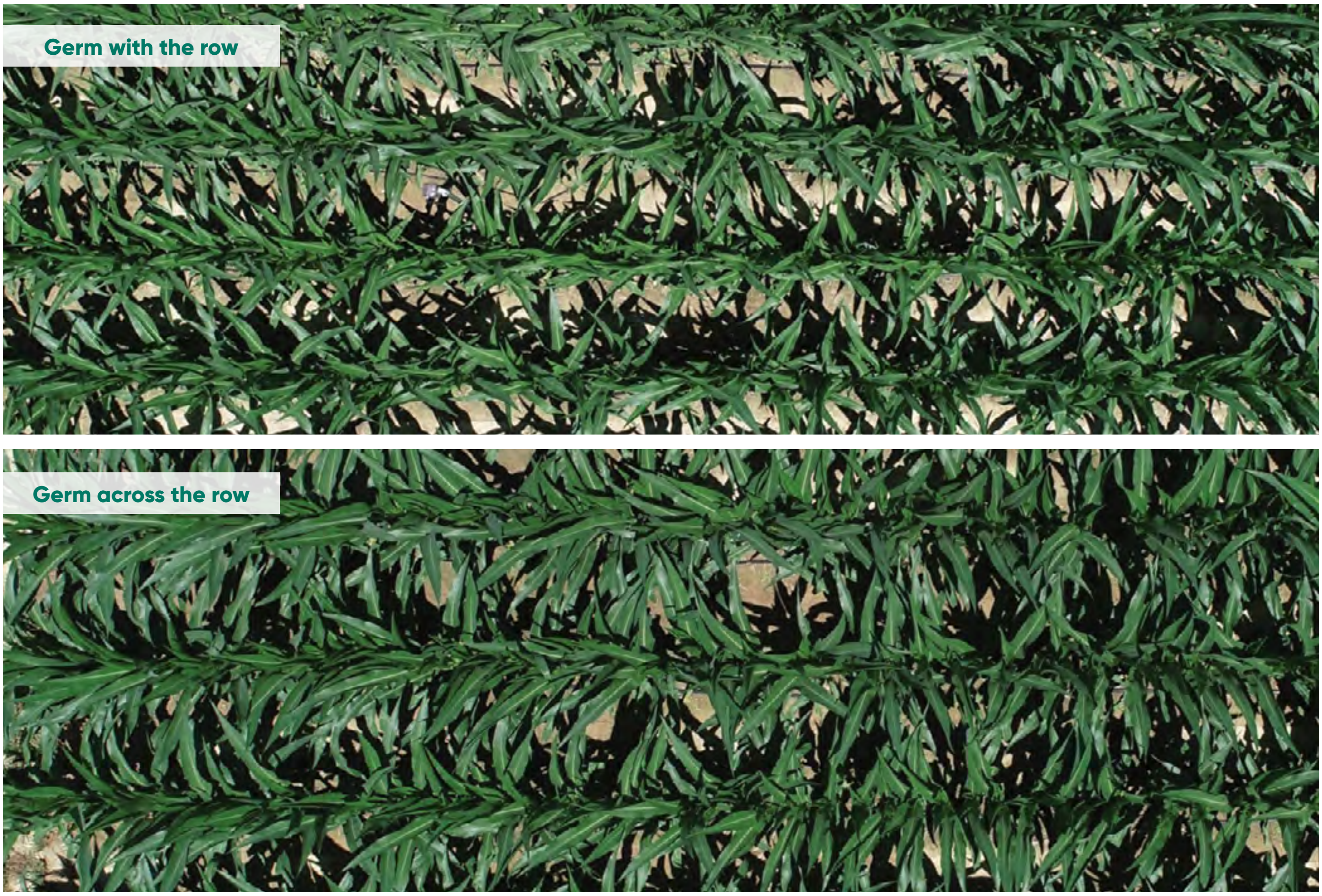


Figure 6. Overhead view of plots with seeds planted tip down with the germ oriented with the row (top) and across the row (above).

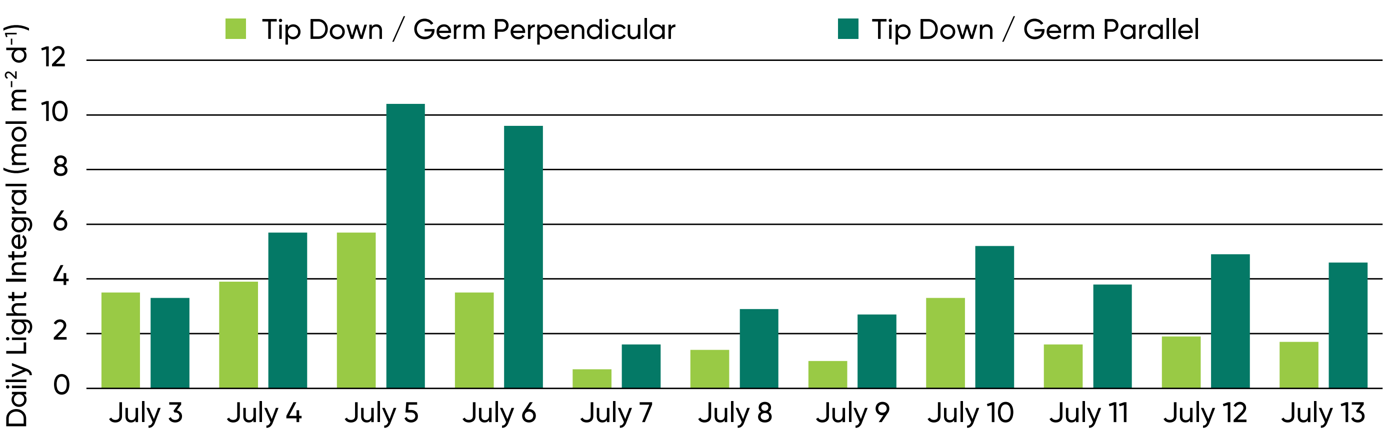


Figure 7. Daily light integral at ground level for plots with seeds planted tip down and germ perpendicular to the row and seeds planted tip down and germ parallel to the row (Larger values = more light penetrating the canopy and reaching the ground).

- Previous research has demonstrated the ability of corn plants to alter their leaf orientation in response to their environment during the early vegetative growth stages, shifting leaf growth preferentially toward the interrow (Jeschke and Uppena, 2015).
- In this study, however; whatever adjustment occurred was not enough to overcome the effects of seed orientation at planting.
- Results of this study show that controlling seed orientation at planting may offer some benefits to corn growth and performance, particularly under stressful conditions.

Acknowledgement

We would like to thank Mike Wagler and Rosedale Ag Service for their many contributions to this demonstration.

return to table of contents

Corn Yield Response to Plant Population in Eastern Ontario

Paul Hermans, Pioneer Area Agronomist, and Mark Jeschke, Ph.D., Agronomy Manager

Key Findings

- Optimum plant population was greater in higher yielding environments than in low yielding environments.
- Pioneer® brand P9301 and P9535 family products differed in their response to plant population and optimum population for maximum yield.
- Differing effects of plant population on ear length was the primary driver of the different population response between the two hybrid families.

Hybrid Response to Population – 2021 Trials

- On-farm trials evaluating corn hybrid response to plant population were conducted at 16 locations across Eastern Ontario in 2021.
- Hybrids were planted at three to five different populations at each location. Most locations included four populations: 28,000, 32,000, 36,000, and 40,000 plants/acre.
- A total of nine different Pioneer® brand corn products were included in the study, with P9301 family products (P9301AM™ or P9301Q™) and P9535AM™ included at the majority of locations (Table 1).
- Each location had either one or two replications.

Table 1. Pioneer brand corn products included in 2021 on-farm population trials and the number of locations for each.

Hybrid/Brand[1]	Number of Locations
P0953AM™ (AM,LL,RR2)	1
P9188AM™ (AM,LL,RR2)	1
P9233AM™ (AM,LL,RR2)	3
P9233Q™ (Q,LL,RR2)	2
P9301AM™ (AM,LL,RR2) P9301Q™ (Q,LL,RR2)	10
P9492AM™ (AM,LL,RR2)	1
P9535AM™ (AM,LL,RR2)	11
P9815AM™ (AM,LL,RR2)	1

- Samples were collected at 11 locations to evaluate population effects on yield components, including kernel rows per ear, kernel row length, and kernel weight.
- Samples were collected from the highest and lowest populations at each site (28,000 and 40,000 plants/acre).
- Ten ears were sampled per entry.

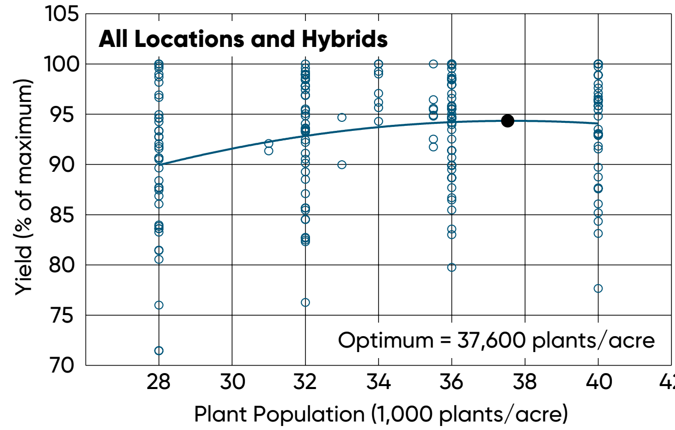


Figure 1. Corn yield response to population across all hybrids and locations. Corn yield is expressed as a percent of the location maximum.

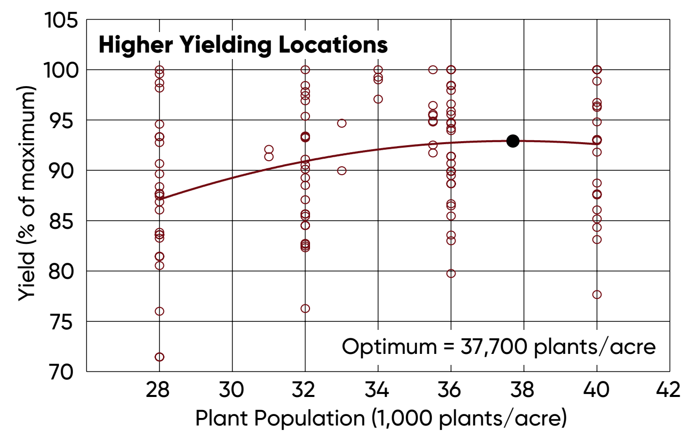


Figure 2. Corn yield response to plant population at nine higher yield level locations. (Location maximum = 220-250 bu/acre.)

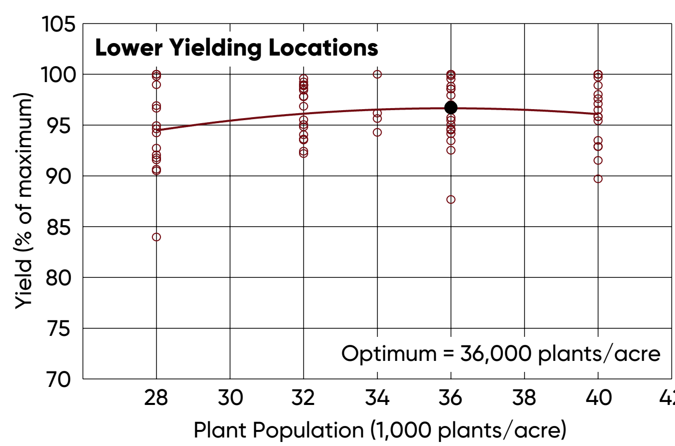


Figure 3. Corn yield response to plant population at seven lower yield level locations. (Location maximum = 180-220 bu/acre.)

return to table of contents

Results

- Across all hybrids and locations, the agronomic optimum plant population was 37,600 plants/acre (Figure 1).
- On-farm trial locations were separated out as higher or lower yielding based on the maximum yield measured at the location to determine if yield response to plant population differed by yield level.
  - » Nine locations were classified as higher yielding, with a maximum yield between 220 and 250 bu/acre.
  - » Seven locations were classified as lower yielding, with a maximum yield between 180 and 220 bu/acre.
- Higher yielding environments would be expected to have a higher optimum plant population and that proved to be the case in this study.
- The optimum plant population across higher yielding locations was 37,700 plants/acre (Figure 2), compared to 36,000 plants/acre for lower yielding locations (Figure 3).
- This study included two Pioneer hybrid families, P9301 and P9535, that were included at the majority of trial locations.
- The optimum plant population for the P9301 family was 37,800 plants/acre (Figure 4), while the optimum for the P9535 family was 35,300 plants/acre (Figure 5).

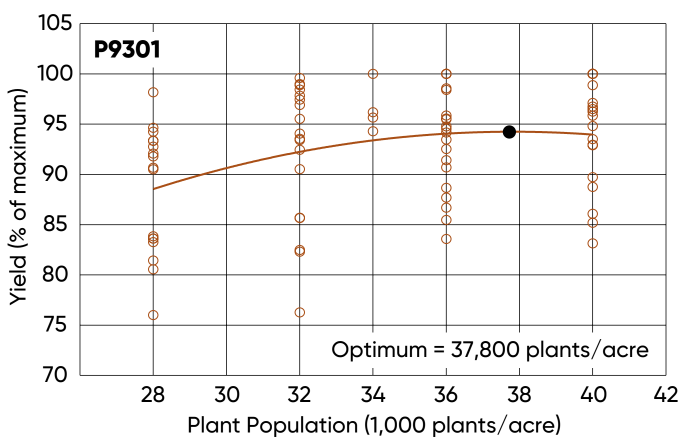


Figure 4. Yield response of Pioneer P9301 hybrid family products to plant population (9 locations).

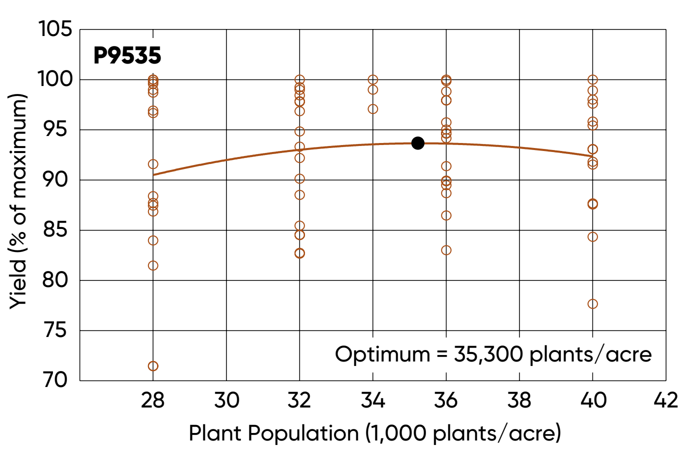


Figure 5. Yield response of Pioneer P9535 hybrid family products to plant population (11 locations).

- Yield per plant – comprised of kernel number and kernel weight – generally declines as plant population increases. The agronomic optimum plant population is the population at which this tradeoff is optimized, maximizing overall yield.
- Figures 6, 7, and 8 show plant population effects on yield components for P9301 and P9535 family products and across all hybrids.
  - » P9535 family products had a relatively flat response to plant population and a lower optimum. The difference in yield between 28,000 and 40,000 plants/acre was relatively small (Figure 5).
  - » P9301 family products had a stronger population re-sponse and higher optimum, with a larger difference in yield between 28,000 and 40,000 plants/acre (Figure 4).

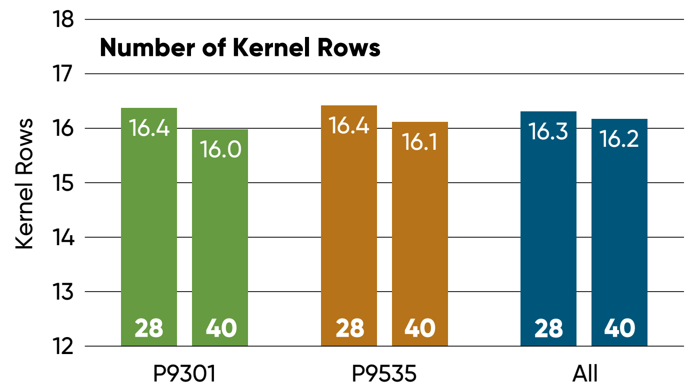


Figure 6. Plant population effect on kernel rows per ear for P9301 and P9535 family products and across all hybrids.

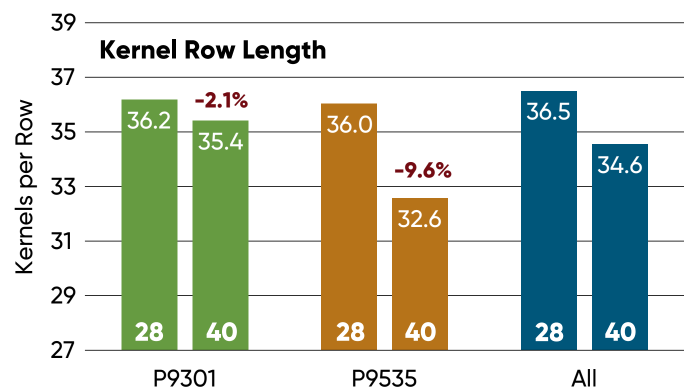


Figure 7. Plant population effect on kernel row length for P9301 and P9535 family products and across all hybrids.

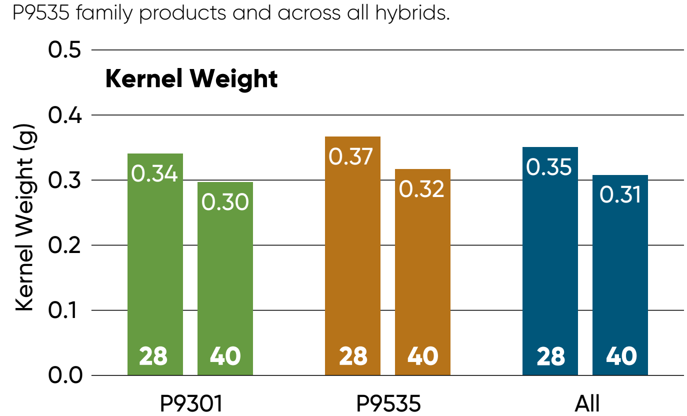


Figure 8. Plant population effect on kernel weight for P9301 and P9535 family products and across all hybrids.

return to table of contents

- Plant population had a minimal effect on the number of kernel rows per ear (Figure 6).
- The maximum number of kernel rows per ear is largely genetically determined and is fixed relatively early in the plant's growth, so plant population would not be expected to have much effect on it.
- Ear length was more affected by plant population, with ears averaging two fewer kernels per row at 40,000 plants/acre than at 28,000 plants/acre (Figure 7).
- Ear length was also the main driver of the difference in plant population response between the two hybrid families.
  - Ear length of P9301 family products was less affected by plant population, decreasing only about 2% at the higher population compared to the lower population.
  - This allowed P9301 family products to continue to add yield at higher populations.
  - Ear length of P9535 family products was more affected by plant population, decreasing nearly 10% at the higher population.
  - This could be described as more of a "flex ear" response, in which individual plants are more responsive to population. Any hybrid will potentially flex down in response to stress by decreasing kernel rows around, kernel row length, or depth of kernels. It appears P9535 family responded to above optimal population by reducing kernel row length but maintaining the number of kernel rows.
- Plant population effects on kernel weight were relatively similar for the two hybrid families (Figure 8).
- P9535 family products generally had a higher average kernel weight than P9301 family products.

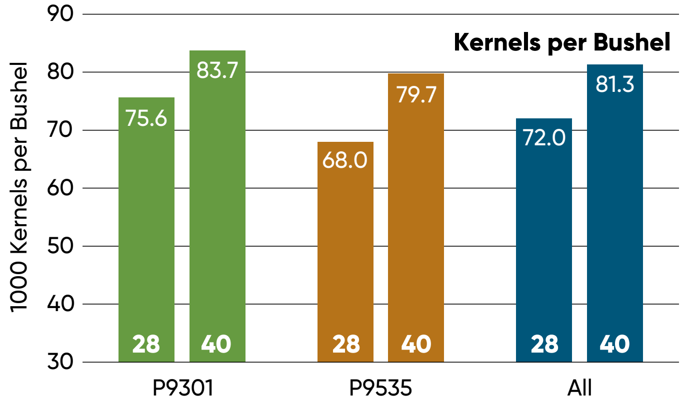


Figure 9. Plant population effect on kernels per bushel for P9301 and P9535 family products and across all hybrids.

- Figure 9 shows kernel weight expressed in terms of kernels per bushel with lower kernels/bu values corresponding to greater kernel weight.
- The average across all hybrids at 40,000 plants/acre was 81,300 kernels/bu, compared to 72,000 kernels/bu at 28,000 plants/acre (Figure 9).
- The greater kernel weight for P9535 family products is reflected in the lower number of kernels per bushel.

Special thanks to our plot co-operators and project supporters:

Emerald Acres, J&H Nixon Farms, Golden Dell Farms, Doug Featherstone, Marlboro Farms, Hog Haven Inc., Golden Rail Farms, Vernon Valley Farms, Mike Glaus, Vanden Bosch Farms, Fife Agronomics, Jim Parks, Starhill Farms, Velthuis Farms Ltd., Ferme Kathyvac, Smiley Farms, Sullivan Agro, and Liam Bracken.

return to table of contents

Soil Temperature and Corn Emergence

Ross Ennen, Senior Research Associate - Seed Science, and Mark Jeschke, Ph.D., Agronomy Manager

Summary

- Corn is a warm season crop. Germination and emergence are optimal when soil temperatures are approximately 85 to 90°F. Cold conditions following planting impose significant stress on corn emergence and seedling health.
- Corn seed is particularly susceptible to cold stress during imbibition. Planting just before a stress event such as a cold rain or snow can result in a reduced stand.
- In lighter textured soils, spring nighttime temperatures can drop significantly below 50°F, even after warm days, inflicting extra stress on corn emergence.
- High amounts of residue can slow soil warming and the accumulation of soil GDUs needed for corn emergence.
- Pioneer® brand corn products are rated for stress emergence to help farmers manage early-season risk. Choosing hybrids with higher stress emergence scores can help reduce genetic vulnerability to stand loss due to cold soil temperatures.
- Pioneer brand corn products include an industry-leading seed applied technology portfolio designed to help farmers establish healthy, uniform crops and maximize productivity.

Acknowledgement

We would like to thank Erin Anderson and Beth Merrill for their contributions to the research summarized in this article.

Successful corn emergence is a combination of three key factors – ***environment, genetics, and seed quality.***

Introduction

Successful corn emergence is a combination of three key factors – environment, genetics, and seed quality (Figure 1). Hybrid genetics provide the basis for tolerance to cold stress. High seed quality helps ensure that the seed will perform up to its genetic ability. Pioneer® brand corn products are selected to provide the best genetics for consistent performance across a wide range of environments, and seed production practices are optimized for maximum quality. However, even with the best genetics and highest seed quality, environmental factors can still influence stand establishment. A combination of field- and lab-based research on the effects of stressful conditions on corn germination and emergence provides valuable insights, which can help farmers make informed decisions and better manage their field operations to maximize stands.

This article will discuss how the level and timing of cold stress affects seed germination as well as emergence and how farmers can mitigate these stresses when planting in challenging environments.

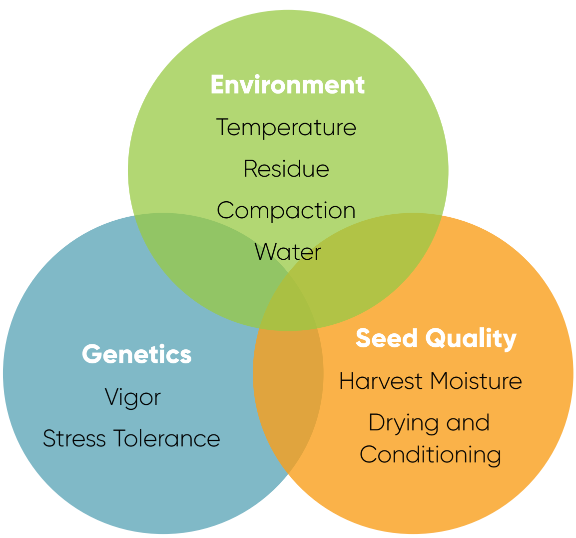


Figure 1. Some critical environmental, genetic, and seed-quality factors that affect stand establishment.

Optimal Temperature For Early Corn Growth

Corn is a warm-season crop and grows best under warm conditions. In North America, early season planting typically puts substantial stress on corn seedlings, especially if planting is followed by cold, wet weather. As planting has shifted earlier, the potential for cold soil at planting and cold, wet weather after planting has increased. In fact, it is not unusual for early planted corn to remain in cold, saturated soil for two to three weeks or longer before emerging.

To illustrate the effects of temperature on corn growth, three hybrids of early, mid, and late maturities were germinated in temperatures ranging from 59 to 95°F (15 to 35°C). Growth rates of both roots and shoots were measured. Both shoots and roots exhibited the fastest growth rate at 86°F (30°C) and continued to grow rapidly at 95°F (35°C), suggesting optimal seedling germination and emergence occurs at much higher soil temperatures than are common in most corn-producing

areas (Figure 2). It is generally recommended that farmers plant when soil temperatures are at or above 50°F. Farmers can expect much slower emergence and growth at the cool soil temperatures that are typical during corn planting in much of the U.S. and Canada.

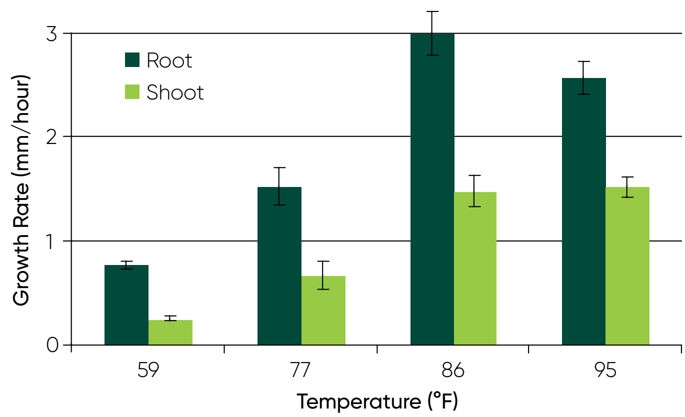


Figure 2. Average early root and shoot growth rates for 3 hybrids under 4 soil temperatures ranging from 59 to 95°F.

Spring soil temperatures can vary greatly year to year. Soil temperatures at planting in combination with near- to moderate-term weather trends have profound effects on the probability of establishing optimal stands and achieving maximum yields. Researchers recorded average soil temperatures at planting depth at several stress emergence research locations in 2018 (Figure 3).

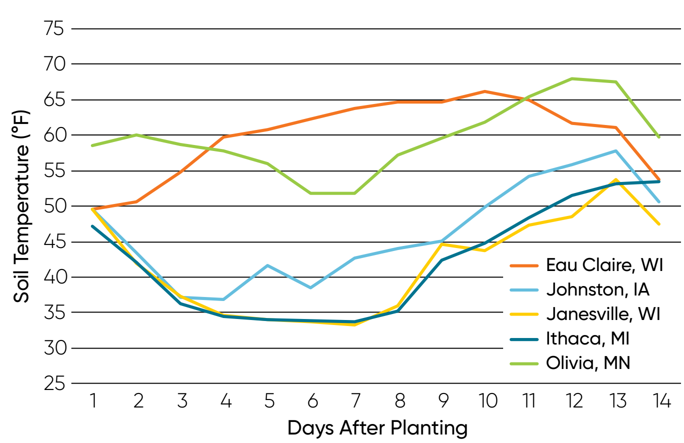


Figure 3. Average late-April soil temperatures recorded at 2-inch depth at several stress emergence testing locations.

At 3 research locations, soil temperature dropped well-below 50°F for a week or more after planting. Figure 4 illustrates the general relationship between soil temperature and stand establishment observed at these locations in 2018.

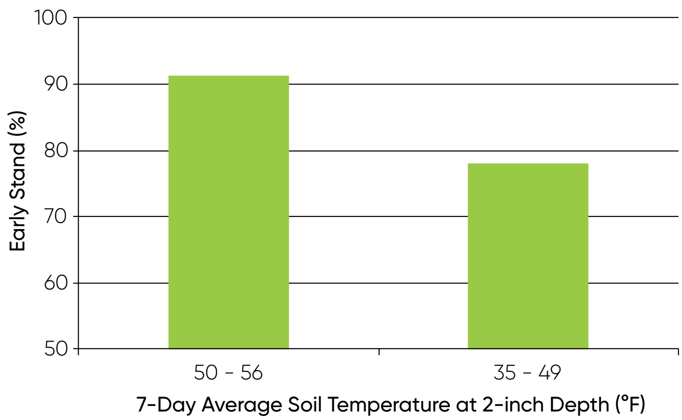


Figure 4. Relationship of soil temperature at planting depth (7-day average after planting) to final stand at stress emergence research locations, 2018.

Low soil temperatures after planting greatly reduced stands at a stress emergence site near Eau Claire, WI, in 2011.

Genetic Differentiation for Emergence in Cold Soils

Pioneer® brand corn products are rated for stress emergence to help farmers manage early season risk. Choosing hybrids with higher stress emergence scores can help reduce genetic vulnerability to stand loss due to cold soil temperatures. To generate stress emergence ratings, hybrids are tested over multiple years and environments, beginning several years before commercialization. The goal is to generate data from many different types of early season stress before assigning ratings.

Hybrids are tested in several early planted field sites, including no-till and continuous-corn locations. Testing sites are located in Minnesota, Wisconsin, Iowa, South Dakota, North Dakota, and Michigan and are chosen to reflect the various seedbed as well as environmental conditions likely to be experienced by farmers. For example, some eastern sites are characterized by extended cold, wet conditions that often persist into late spring and early summer, while northern and Midwestern sites are more likely to provide extreme day/night temperature fluctuations. These testing sites with their diverse and unique conditions provide a more thorough understanding of hybrid responses to early season stress. A typical testing site is characterized by large amounts of residue, cold soil (below 50°F) at planting followed by cold rain or snow and emergence usually requiring two to three weeks.

Pioneer brand corn products are also tested in lab assays that simulate stressful field conditions. These tests, which have been validated by multi-year field trials, provide consistent and reproducible test conditions coupled with the flexibility of year-round testing. These lab assays are used to support hybrid advancement decisions and also to support breeding efforts to improve early season stress tolerance through maker-assisted selection.

In 2018, a wide range of stress emergence conditions and soil temperatures were observed in stress emergence field plots. To demonstrate how stress emergence ratings relate to stand establishment in the field, hybrids were grouped by "low stress emergence" – those with a stress emergence rating of 4 and "high stress emergence" – those with a stress emergence rating of 6.

The trials included 199 low stress emergence hybrids and 159 high stress emergence hybrids. Early stand counts for all hybrids within each group were averaged at each location. As stress level increased, both the low stress emergence and high stress emergence hybrids experienced stand reduction. However, the hybrids with a stress emergence score of 6 were able to maintain higher stands as compared to those with a low stress emergence score (Figure 5).

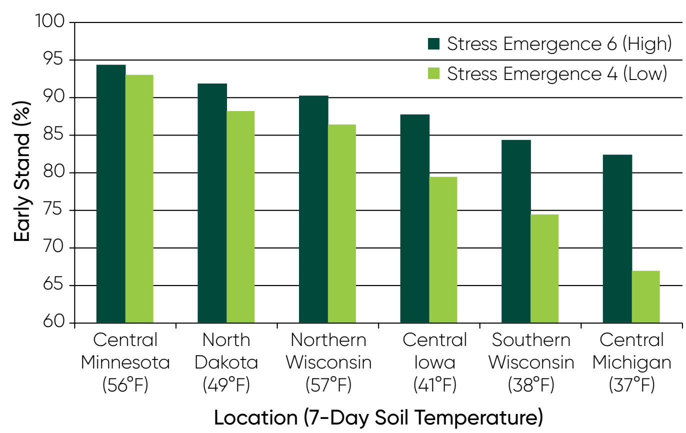


Figure 5. Average stand establishment for high and low stress emergence score hybrids in six stress emergence locations in 2018. Locations are sorted from least stressful (left) to most stressful (right) based on average early stand.

Timing of Cold Stress Impacts Germination

Early planting often exposes seeds to hydration with cold water, which can cause direct physical damage. 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. The degree of damage ranges from seed death to abnormalities, such as corkscrews or fused coleoptiles (Figure 6).

Figure 6. Abnormal mesocotyl and coleoptile development due to cold stress in an early planted Illinois field.

To help understand the importance of the timing of cold stress, two hybrids with stress emergence scores of 4 (below average) and 7 (above average) were allowed to germinate in rolled towels for 0, 24, or 48 hours at 77°F (25°C). The hybrids were then subjected to a stress of melting ice for three days and allowed to recover for 4 days at 77°F (25°C). Hybrids were evaluated for the number of normal seedlings reported as percent germination (Figure 7).

Both hybrids showed significant stand loss when the cold stress was imposed immediately (0 hours). However, the hybrid with a higher stress emergence score had a higher percent germination than the hybrid with a low stress emergence score. Germination rates for both hybrids were greatly improved if allowed to uptake water and germinate at warmer temperatures for at least 24 hours before the ice was added.

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.

Planting just before a stress event, such as a cold rain or snow can cause significant stand loss. The chances of establishing a good stand are greatly improved if seed are able to germinate at least one day in warmer, moist conditions before a cold-stress event. Also, choosing a hybrid with a higher stress emergence score can help moderate stand losses due to cold stress.

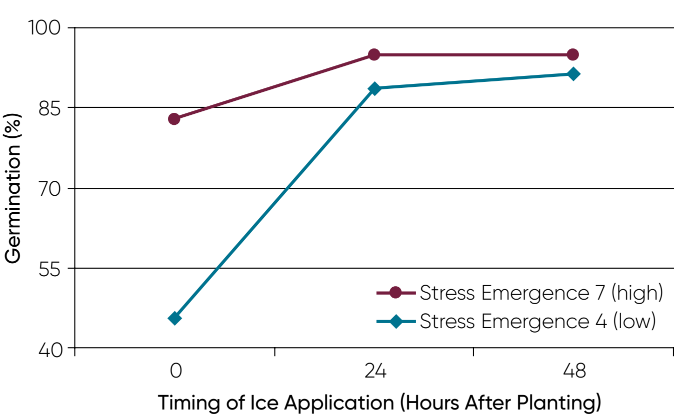


Figure 7. Germination of two hybrids with stress emergence scores of 7 (above average) and 4 (below average) following imbibitional chilling induced by melting ice. Ice was applied immediately after planting (0 hours), after 24 hours, or 48 hours of pre-germination in warm conditions.

One reason why temperature during imbibition is critical to corn emergence is the fact that seed imbibes most of the water needed for germination very rapidly. To illustrate the rapid timing of water uptake, seed was submerged in 50°F water for three hours and weighed at intervals of 30, 60, 120, and 180 minutes to determine water uptake (Figure 8).

The data show that seed imbibes the most water within the first 30 minutes after exposure to saturated conditions. If this early imbibition occurs at cold temperatures, it could kill the seed or result in abnormal seedlings. Growers should not only consider soil temperature at planting but also the expected temperature when seed begins rapidly soaking up water. Seed planted in warmer, dry soils can still be injured if the dry period is followed by a cold, wet event.

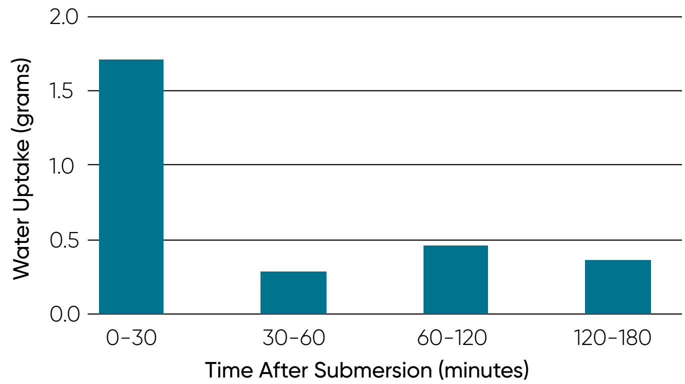


Figure 8. Amount of water uptake by corn seed during the first three hours after submersion in 50°F water.

Soil Temperature Fluctuations and Emergence

Farmers are often able to plant fields with sandier soils earlier in the spring because they dry out faster than heavier soils. However, reduced stands after early planting have often been noted in sandier soils. Sandy soils are more porous and have lower water-holding capacity than heavier soils. As such, they tend to experience wider temperature fluctuations, especially on clear nights with cold air temperatures.

Seedling injury caused by temperature fluctuations.

In 2015, soil temperatures were recorded at a 2-inch depth at a research location with sandy soils near Eau Claire, WI. Daytime soil temperatures reached acceptable levels for corn development (over 50°F) for the first week after planting. However, the early morning soil temperatures dipped as low as 38°F, and on some days, the soil temperature difference between 6 a.m. and 6 p.m. was over 20°F (Figure 8). An average 16 percent stand loss was observed at this location, suggesting that day-night temperature fluctuation after planting can cause added stress to germinating corn. Farmers should be aware of expected night temperatures when choosing a planting date.

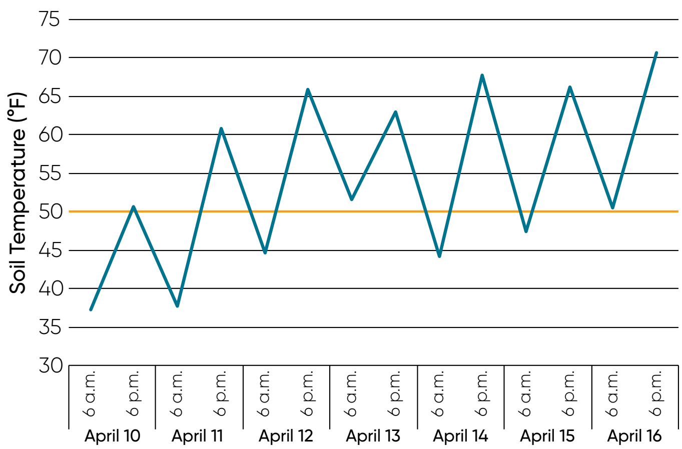


Figure 9. Soils temperatures at 6 a.m. and 6 p.m. for seven days after planting in a stress emergence field location near Eau Claire, WI, in 2015.

Impact of Crop Residue on Soil Temperature

Another factor to consider when choosing planting date is the amount of residue in the field. High amounts of residue can present management challenges. Residue tends to hold excess water and significantly lower soil temperature in the spring, depriving seed of critical heat units needed for rapid emergence. These conditions can also promote seedling disease, particularly in fields that are not well drained or have a history of seedling blights.

In 2011, soil temperature data loggers were placed in a field near Perry, IA, to assess early soil temperatures in a strip-till field. One data logger was placed in the tilled planting strip (low residue), and one was placed in between the rows under high residue. Soil GDUs were calculated from the data logger temperatures to approximate how long emergence would take under low and high residue conditions. In general, approximately 125 soil growing degree units (GDUs) are needed after planting for corn emergence. From April 1 to April 30, soils under low residue were able to accumulate 99 soil GDUs. During the same timeframe, neighboring soils under heavy residue accumulated only 28 soil GDUs.

In mid-April 2019, a 15-degree midday temperature difference was noted in the same field between soil under low residue and soil about 20 yards away under soybean residue (Figure 10). Using a row cleaner to clear residue off the row in high-residue fields allows for warmer daytime soil temperatures and faster GDU accumulation.

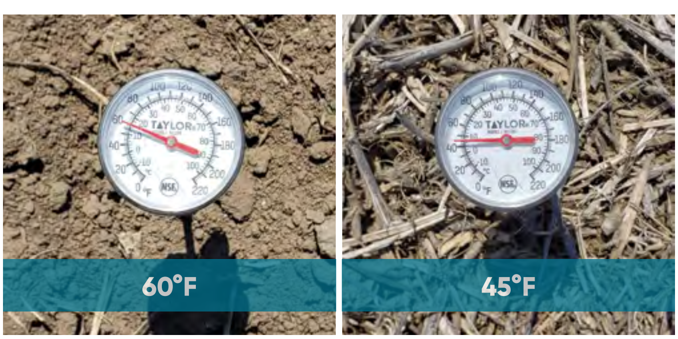


Figure 10. A 15-degree temperature difference was observed midday on April 15, 2019, in a central Iowa field between soil under no residue and soil under heavy residue.

Seedling Disease and Stress Emergence

Stress emergence is an agronomic trait intended to reflect genetic variability for tolerance to abiotic stress in the early season. It is not a rating for disease resistance. Early season stress can promote seedling disease if certain conditions are met, including inoculum presence and prolonged cool, wet conditions. Injury to emerging seedlings will also promote seedling disease. Injury can be caused by chilling, such as imbibitional damage, or by feeding of insects, such as seedcorn maggots, white grubs, and wireworms.

In environments with heavy inoculum pressure, disease progression is often in a race with seedling growth. Conditions that promote rapid soil warming will generally favor seedling growth and reduce disease incidence. On the other hand, extended cool, wet conditions will generally favor disease progression.

Many soil pathogens, including some *Pythium* species, are most active at temperatures in the 40s and 50s (°F). Low temperatures, such as these, can injure emerging seedlings and facilitate infection. Low temperatures also impede stand establishment and increase the window of vulnerability to infection. Fungicide seed treatments generally provide good efficacy against target organisms for 10 to 14 days after planting. However, protection will be diminished if emergence and stand establishment are delayed beyond this period.

Tips to Help Mitigate Early Season Stress Effects on Emergence

Delayed emergence due to cold, wet conditions lengthens the duration during which seed and seedlings are most vulnerable to early season insects and diseases. Seed treatments can help protect stands from both disease and insect pests. For more information on seed treatment options for Pioneer® brand corn products, contact your local Pioneer sales professional or visit www.pioneer.com.

Planting date is one of the most important factors in stand establishment. The likelihood of reduced stands is greatest when planting into cold, wet soils or directly before cold, wet weather is expected. To help mitigate risk, consider the following tips:

- If a cold spell is expected around planting time, it is advisable to stop planting one or two days in advance. Allow seed to begin hydration in warmer soils in order to minimize damage due to cold imbibition.
- In sandy fields, be aware that low nighttime temperatures can dip soil temperatures below advisable planting levels. Large temperature swings in lighter soils can also hurt emergence.
- If planting in fields with high amounts of residue, consider strip-tillage or use a row cleaner to allow soils to warm up faster.
- In the Northern Corn Belt, selecting hybrids with higher stress emergence scores and the right seed treatment can help reduce the risks associated with planting in cold-stress conditions.

return to table of contents

Delayed Corn Planting in the Southern U.S.

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Corn yield potential in the Southern U.S. generally declines when planting is delayed beyond April; however, good yields are still achievable through mid-May in many areas.
- Late-planted corn generally develops at a faster rate due to greater heat unit accumulation, which can affect the timing window for herbicide and nitrogen applications.
- Additional management of late-planted corn may be required to minimize yield-limiting factors such as heat stress, insect pressure, and disease pressure.

Planting Date Impact on Corn Yield

- Recommended planting dates for corn in the Southern U.S. can range from late February to April depending on location.
- Corn yield potential generally declines when weather conditions cause planting to be delayed beyond April; however, relatively good yields are still achievable through the first half of May in many areas.
  - In an eight-year University of Arkansas study, corn yield was maximized with April planting, but yield potential remained above 90% through the first half of May (Table 1).
  - In a three-year Mississippi State University study, 90% yield potential was achievable with irrigated corn planted through May 5, and 84% through May 15 (Table 2).
  - Yield potential in both studies declined below 80% when planting was delayed until late May.

Table 1. Delayed corn planting effects on corn yield in an eight-year study at Marianna, Arkansas (Kelley, 2021).

Planting Date	Relative Yield (%)
Prior to April 30	100
May 1-7	97
May 8-14	91
May 15-21	85
May 22-30	80
June 1-7	75
June 8-14	67

- Irrigated corn is generally able to sustain yield potential with delayed planting longer than dryland corn. Irrigation can also help mitigate the added risk of yield loss from heat stress during pollination and grain fill that comes with later planting.

Table 2. Delayed corn planting effects on irrigated corn yield in a 3-year study conducted at Starkville and Stoneville, Mississippi (Larson, 2016).

Planting Date	Relative Yield (%)	Planting Date	Relative Yield (%)
March 31	100	May 10	87
April 5	100	May 15	84
April 10	99	May 20	80
April 15	98	May 25	76
April 20	97	May 30	72
April 25	95	June 5	66
April 30	93	June 10	60
May 5	90	June 15	55

Growth and Development of Late Planted Corn

- Late-planted corn generally develops at a faster rate due to greater heat unit accumulation.
- Timing of corn development stages in a University of Arkansas planting date study is shown in Table 3.
- More rapid development of late-planted corn means that applications of sidedress nitrogen and herbicides will generally need to be made sooner after planting compared to earlier-planted corn.
- Late-planted corn often grows taller due to longer day lengths during vegetative growth, which can make it more susceptible to lodging.

return to table of contents

Table 3. Planting date effect on timing of corn development stages in a 2011 University of Arkansas planting date study using a 114-day hybrid (Kelley, 2021).

Growth Stage	Corn Planting Date			
	March 24	April 18	May 10	June 3
	days to growth stage			
Emergence	12	9	6	5
V5	38	32	27	19
V8	57	44	36	28
V15	71	58	52	42
R1	77	65	57	49
R5.5	117	101	98	89
Harvest	152	135	126	118

- In addition to accumulating GDUs more rapidly, late-planted corn can also adjust its development, requiring fewer GDUs to reach maturity.
  - A three-year study conducted by researchers at Purdue and Ohio State Universities found an average of 244 less GDUs were required when planting was delayed from late-April or early May to early or mid-June (approximately 40 days) (Table 4).
  - This is an average reduction in hybrid GDU requirement of about six GDUs per day of planting delay.

Table 4. Reduction in GDUs required to reach 50% black layer with delayed planting in a three-year study (Nielsen, 2003).

Location	Change in GDUs to Black Layer		
	Year 1	Year 2	Year 3
West Lafayette, IN	-256	-292	-335
Springfield, OH	-233	-258	-91
Average	**-245**	**-275**	**-213**

Management of Late-Planted Corn

- Planting corn later than normal does pose some challenges and additional management may be required to prevent or minimize yield-limiting factors such as heat stress, insect pressure, and disease pressure.

Foliar Diseases

- Late-planted corn is generally at greater risk for yield loss from foliar diseases because the corn is not as far along in its development when foliar diseases begin to infect the crop.
- Southern rust is of particular concern because of its ability to rapidly infest a field under favorable conditions. Reinfection can occur in as little as seven days, so fields may be damaged very quickly (Figure 1).
- Choose hybrids with solid disease resistance. Scout and apply foliar fungicides as needed. Economic yield responses to foliar fungicides are generally more likely with late-planted corn.

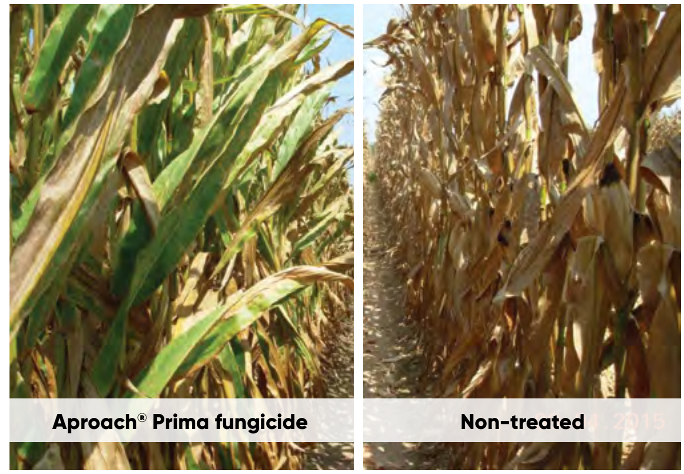


Figure 1. Corn treated with 6.8 fl oz/acre of Aproach Prima fungicide on July 16, 2015, in a Pioneer Agronomy study near Winchester, AR. Southern rust pressure was low at the time of application but increased in severity and ultimately caused premature death in the non-treated check before the end of the season (Malone and Poston, 2015).

Corn Earworm

- Late-planted corn can be at greater risk for damage from corn earworm.
- Light traps or pheromone traps can indicate when adults are flying. Scouting can be done in the field by looking for eggs on the green silks and turning back the silks at the tip of the ear to look for larvae.
- Pioneer® brand corn with Optimum® Leptra® insect protection provides strong above-ground insect control with a superior level of efficacy against ear-feeding pests for cleaner ears and improved grain quality.

Heat Stress and Irrigation Timing

- If available, irrigate in a timely fashion especially during pollination. This will help ensure that the corn plant cools adequately during periods of intense heat that later-planted corn has to endure.
- Higher temperatures during pollination and grain fill increase the vapor pressure deficit, which increases the amount of water needed by the crop to sustain photosynthesis.
- Corn planted after April may require 1 or 2 more furrow irrigations or 2 or 3 more pivot irrigations compared to corn planted in March or April (Kelley, 2021).

return to table of contents

Timing of Pollen Shed in Corn

Stephen Strachan, Ph.D., *Former Research Scientist*

Key Findings

- Peak pollen shed resulting in peak kernel set occurs mid-morning after the dew dries and decreases as the day progresses.
- Pollen grains mature throughout the day and night and are released as anthers dehisce to open pores.
- If anthers are dry, anther pores open shortly after pollen grains mature.
- If anthers are moist, mature pollen grains are stored in anthers until anthers dry and dehisce.

Pollen Shed in Corn

- Pollen shed in corn occurs over a period of multiple days but varies over the course of a day.
- Observations over the years indicate that pollen shed typically starts after the dew evaporates, peaks during mid-morning, and tapers as the day progresses. (Nielsen, 2018).
- A field study was conducted in 2021 to observe how the intensity of pollen shed changes throughout the day by observing kernel set.

Study Description

- Ears in a field of Pioneer® P1082AM™ (AM, LL, RR2) brand corn were covered prior to the beginning of silk emergence.
- Silks of selected ears were exposed to pollen for a short time and then re-covered after this brief period of exposure.
- Intervals of exposure were from 7 to 10 a.m., 10 a.m. to 1 p.m., 1 to 4 p.m., 4 to 7 p.m., or from 7 p.m. to 7 a.m. the following morning.
- This study was conducted for four consecutive days – July 16, 17, 18, and 19, which were the second, third, fourth, and fifth days after the field was at 50% silk, and the first, second, third, and fourth days after the field was at 50% anthesis.
- Selected ears were harvested at maturity and kernel counts per ear were collected. There were six replications of each treatment timing for each day.

Field Conditions and Observations

- The study field was under very little stress during pollination. The field received two inches of rain two days before pollen shed started.
- During the first week of pollination, skies were sunny and daily highs were in the mid- to high-80s (°F).

Figure 1. Corn tassel showing open anther pores.

- The dew evaporated at approximately 10 a.m. on July 16, 9:30 a.m. on July 17, and at 8:30 a.m. on July 18 and 19.
- Pollen shed appeared to be heavy and silks were growing rapidly during the first two days of this study.
- Pollen shed appeared to be less intense on the third day.
- On the fourth day, pollen shed appeared to be less than that of the previous day and the rate of silk growth also decreased.

Results

- Kernel set per ear varied dramatically based on timing of silk exposure to pollen (Figure 2).
- Peak times for pollen shed and subsequent kernel set occurred shortly after the dew dried in the morning.
- On July 16 and 17, the dew dried at or near the end of the 7 to 10 a.m. exposure window. Maximum kernel set on these two days occurred with silk exposure between 10 a.m. and 1 p.m.
- On July 18 and 19, the dew dried well within the 7 to 10 a.m. exposure window. On these two days, maximum kernel set occurred with silk exposure between 7 and 10 a.m.
- For all four days, peak kernel set occurred shortly after the dew dried and decreased throughout the day (Figure 3).
- Total kernel set by day was consistent with perceived pollen densities in the field. Pollen densities appeared to be heavy during July 16 and 17, started to decline on July 18, and were substantially lower on July 19.
- Total kernel set with silk exposure on July 16, 17, and 18 was good, while kernel set with silk exposure on July 19 was reduced.

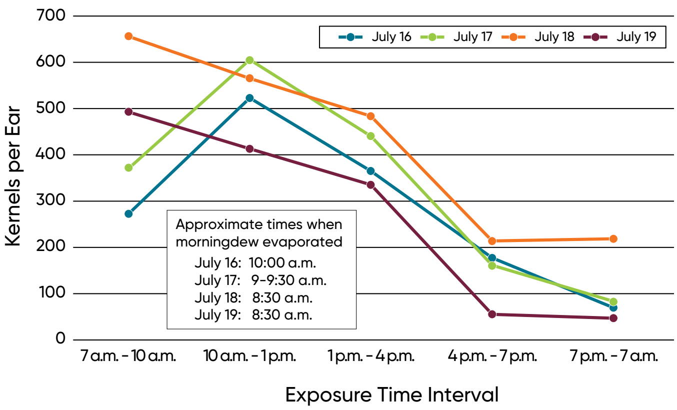


Figure 2. Kernels set per ear with silk exposure to pollination at different times of day.

- According to Nielsen (2018), maximum pollen shed occurs on the second day of tassel shed and progressively decreases daily as the tassel completes its pollination life cycle.
- These field results for kernel set are consistent with the pollen shed information published by Nielsen (2018).
- For all four days, little kernel set occurred when silks were exposed during the 7 p.m. to 7 a.m. time interval. It could be that pollination occurred during the evening hours before the nighttime dew settled. No observations were recorded for when the nighttime dew appeared.

Conclusions

- Pollen release from anthers requires two events. First, pollen grains mature inside anthers. Secondly, pores of anthers open to release pollen.
- If anthers are dry, anthers open very shortly after pollen grains mature. Results of this study suggest that pollen grains mature inside anthers throughout the day and night.
- Successful kernel set throughout the day suggests anthers release pollen throughout the day because pores open shortly after pollen grains mature.

- Although pollen grains continue to mature during the night, few pollen grains are released during the night because nighttime dew keeps anthers too moist to open.
- Moist anthers retain pollen until the morning dew evaporates and then release newly matured pollen as well as stored mature pollen.
- Release of these stored pollen grains creates the opportunity for maximum pollen shed during the morning after the dew has dried.
- This sequence also explains why anthers do not shed pollen on rainy days or on days with high humidity but will shed a relative abundance of pollen on the next dry day or when anthers have the opportunity to dry.

Acknowledgement

We would like to thank Phil Prybill for supplying the corn hybrid and the land to conduct this study.

Figure 3. Representative ears showing the results of silk exposure to pollen at specific time intervals.

return to table of contents

Functions of Water in Corn Growth and Development

Stephen Strachan, Ph.D., Former Research Scientist

Summary

- In Midwest environments, corn requires about 25 acre-inches (680,000 gal/acre) of water during its growing season.
- Approximately 400,000 gallons of water per acre transpire through corn plants while the remainder evaporates from the soil surface.
- Water serves four major functions in corn production:
  - Evaporative cooling to maintain proper plant temperatures for growth
  - Carrier for nutrient and sugar transport
  - Hydraulic force for cell growth, development, and expansion
  - Source of hydrogen for sugars, starches, and plant cell components
- Managing water to supply the correct amount of water at the proper time is essential to produce maximum grain yields.

Managing Water for Corn Production

Water, whether provided via rainfall or irrigation, is essential for corn production. In the Midwestern Corn Belt, a successful corn crop consumes approximately 25 acre-inches of water (680,000 gallons of water per acre) during its life cycle (Strachan and Jeschke, 2017). According to research at Iowa State University (Licht and Archontoulis, 2017), approximately 55-60% of this water (about 400,000 gallons per acre) transpires through the corn plant while the remainder evaporates from soil.

If the field yields 300 bushels per acre, corn plants transpire a little over 1,300 gallons of water for each bushel of grain. On a per plant basis, if the field population is 32,000 plants per acre, each corn plant transpires about 12.5 gallons of water between germination and maturity. If we also include the amount of water lost through evaporation from soil, each bushel of corn requires about 2,300 gallons (about 19,000 pounds) of water or a little over 21 gallons of water per corn plant. If we assume a 300 bushel per acre yield and a nitrogen conversion factor of 1.1 pounds of N per bushel of corn, the water to nitrogen use ratio is about 58:1 (19,000 pounds of water/330 pounds of nitrogen) (Table 1).

Although water is often viewed as a "resource", corn producers may need to think of water more as a "nutrient" that should be managed. Climatologists are predicting more occurrences of extended periods of excessive rainfall and periods of dry and droughty conditions. Corn producers may need to adapt their water management programs to continue to produce corn under these more varied and stressful environments. A better understanding of what water does in the corn plant contributes toward making the correct decisions.

Functions of Water in Corn Production

Water serves four main functions in the corn plant. These are:

1. Evaporative cooling to maintain plant temperature
2. Carrier for nutrient and sugar transport
3. Hydraulic force for cell growth, development, and expansion
4. Source of hydrogen for sugars, starches, and plant cell components

1. Evaporative Cooling

Temperature is a measure of the average speed of molecules in a system. The more heat that is applied to a system, the faster the molecules move, and the higher the temperature. As the faster-moving molecules escape from the system these molecules do two things – they extract heat from the system as they escape, and their leaving the system reduces the average speed of the molecules left behind in the system thus reducing the temperature.

Table 1. Resources (water and nutrients) required to produce a 300 bu/acre crop of corn grain.

Resource	Content (15.5% moisture)	Removal (300 bu/acre)
	lbs/bu	*lbs*
Water from soil[a] (evap. + transp.)	18,800	5.6 million
Water transpired through the plant[b]	11,100	3.3 million
Oxygen (O)[c]	21.4	6,430
Carbon (C)[c]	21.0	6,290
Hydrogen (H)[c]	2.85	857
Nitrogen (N)[d]	0.615	185
Phosphorus (P_2O_5)[d]	0.428	128
Potassium (K_2O)[d]	0.273	81.9
Magnesium (Mg)[d]	0.0733	22.0
Sulfur (S)[d]	0.0506	15.2
Calcium (Ca)[d]	0.0132	3.96
Iron (Fe)[d]	0.00168	0.504
Zinc (Zn)[d]	0.00126	0.378
Boron (B)[d]	0.00028	0.084
Manganese (Mn)[d]	0.00023	0.069
Copper (Cu)[d]	0.00015	0.045
Molybdenum (Mo)[e]	Trace	Trace
Chlorine (Cl)[e]	Trace	Trace

[a]Strachan and Jeschke, 2017; [b]Light and Archonoulis, 2017; [c]Latshaw and Miller, 1924; [d]Heckman et al., 2003; [e]Salisbury and Ross, 1978.

Water has a tremendous ability to absorb heat. One gram of water removes 540 calories of heat energy as the water converts from liquid water to water vapor. Sunlight generates heat. Corn plants grow most rapidly at about 86°F (30°C). Their rate of growth slows dramatically as plant temperatures exceed 86°F (30°C). During those hot summer days, corn plants must transpire a lot of water to maintain optimal operating temperatures. As this water evaporates, the faster-moving liquid water molecules within stomatal enclosures convert to molecules of water vapor and escape into the atmosphere through stomatal openings (Figure 1).

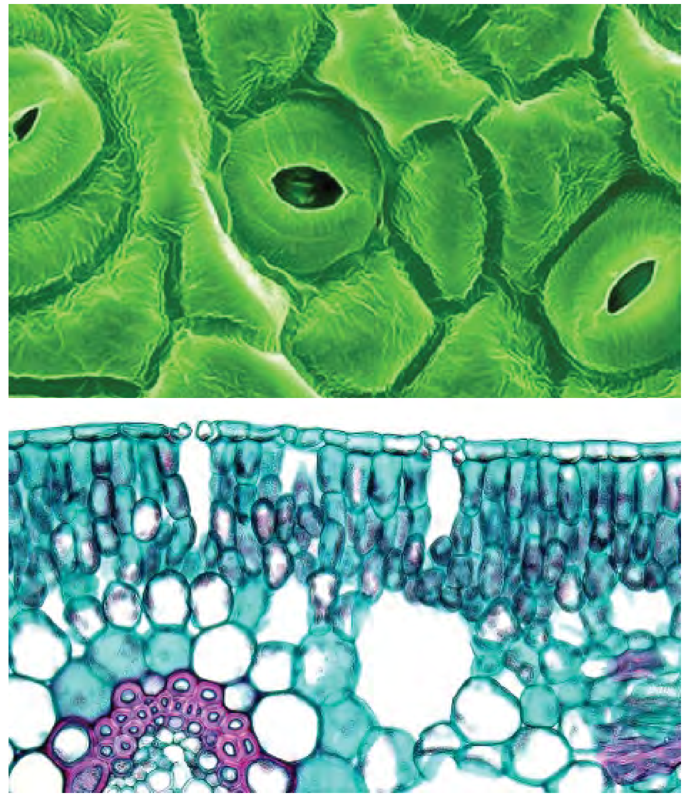


Figure 1. (A) Stomatal pores and stomatal chambers. Stomatal pores allow for the exchange of water and CO_2 between the atmosphere and leaf internal structures. (B) Stomatal chambers serve as locations where liquid water converts to water vapor for subsequent escape into the atmosphere through stomatal pores.

Corn has a high capacity to exchange water and carbon dioxide with the atmosphere. There are approximately 36,000 stomates per square inch on the upper leaf surface and approximately 50,000 stomates per square inch on the lower leaf surface of a corn leaf (Dodd, 2020). As these molecules of water vapor exit through plant stomata, they remove heat from the system, reduce the average speed of water molecules remaining in the corn plant, and reduce the plant temperature (Figure 2).

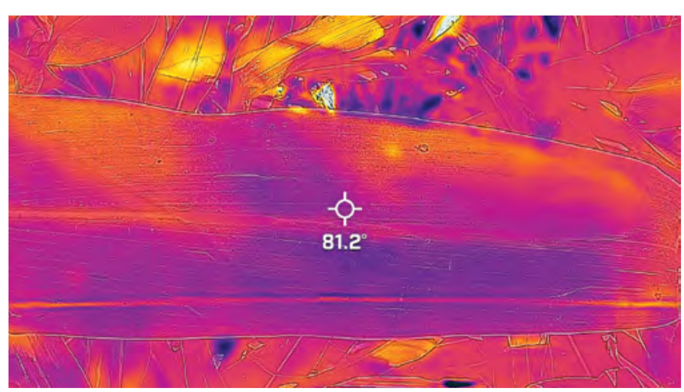


Figure 2. Infrared imagery of a corn leaf showing the capacity of evaporative cooling to maintain plant temperature. Leaf temperature (81.2°F, 27.3°C) is nearly ten degrees (F) lower than the ambient air temperature (91°F, 32.8°C).

2. Carrier for Nutrient and Sugar Transport

Water carries and moves nutrients, sugars, and other plant products throughout the corn plant. How fast does water move in the corn xylem? There appears to be no literature reference to answer this question for corn. However, in trees, peak xylem velocity is about 10 to 30 inches per minute for trees with large xylem vessels and about 0.5 to 4 inches per minute for trees with small xylem vessels (Taiz et al., 2014). It is therefore reasonable to assume that maximum water velocity in corn xylem is likely in the range of 0.5 to 4 inches per minute. Nutrients that readily move with water could easily move from the corn root to the tassel or ear within a day. Nitrogen is a highly water-soluble nutrient. This explains why corn appears to "green up" relatively quickly after nitrogen fertilizer is applied as a sidedress treatment to emerged corn.

The driving force for water movement through the xylem is water evaporation through stomata. A corn's vascular system permeates the entire corn plant, and many vascular bundles pass very closely to plant stomata (Figure 1). The vascular system consisting of xylem and phloem rapidly moves water and nutrients long distances in the corn plant. However, water movement from cell to cell is much slower because cellular membranes inhibit water movement.

3. Hydraulic Force for Cell Growth

Water in a plant cell behaves just like oil in a hydraulic cylinder. As the cell grows, the cell pulls in ionic nutrients, produces and consumes sugars, and generates many complex organic molecules and organelles during the growth process. All of these cellular components pull water into the cell through a myriad complex of ionic charge and hydrogen bonding interactions with water molecules. As water is pulled into the cell, this additional water creates hydraulic pressure that pushes outward against the cellular membrane and expands the membrane just like additional oil in a hydraulic cylinder pushes against the cylinder piston to extend the piston rod. Plant cells continue to expand until the call wall forms. The rigid cell wall defines the size and shape of a plant cell during the remainder of the plant life cycle. In dry or drought-stressed environments, less water is available to support cell growth and expansion. The consequence of this is small or severely stunted corn.

4. Source of Hydrogen

Hydrogen is an essential nutrient that comprises approximately six percent of the final corn weight. All of the hydrogen in a corn plant is derived from water. During photosynthesis, the water molecule (H_2O) is split to form hydrogen (H) and oxygen (O). The hydrogen atoms are first incorporated into simple sugars, and these sugars are subsequently modified and incorporated to form all of the organic molecules and cellular components in the plant. The corn plant uses some of the oxygen to support respiration, but most of the oxygen is released into the atmosphere as molecular O_2.

$$6\ CO_2 + 6\ H_20 \xrightarrow{\text{photosynthesis}} \underset{\text{(Sugar)}}{C_6H_{12}O_6} + 6\ O_2$$

Managing Water to Maximize Corn Grain Yield

Water is essential for corn growth. Water: (1) helps to cool the corn plant to maintain temperatures supportive of rapid growth, (2) carries nutrients, sugars, and other essential molecules throughout the plant to support growth, (3) supplies the turgor pressure or hydraulic force for cell growth, development, and expansion, and (4) supplies hydrogen for incorporation into chemical compounds and cellular components.

A restriction in activity of any of these four processes reduces corn growth and grain yield. Water must therefore be managed. If excess water is present, this water must be rapidly removed because corn does not grow in flooded soil. Tiling fields and reducing tillage improves water permeation through soil. Reducing tillage allows soils to develop more structure and better retain naturally forming drain channels resulting from animal activity (for example: earthworms) and decaying plant roots. When water is limited, irrigation is often the first choice to supply water. For all corn producers, reducing water loss via evaporation from the soil surface also increases the amount of plant-available water. A management program that retains mulch or plant residue on the soil surface slows water loss via evaporation from the soil. Another management tool to retain water is to increase soil organic matter. Soil organic matter acts like a sponge in soil and can retain substantially more plant-available water than the soil mineral fraction.

return to table of contents

Corn Leaf Removal Impact on Yield and Stalk Quality

Nate LeVan and Troy Deutmeyer, Pioneer Field Agronomists, and Dan Berning, Agronomy Manager

Key Findings

- The impact of leaf removal on yield and late season stalk integrity is highly dependent on which leaves on the plant are removed.
- Yield components of kernel number and ear weight were both affected by loss of leaf area at the R4 and R5 stage of crop development.
- This study demonstrated the importance of protecting the crop from leaf area loss as late as the R5 stage of crop development.

Figure 1. All leaves below the ear removed at R3 stage of crop development.

Objectives

- Loss of healthy leaf area in corn due to factors such as foliar diseases, pest infestations, or hail damage reduces the supply of photosynthate for filling the ear, which can reduce yield.
- Lost leaf area can also lead to reduced stalk quality and standability as the plant remobilizes carbohydrates from the stalk to compensate for the reduction in photosynthesis.
- Field demonstrations were conducted in Iowa in 2022 in which leaves were removed from corn plants during grain fill to show the effects of reduced leaf area on yield and stalk quality.
- In one demonstration, leaves were removed at the R2-R3 development stage and in the other at the R4 stage and R5 stage.

Leaf Removal at R2-R3

- Leaves were removed at R2-R3 stage of crop development at 3 locations across north-central Iowa in 2 different hybrids at each location to reduce photosynthetic area. Four separate leaf removal treatments were compared:
  - All leaves below the ear (Figure 1)
  - Ear leaf only
  - All leaves above the ear (Figure 2)
  - No leaves removed (check)
- Each treatment block consisted of 4 rows by 17.5 feet.
- Harvest yield was determined by weighing the ears in each treatment, measuring the grain moisture, and correcting the yield to 15.5% grain moisture.

Figure 2. All leaves above the ear removed at R3 stage of crop development.

return to table of contents

Leaf Removal at R2-R3 – Results

- Removing **ear leaf only:**
  - No change in grain moisture (Figure 3).
  - 1% reduction in ear weight and grain yield (Figure 4).
  - No effect on stalk quality.
- Removing the **leaves below the ear:**
  - No change in grain moisture.
  - 4% reduction in ear weight and grain yield.
  - No effect on stalk quality.
- Removing the **leaves above the ear:**
  - 0.53% dryer than the check.
  - 22% reduction in ear weight and grain yield.
  - Significant amount of stalk cannibalization.

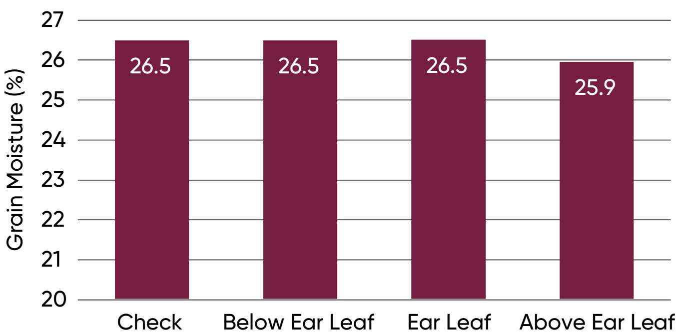


Figure 3. Grain moisture (bu/acre) of defoliation treatments averaged across 3 north-central Iowa locations.

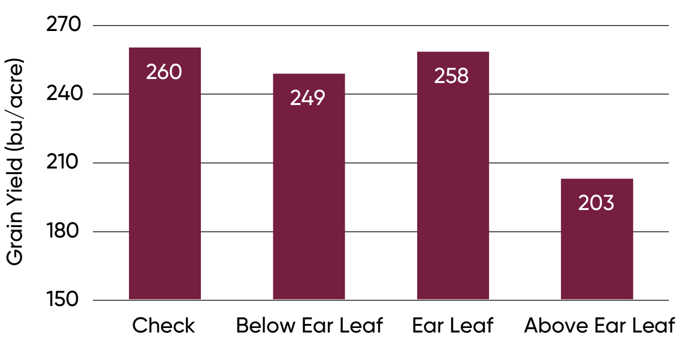


Figure 4. Grain yield (bu/acre) of defoliation treatments averaged across 3 north-central Iowa locations.

Figure 5. Plant health comparison at harvest.

Leaf Removal at R4 and R5

- Leaves were removed at R4 and R5 stage of crop development at 1 location in northeast Iowa on one hybrid to induce loss of photosynthetic area. Four separate treatments were compared:
  1. All leaves below the ear
  2. Ear leaf only
  3. All leaves above the ear
  4. No leaves removed (check)
- The field was sprayed at brown silk with fungicide and again 21 days later to prevent foliar disease development.
- Harvest yield was determined by weighing 20 ears in each treatment, measuring the grain moisture, and correcting the yield to 15.5% grain moisture.
- Five random ears from each treatment were used to determine average kernel row number and length of each treatment.

Leaf Removal at R4 and R5 – Results

- Removing leaves above and below the ear leaf at the R4 stage of development tended to have a greater impact on yield loss than defoliation at R5.
- Removing the **ear leaf only:**
  - 1.5% reduction in ear weight at R4 removal (Figure 4).
  - 3.0% reduction in ear weight at R5 removal.
  - No effect on stalk quality (Figure 5).
- Removing the **leaves below the ear:**
  - 12.0% reduction in ear weight at R4 removal.
  - 6.8% reduction in ear weight at R5 removal.
  - Little to no effect on stalk quality.
- Removing the leaves **above the ear:**
  - 27.7% reduction in ear weight at R4 removal.
  - 19.8% reduction in ear weight at R5 removal.
  - Significant amount of stalk cannibalization with both timings (Figure 6).

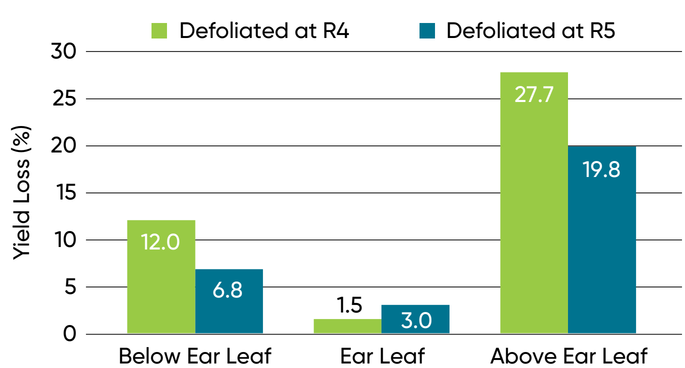


Figure 6. Percent yield loss with defoliation at R4 and R5 at the northeast Iowa demonstration location.

Figure 7. Stalk integrity comparison at harvest.

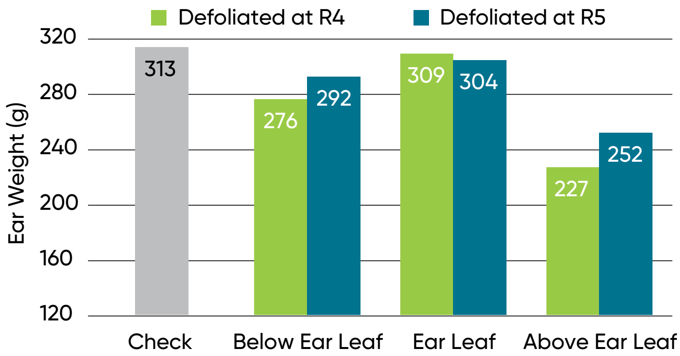


Figure 8. Ear weight with defoliation at R4 and R5 at the northeast Iowa demonstration location.

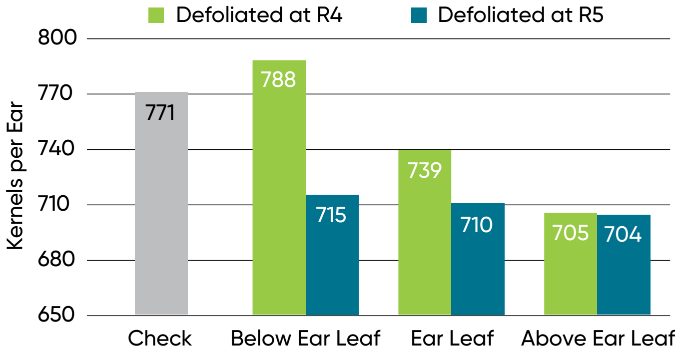


Figure 9. Average kernel count per ear with defoliation at R4 and R5 at the northeast Iowa demonstration location.

Conclusions

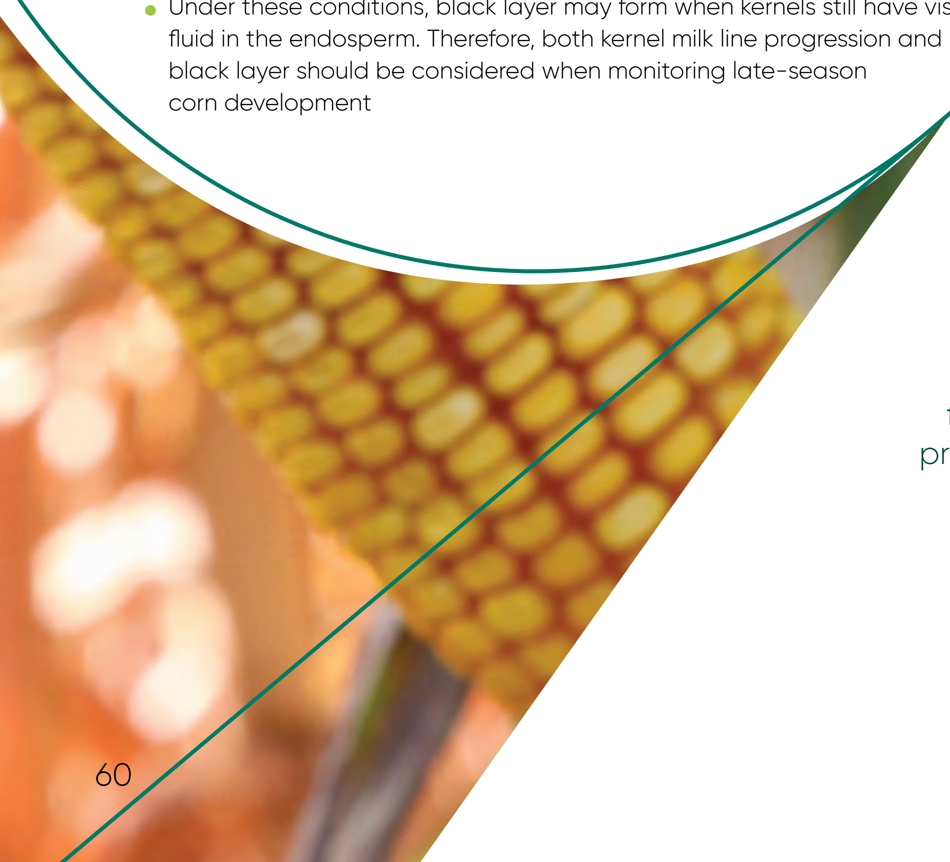
- Both demonstrations illustrate the ENTIRE canopy is important to final yield, even as late as the R5 stage of crop development.
- Growers should proactively protect healthy leaf area with fungicide applications when there is a risk a foliar disease infestation reaching an economic level.
  - Some diseases, such as tar spot, have a two-week incubation period and can develop very rapidly. It is important to recognize and consider this in a scouting and treatment plan.
  - If enough leaf area is lost prior to grain physiological maturity, it can lead to solubilization and remobilization of the carbohydrates in the stalk. This can result in poor late season stalk integrity, stalk lodging and harvest issues.

Kernel Black Layer Formation in Corn:

Anatomy, Physiology, and Causes

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

- The corn kernel "black layer" is widely used as an indicator of physiological maturity. Knowledge of the anatomical and physiological processes surrounding black layer development is useful to understand conditions that cause its formation.
- The black layer forms when a layer of cells compress and turn dark where the kernel attaches to the cob. Specialized nutrient transfer cells at the base of the kernel also collapse, and this barrier stops movement of sugars into the kernel.
- Several field and lab experiments confirmed that black layer forms whenever sucrose supply to the developing kernel is decreased to a threshold level.
- Factors that stop this flow include plant maturity – but also leaf loss due to hail, frost, and disease, plus periods of very cool temperatures (without frost) during grain fill.
- Under these conditions, black layer may form when kernels still have visible fluid in the endosperm. Therefore, both kernel milk line progression and black layer should be considered when monitoring late-season corn development



The black layer usually forms first in the tip kernels with progression ***a few days later*** to the large kernels at the base.

return to table of contents

Introduction

Agronomists widely use the corn kernel "black layer" as an indicator of physiological maturity. It is also generally known that visible factors, such as green leaf loss or defoliation due to hail, frost, or disease can cause the black layer to form earlier than with the normal maturation process. It is less recognized that periods of very cool weather (without frost) during grain fill can also cause the black layer to form early. Little background information is readily available on the anatomical and physiological processes surrounding black layer formation. In this article, these aspects of corn development will be highlighted from a historical perspective on how the science behind this knowledge evolved.

Early Anatomical Observations

One of the first reviews of the black layer concept was in a paper on corn susceptibility to kernel rots in the 1930s in which the formation of a black "closing" layer was described in the placental region of maturing corn kernels (Johann, 1935). The structure of the black layer was detailed in the 1950s by Nebraska scientists Kiesselbach and Walker (1952).

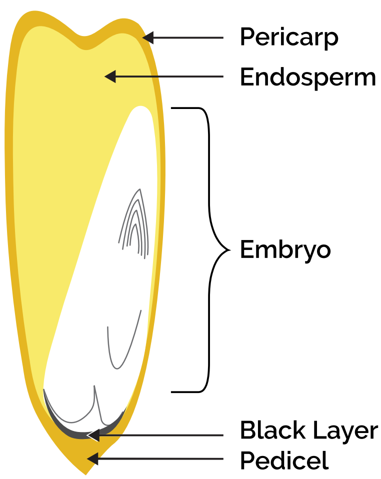


Figure 1. Anatomy of a corn kernel showing key structures involved in black layer formation near physiological maturity. The black layer forms in a region of cells several layers thick between the endosperm base of the kernel and the vascular area of the pedicel.

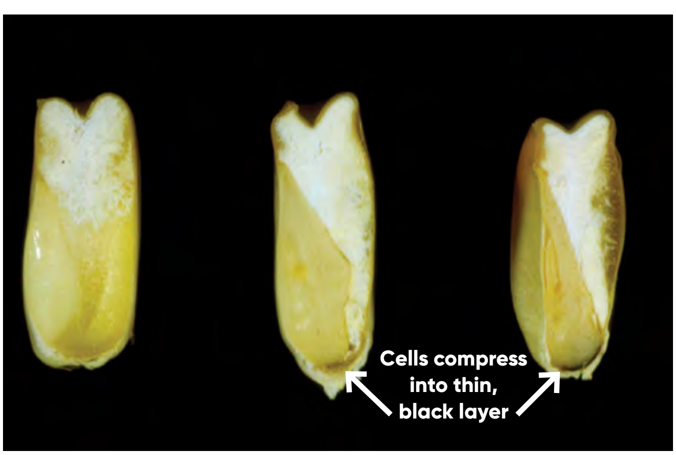


Figure 2. Close view of progression in color changes in the placental region of the corn kernel as cells compress or collapse into a dense layer, which eventually appears visibly black.

Glossary of Terms

Endosperm - Tissue which surrounds the developing seed embryo and provides food for seed growth

Pedicel - Structure that attaches the kernel to the cob

Pericarp - Outer wall of the kernel (seed)

Physiological Maturity - When the crop has reached maximum possible grain yield and kernel growth is complete

Placenta - Part of the ear where the developing kernels (or ovules) are attached to the cob

Suberized - Deposition of suberin on the walls of plant cells; suberin is a waxy, waterproof substance

Testa - Seed coat

Translocation - Conduction or movement of soluble food from one part of the plant to another

Vascular Area - Plant tissues specialized for moving water, dissolved nutrients, and food from one part of a plant to another

In early seed development, a black layer forms in a region of cells several layers thick between the endosperm base of the kernel and the vascular area of the pedicel (see Figures 1-4). Near physiological maturity, these cells compress or collapse into a dense layer, which appears visibly black. Concurrently, the cells at the base of the endosperm also become crushed. These are specialized vascular cells, which absorb and transfer to the kernel plant nutrients plus sucrose and other sugars produced by the plant in photosynthesis. This stops their capability for movement of sugars and nutrients from within the plant into the kernel. A suberized barrier forms around the seed tip when the black layer connects with the kernel pericarp (outer wall) and testa (seed coat).

Figure 3. Progression of black abscission layer formation.

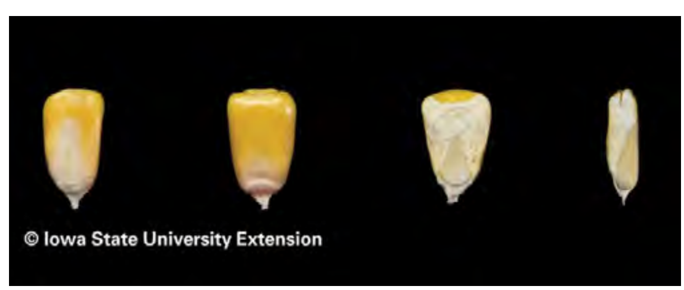


Figure 4. Kernels from a R6 plant showing embryo (germ), endosperm (starch), and black layer.

Within the ear, the black layer usually forms first in the tip kernels with progression a few days later to the large kernels at the base. Canadian researchers (Daynard and Duncan, 1969) proposed that as a survival mechanism when food supply (sugars produced in photosynthesis and other nutrients) to the ear is limited from the rest of the plant, these resources are apportioned within the ear so that some kernels can develop fully while others abort early or are "shut off" from the translocation pathway by formation of the black layer. These limits would likely be greatest for the tip kernels, which are last to be pollinated and farthest from the food sources within the plant. This led to the hypothesis that black layer forms whenever movement of sugars and other plant nutrients to the kernel is decreased to a threshold level, either due to plant stresses, which reduce supply of sugars produced by photosynthesis for the plant, or due to plant maturity when the plant stops photosynthesis and soil nutrient uptake under favorable growing conditions.

In the late 1960s and early 1970s, researchers reported that black layer formation occurred after an extended period of cool weather – before either leaf disease or frost had reduced green leaf area or before plant maturity. Raymond Baker, the first Pioneer corn breeder and author of an early popular press article on black layer development, stated "An extended period of cool weather in the fall when the daily average temperatures stay below 55°F for a week will usually stop growth without an actual freeze" (Baker, 1970). In Ontario in 1969 and 1970, premature black layer formation developed one to four days after a week with daily maximum average temperatures of 55°F or less (Daynard, 1972).

Minnesota Physiology Studies Explore Black Layer Causes

These observations led Minnesota researchers to evaluate the cause of corn black layer formation by conducting both field defoliation and lab experiments. In the lab experiment, both temperature and sucrose movement into developing kernels could be varied (Afuakwa et al., 1984). Defoliation limits sucrose supply by reducing the plant's photosynthetic capacity. Previous research had shown that cold weather greatly slows or stops translocation, or movement, of sucrose within the plant, which would reduce availability to the kernels. Sucrose supply could be directly evaluated by culturing kernels in a lab with or without sucrose.

Field defoliation experiments showed that black layer development occurred at a range of grain moistures, kernel sizes, and calendar days or heat units (Figures 5 and 6). Early loss of leaves caused black layer to form at higher grain moistures, lower kernel weight, and with reduced days or heat units than normal.

Kernel moisture when black layer formed ranged from 32% for plants grown in the field to 76% for kernels developing under controlled lab conditions at 86°F without sucrose (Figure 7). Calendar days from pollination to black layer appearance ranged from 29 days at 86°F in the lab without sucrose to 65 days under cool temperatures (50°F and 59°F). Black layer formed when kernel weight averaged 45 mg when cultured at 86°F without sucrose to 270 mg for field-grown plants.

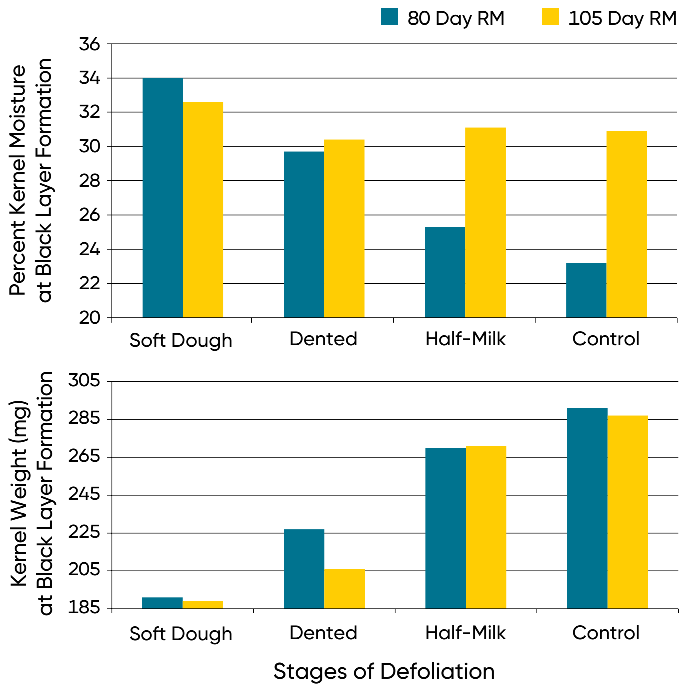


Figure 5. Adapted from Afuakwa et al., 1984. Percent kernel moisture at corn black layer formation following defoliation at three growth stages **(top).** Effect of defoliation at three growth stages on corn kernel weight at black layer **(bottom).**

Values are averages of two years and two hybrids for each Relative Maturity (RM).

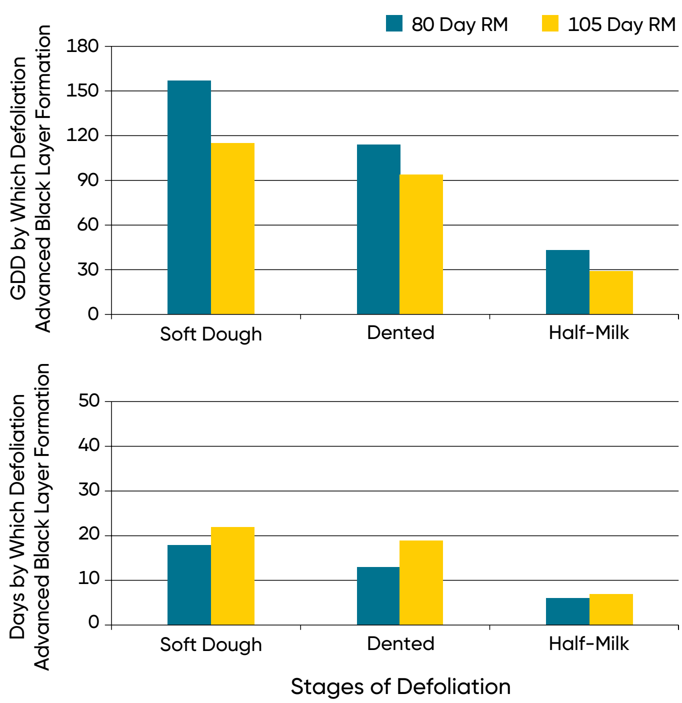


Figure 6. Adapted from Afuakwa et al., 1984. Number of Growing Degree Days (GDD) **(top)** and number of calendar days **(bottom)** by which defoliation advanced corn black layer formation.

Values are averages of two years and two hybrids for each Relative Maturity (RM).

return to table of contents

Kernels from plants grown in the field or in the lab with both higher temperatures and high sucrose supply had dented, and kernels were without visible endosperm liquid when the black layer developed. However, when the black layer appeared for lab-cultured kernels without sucrose, there was no denting or clear milk line. Contents were becoming firm but still were moist throughout the endosperm.

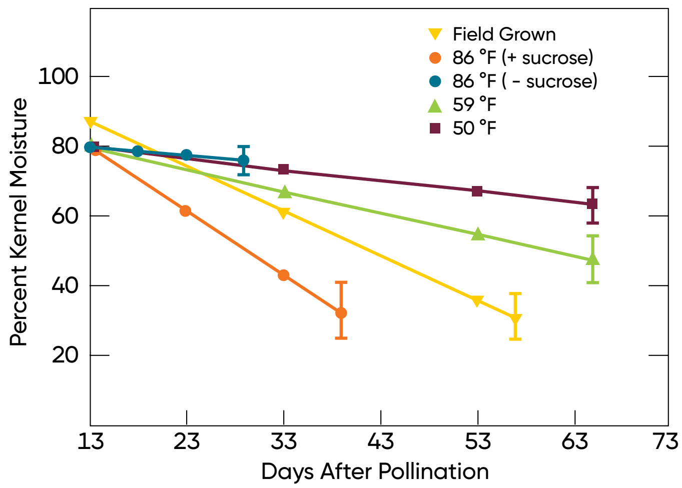


Figure 7. Adapted from Afuakwa et al., 1984. Effect of temperatures and sucrose availability on percent corn kernel moisture of in vitro (lab) grown corn kernels.

Percent kernel moisture of field-grown kernels is included for comparison (maroon line with triangles). Measurements stopped once kernel black layer had formed in more than half of the kernels sampled. Vertical bars are shown only for the last sampling period and show one standard error of the mean.

Sucrose Supply is Key Factor

These results confirmed that black layer formation is more related to continuous sucrose supply to the developing kernel than any specific environmental sequence or physical aspect of the kernel. The researchers concluded that conditions that reduce this supply could also impact flow to kernels of other metabolism products or hormones, but sucrose supply to the developing kernel appears to be a key factor.

Monitor Both Milk line and Black Layer

While disappearance of milky kernel contents can be an indicator of physiological maturity (Afwaukwa and Crookston, 1984; Figure 8) in northern regions with cool weather periods during grain-fill or when other factors, such as major leaf loss or stalk breakage, cause reduced photosynthesis or plant death, black layer may appear in kernels that still have visible fluid in the endosperm. In these instances, the milk line may disappear, and the entire kernel tends to become soft or doughy. Grain drying will occur without the usual milk line progression (Figure 9).

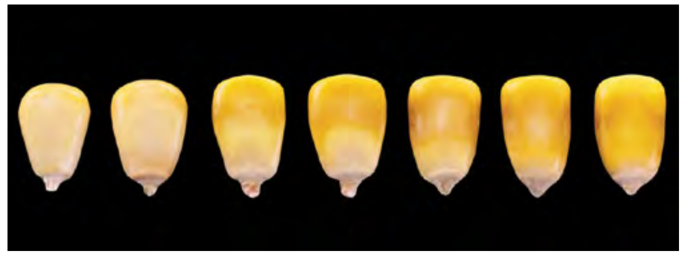


Figure 8. Progression of milk line in corn kernels from R5, or early dent, **(left)** to R6, or physiological maturity, **(right).** *Photo courtesy of Steve Butzen, Pioneer.*

Figure 9. Plant death due to stalk breakage causes corn milk line to disappear and black layer to form without the usual progression of milk line to the base of the kernel. Similar responses can occur with major leaf loss or extended periods of cool temperatures. *Photo courtesy of Dr. R.L. Nielsen, Purdue University.*

return to table of contents

Kernel Weight Differences by Hybrid in Iowa

Ryan Van Roekel, Ph.D., Dennis Holland, Alex Woodall, Bill Long, Matt Vandehaar, and *Nate LeVan, Pioneer Field Agronomists,* and *Jason Kienast, Sales Representative*

Key Findings

- Kernel weight is a key component of grain yield that can vary by hybrid and be affected by environmental conditions and management practices.
- A six-year field study found that kernel weight can vary widely due to differences in growing conditions (from 52,000 to 137,000 kernels/bu) but that certain hybrid families consistently have higher or lower kernel weights than average.
- These estimates for kernel weight by hybrid family can be useful for yield estimation, management decisions, and diagnosing yield results that differ from expectations.

Background

- Corn grain yield is related to the number of kernels per acre and the weight of those kernels.
- Kernel number is generally regarded as the most important component in determining yield and the most responsive component to environment and management.
- However, large variations in observed kernel weights suggest that this yield component can also have a large effect on yield.
- Kernel weight is considered a heritable trait and is known to vary between hybrid families.
- Kernel weight at harvest can be affected by the crop's ability to set a high potential kernel weight in the weeks immediately following silking, and its capacity to reach that potential during the grain fill period.
- Corn has a limited ability to increase kernel weights once the potential has been set (unlike soybean) so it is important to maximize potential kernel weight.
- To achieve big kernels at harvest, favorable management and conditions are required within the first 20 days after silking in order to set a large potential kernel weight, followed by favorable conditions during grain fill that will allow the corn to reach that full potential.
- When late season stresses occur, corn is very sensitive to grain fill stress due to its relatively limited ability to remobilize resources to fill kernels compared to other crops like soybean and wheat.
- As such, it is common for a late season drought or nutrient deficiency to reduce kernel weights at harvest, even for hybrids that normally have large kernels or when conditions were favorable to set a high kernel weight potential soon after pollination.

Yield Estimation Considerations

- Corn grain yield can be estimated in-field based on estimates of yield components: ears per acre, kernels per ear, and kernel weight.
- The first two components are relatively straightforward to estimate – conducting several stand counts of 1/1000th of an acre can provide an estimate of ears per acre and kernel counts can be used to estimate kernels per ear.
- Furthermore, new technology has greatly improved the speed and accuracy of estimating the first two of the components:
  - UAV imagery powered by Drone Deploy can provide field-wide stand counts.
  - The Yield Estimator tool in the Granular Insights app will quickly count kernels per ear.
  - The Vegetation Index from satellite imagery in Granular Insights can be used to guide sampling according to field variability to get a better estimate of whole-field yield.
- However, estimating the third yield component, kernel weight, remains challenging.
- A common practice is to assume 90,000 kernels/bushel, but this practice often underestimates yield and does not consider differences among hybrids or environments.
- While work is underway to develop a more reliable way to estimate kernel weights, research was undertaken to characterize common hybrid families in local plots to provide an estimate as to how genetics influence kernels weights under normal management to provide more accurate yield estimates.
- Additionally, knowing a hybrid's expected kernel weight can help with understanding the yield impact of late-season management or environmental issues that may prevent a hybrid from reaching its normal kernel weight.

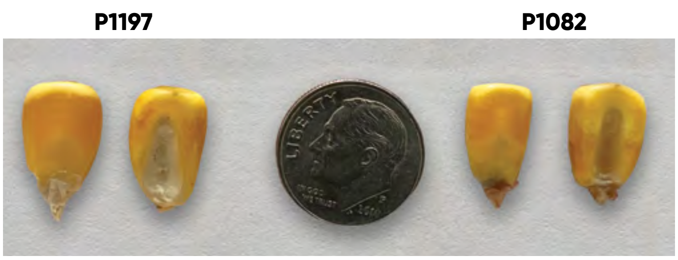
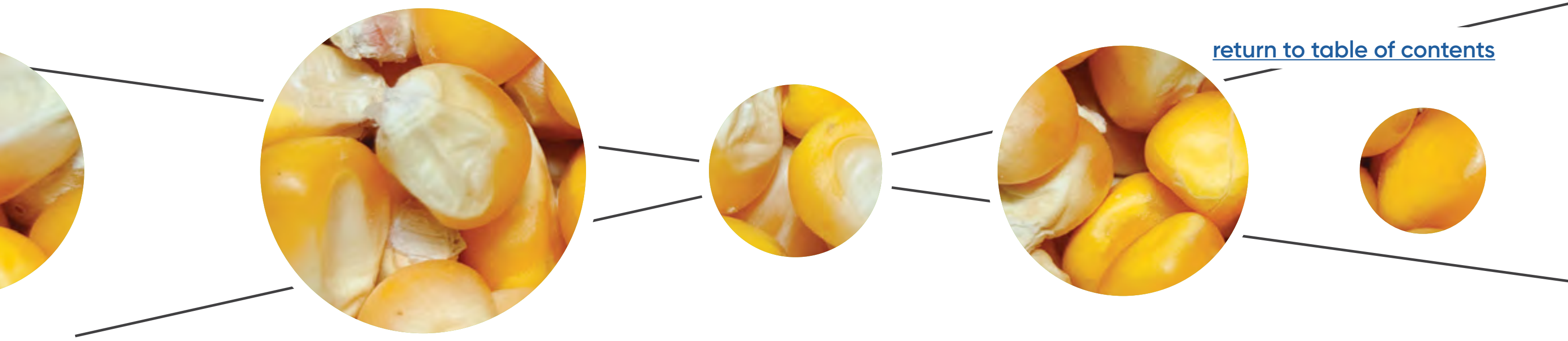


Figure 1. Representative kernels from the middle of an ear from hybrid families with above-average (P1197) and below-average (P1082) kernel weight. *Photo courtesy of Bill Long in 2019.*

return to table of contents



Study Description

- Kernel weight data was collected from a selection of plots across Iowa from 2016 to 2021.
- Kernel weights for each hybrid at a location were measured in one of two ways:
  - » A subsample of 100 random kernels, or more, were weighed and corrected to 15% moisture.
  - » Multiple stand, ear, and kernel counts were performed prior to harvest to provide a reasonably accurate estimate of ears per acre and kernels per ear. This data was divided by the hybrid's yield at 15% to determine kernels per bushel.
- Both methods have limitations, but hybrid trends were consistent, and the datasets were combined to increase the number of locations.
- A location average kernel weight was calculated from the average of all hybrids at each plot location.
- To account for environmental differences between locations, a relative kernel weight for each hybrid within a location was calculated as a percentage of the location average. Those percentages were then averaged by hybrid family over all plot locations, as shown in Table 1.
- The standardized kernels per bushel in Table 1 were calculated as 80,000 kernels/bu divided by the relative kernel weight percentage to provide a reasonable estimate for kernels/bu by hybrid family. This value is not the actual mean of the observed kernels/bu because the dataset is unbalanced for locations between hybrids. As such caution should be used with these results.

Results

- Kernel weight (kernels/bu) was found to vary widely by hybrid, location and yield level.
- The grand mean of all kernel weight observations was 82,124 kernels/bu but ranged from 52,192 to 136,518 kernels/bu. Grain yield averaged 217.3 bu/ac with a range from 116.2 to 297.3 bu/acre.
- Individual hybrids also had a wide range in kernel weights between locations. For example, the P1197 family ranged from a high of 54,656 kernels/bu down to 115,749 kernels/bu. However, across all locations, its kernel weight averaged 105.7% of the location average.
- On average, there was a trend for higher yields to be associated with higher kernel weights (Figure 2).

Table 1. Kernel weight as a percentage and standardized kernels/bu by hybrid family.

Hybrid Family	Kernel Weight (% of Loc. Mean)*	Standardized Kernels per Bushel**	# Loc.
P9492	91.0	88,000	4
P9823	102.0	78,500	6
P0075	101.8	78,500	33
P0220	101.3	79,000	36
P0306	106.0	75,500	39
P0339	104.8	76,500	39
P0404	102.2	78,500	10
P0421	104.4	76,500	35
P0589	103.4	77,500	43
P0595	101.5	79,000	31
P0622	102.7	78,000	42
P0688	94.7	84,500	46
P0720	104.2	77,000	9
P0924	105.2	76,000	12
P0953	101.3	79,000	17
P0977	102.8	78,000	30
P0995	99.6	80,500	5
P1082	97.7	82,000	47
P1093	90.1	89,000	53
P1108	101.8	78,500	31
P1185	96.5	83,000	50
P1197	105.7	75,500	61
P1213	104.2	77,000	20
P1222	104.2	77,000	8
P1244	95.1	84,000	24
P1353	97.1	82,500	31
P1359	102.7	78,000	10
P1366	96.1	83,500	78
P1380	100.4	79,500	17
P1563	97.4	82,000	17
P1587	106.5	75,000	12

*Calculated as hybrid kernels per bushel compared to the location average kernels per bushel, then averaged over all locations.

** Calculated as the kernel weight percentage applied to a "normal" value of 80,000 kernels per bushel, rounded to the nearest 500.

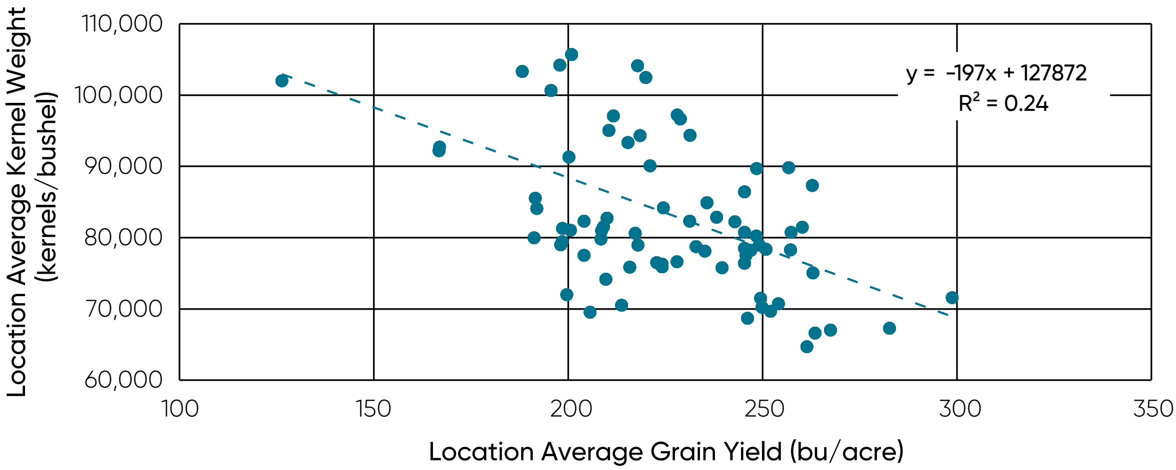


Figure 2. Kernel weight as compared to grain yield on average by location.

Discussion

With the wide variation in observed kernel weights between hybrids and locations, it is important to exercise caution when using the standardized kernels/bu shown in Table 1.

- Environmental and management factors can and will greatly influence a hybrid's ability to maintain its grain fill and express its full kernel weight potential.
    - For example, the location average kernel weight in 2020 was 85,962 kernels/bu due to late-season drought conditions compared to 2019 at 76,950 kernels/bu with more favorable weather.
- Often issues like drought, disease pressure, or nitrogen deficiencies can hinder late season plant health and limit a hybrid's grain fill period and resulting kernel weight.
- When ignoring hybrid interactions and comparing location average kernels/bu to average yield, a correlation was observed where higher yield plots had higher kernel weights (Figure 2).
- The variation in kernel weight compared to yield could be due to the size of the potential kernel weight determined soon after pollination, or the fulfillment of that potential later in grain fill.
    - For example, there is a wide range in average kernel weights for plots that had an average yield near 200 bu/acre.
    - The 200 bu/acre plots with 70,000 kernels/bu were likely near their maximum potential kernel weight, while plots with 105,000 kernels/bu likely had late season stress that prevented them from living up to their potential.
    - Within each of these plots, some hybrids had differing trends for maintaining kernel weight with stress or increasing kernel weight with more favorable conditions, likely by setting a higher potential kernel weight.
- Future work will attempt to document potential kernel weights and then observe their fulfillment by hybrid in differing locations.

It is important to note that high kernel weights are not always required for high yields, especially for some hybrids.

- P1366 is an example of a hybrid family with below average kernel weight that is capable of very high yields (up to 297 bu/acre in this study).
- P1366 tends to achieve high yields through kernel number (more rows around and/or ear length) vs hybrid families like P1197, which tends to have kernel numbers closer to average but high kernel weights.

Also note that kernel weight is not correlated with test weight. Test weight is the weight of a volumetric bushel, while kernel weight is a measure of how many kernels are in a 56 lb bushel.

- An example of this distinction is the P1093 hybrid family, which has very high test weight with excellent grain quality but its high-density kernels tend to be smaller in size and thus weigh less per kernel.

When estimating yields, it is best to stick with an average kernel weight estimate of 80,000 kernels/bu for most hybrids.

- Consider using a lower kernels/bu (i.e., 75,000) for hybrid families like P0306, P1197 & P1587 and higher kernels/bu (i.e., 90,000) for hybrid families like P9492 & P1093.
- If late-season growing conditions are excellent, using a factor of 70,000 kernels/bu may be more appropriate.
- Conversely, if late-season conditions are poor, a factor of 100,000 kernels/bu might be more accurate.
- Be sure to get multiple, accurate estimates of kernels/ear and ears/acre to avoid overestimating yield.

Conclusions

- Kernel weight is a key component of corn grain yield that varies greatly by hybrid and environment.
- Having an idea of a hybrid's normal kernel weight can be useful for more accurate yield estimates.
- This knowledge also helps provide an understanding of how a hybrid makes its yield (kernel number vs kernel weight), which can be useful when making management decisions or when diagnosing yield results that differ from expectations.

return to table of contents

Phantom Yield Loss in Corn – *A Five-Year Nebraska Field Study*

John Mick, Pioneer Field Agronomist

Key Findings

- It is not uncommon to observe lower yield in a portion of a corn field harvested later than the rest, a phenomenon commonly referred to as phantom yield loss.
- Yield declined by an average of 9.1 bu/acre with later harvest in a five-year study in south-central Nebraska.
- Neither the change in grain moisture nor the duration of time between earlier and later harvest had any relationship with the difference in yield.

Lower Yields Observed with Later Harvest

- When harvest is delayed due to weather or other factors, it is not uncommon to observe lower yields in the portion of the field harvested later than the portion harvested earlier, a phenomenon commonly referred to as mystery yield loss or phantom yield loss.
- There are a number of possible reasons why yield may decline or appear to decline with later harvest, including ear drop, stalk lodging, insect feeding, ear rots, harvest loss, and inaccurate yield monitor calibration.
- Dry matter loss resulting from kernel respiration during grain dry down has also been hypothesized as an explanation for lower yields with later harvest dates.
  - However, research on kernel respiration rates does not appear to support this hypothesis as a plausible mechanism for the differences in yield being observed in some cases (Knittle and Burris, 1976; Saul and Steele, 1966).
  - Several Pioneer and university studies have shown no evidence of kernel dry matter loss following physiological maturity (Cerwick and Cavalieri, 1984; Elmore and Roeth, 1996; Licht et al, 2017; Reese and Jones, 1995; Thomison, et al, 2011).
- A Pioneer Agronomy study conducted in 2018 examined the role of harvest loss in differences in yield between earlier and later harvest timings (Leusink and Jeschke, 2019).
  - Yield declined by an average of 8.9 bu/acre with later harvest in this study.
  - Trial locations varied widely in the difference in grain moisture and the number of days between the two harvest timings, neither of which correlated with observed differences in yield.
  - Greater harvest losses were observed with grain moisture levels below 19%; however, measured harvest losses (ears and kernels on the ground) did not fully account for the differences in yield.

Study Description

- A study comparing corn yield between earlier and later harvest timings was conducted over five years in south-central Nebraska.
- At each study location, yield was compared between a portion of the field harvested relatively early and proximal portion of the field planted to the same hybrid harvested later in the fall.
- A total of 34 comparisons were made over the five years of the study, including 11 in 2018, 8 in 2019, 8 in 2020, 6 in 2021, and 2 in 2022.
- Comparisons included 18 different hybrids ranging from 105 to 118 CRM. Ten of the comparisons were in dryland production and 24 were irrigated.
- Grain moisture at the earlier harvest timing averaged 20.7% across locations with a range of 15.3% to 25.3%.
- Grain moisture at the later harvest timing averaged 16.9% across locations with a range of 12.9% to 20.6%.

Results

- Yield declined by an average of 9.1 bu/acre with later harvest in this study (Table 1); a result very similar to the 8.9 bu/acre average decline observed in the 2018 Pioneer Agronomy study.
- Yield differences between harvest timings ranged from a decrease of 29.9 bu/acre with later harvest to an increase of 2.2 bu/acre (Table 1).
- There were no factors that seemed to correlate with or predict yield difference between earlier and later harvest.
  - Neither the change in grain moisture nor the duration of time between earlier and later harvest had any relationship with the difference in yield (Figure 1).
  - Grain moisture at the later harvest timing had no apparent relationship with the difference in yield either, even though greater harvest losses would be expected as moisture dropped below 19%.
  - Calendar date of the earlier and later harvest timings also seemed to have no impact on yield loss.

return to table of contents

Table 1. Harvest date, grain moisture and yield of early and late harvest timings for 34 comparisons over five years.

Year	Harvest Date		Grain Moisture (%)		Yield (bu/acre)		Difference		
	Early	Late	Early	Late	Early	Late	Days	Moisture	Yield
2018	Sept 17	Sept 23	23.1	19.1	231.1	220.5	6	4.0	10.6
	Sept 20	Sept 28	19.7	17.5	213.1	210.4	8	2.2	2.7
	Sept 20	Sept 28	19.9	18.0	232.1	221.4	8	1.9	10.7
	Sept 20	Sept 28	20.1	18.0	243.7	238.4	8	2.1	5.3
	Sept 20	Oct 25	19.6	14.0	260.4	261.2	35	5.6	+0.8
	Sept 23	Sept 26	19.1	17.9	220.5	210.2	3	1.2	10.3
	Sept 24	Oct 16	15.9	15.3	162.1	155.8	22	0.6	6.3
	Sept 25	Oct 17	20.4	19.2	271.2	264.7	22	1.2	6.5
	Sept 25	Oct 15	21.1	15.1	269.5	248.4	20	6.0	21.1
	Oct 2	Oct 24	21.6	16.4	290.5	280.3	22	5.2	10.2
	Oct 16	Oct 27	15.3	15.0	155.8	154.3	11	0.3	1.5
2019	Sept 18	Oct 15	23.4	16.5	255.8	229.1	27	6.9	26.7
	Sept 19	Oct 15	25.3	15.0	203.8	197.9	26	10.3	5.9
	Sept 25	Oct 12	20.0	16.9	230.5	221.4	17	3.1	9.1
	Sept 27	Oct 13	20.9	19.3	236.5	229.7	16	1.6	6.8
	Sept 27	Oct 12	23.5	20.2	250.3	241.4	15	3.3	8.9
	Sept 30	Oct 23	24.0	16.6	264.7	249.9	23	7.4	14.8
	Oct 7	Oct 15	20.2	17.0	193.1	184.0	8	3.2	9.1
	Oct 7	Oct 15	21.5	16.5	192.5	183.6	8	5.0	8.9
2020	Sept 23	Oct 2	22.4	17.0	225.9	196.0	9	5.4	29.9
	Sept 24	Oct 1	23.9	17.8	270.6	266.3	7	6.1	4.3
	Sept 25	Sept 30	20.5	18.9	234.5	226.2	5	1.6	8.3
	Sept 28	Oct 13	21.5	17.0	244.6	229.9	15	4.5	14.7
	Sept 28	Oct 6	24.4	20.6	255.3	246.6	8	3.8	8.7
	Oct 1	Oct 9	19.7	15.9	284.9	280.6	8	3.8	4.3
	Oct 3	Oct 17	17.8	13.4	266.3	253.1	14	4.4	13.2
2021	Sept 20	Oct 10	19.8	18.6	217.9	211.3	20	1.2	6.6
	Sept 27	Oct 10	19	15	220.8	210.8	13	4.0	10.0
	Sept 29	Oct 22	19.8	14.7	265.3	267.5	23	5.1	+2.2
	Sept 29	Oct 22	18.4	12.9	253.5	251	23	5.5	2.5
	Oct 2	Oct 12	20	17.2	269.6	261.2	10	2.8	8.4
	Oct 2	Oct 12	22	18.7	259.4	254.7	10	3.3	4.7
2022	Sept 27	Oct 10	23.1	17	214.3	206.8	13	6.1	7.5
	Oct 6	Oct 10	17	15.2	220.8	207.9	4	1.8	12.9

Discussion

- Results of this study corresponded with those of previous studies and grower observations that corn yield often declines with later harvest.
- However, neither the change in grain moisture nor the length of additional time in the field seemed to have any effect on the observed decrease in yield.
- The 2018 Pioneer Agronomy study showed an increase in harvest loss as grain moisture at harvest declined and suggested the possibility that additional unmeasured harvest loss may have contributed to observed declines in yield.

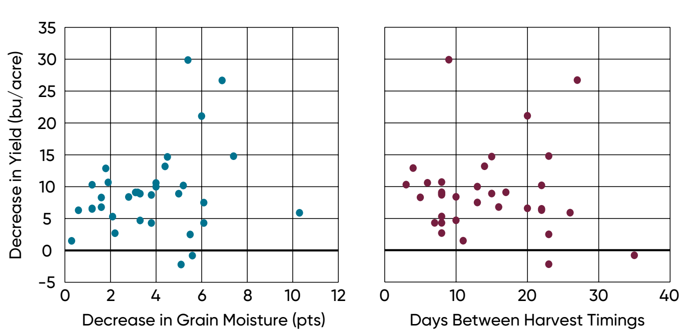


Figure 1. Yield loss with later harvest as a function of grain moisture loss (left) and additional days of field drying (right) showing no correlation to either factor.

return to table of contents

- The 2018 study measured ear drop and whole kernels on the ground after harvest; any kernels lost through breakage before or during harvest would not have been quantified.
- A higher rate of ear molds and stress cracks as corn dries down in the field could lead to higher rates of kernel breakage during harvest.
- Harvest loss was no quantified in this study; however, observations at multiple locations were suggestive of greater harvest losses with later harvest (Figures 2-7).

Figure 2. Compromised kernel integrity due to ear or kernel mold.

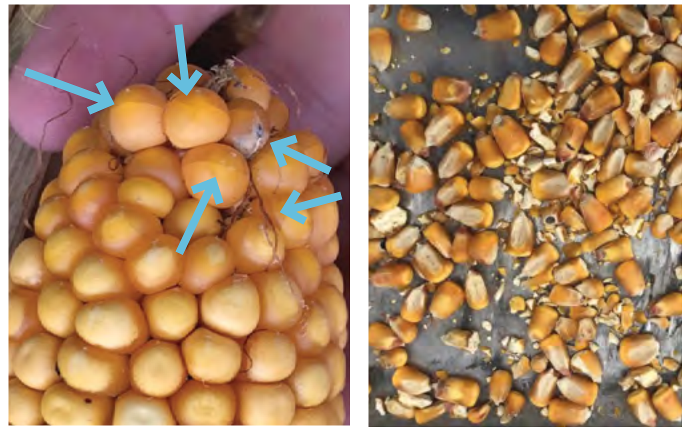


Figure 5. Stress cracks that can lead to more fines.

Figure 3. "Fines" – broken kernel particles blown out the back of the combine. Plot was harvested November 4th at 16% moisture.

Figure 6. Kernels on the ground from shelling at the head.

Figure 4. 'Cob shrink' causing kernels to fall out.

Figure 7. Accumulated grain dust from pulverized kernels in a field infested with Fusarium ear rot.

return to table of contents

Corn Maturity and Dry Down

Mark Jeschke, Ph.D., Agronomy Manager

Moisture Loss During Grain Fill

- Kernels lose moisture through the grain-filling period due to a combination of evaporative water loss and accumulation of kernel dry matter.
- Corn plants channel photosynthate into the kernels during the grain-fill period, increasing kernel dry weight.

Table 1. Days following silking to reach corn reproductive growth stages and approximate grain moisture (Abendroth et al., 2011).

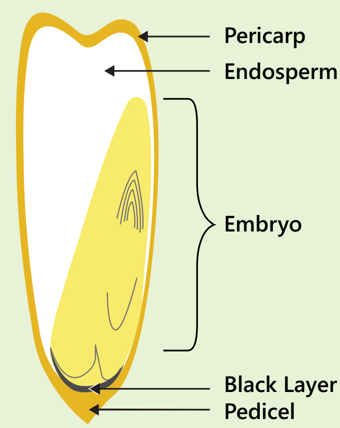
Growth Stage	Days After Silking	Approx. Moisture
Blister Stage (R2)	10-12	85%
Milk Stage (R3)	18-20	80%
Dough Stage (R4)	24-26	70%
Dent Stage (R5)	31-33	60%
Maturity (R6)	64-66	35%

Physiological Maturity and Black Layer

- Physiological maturity is the point at which the hard starch layer reaches the base of the kernel and kernel dry matter accumulation is complete.
- Kernel moisture at physiological maturity is typically around 35%, but can vary due to differences in hybrid characteristics and environmental conditions.
- Following physiological maturity, an abscission layer, known as the black layer, will form at the base of the kernel.
- Within the ear, the black layer usually forms first in the tip kernels with progression a few days later to the large kernels at the base.

Black Layer Formation

- In early seed development, a black layer forms in a region of cells several layers thick between the endosperm base of the kernel and the vascular area of the pedicel.
- Near physiological maturity, these cells compress into a dense layer, which appears visibly black.
- Concurrently, the cells at the base of the endosperm also become crushed. These are specialized vascular cells, which absorb and transfer nutrients to the kernel, plus sucrose and other sugars produced by the plant in photosynthesis.
- This stops their capability for movement of sugars and nutrients from within the plant into the kernel.



Stage R5

Beginning Dent

Grain Moist.**~50-55%**

~400 GDUs remaining to maturity

Yield loss from killing frost at this stage: 35-40%

Stage R5.25

1/4 Milk Line

Grain Moist.**~45-50%**

~300 GDUs remaining to maturity

Yield loss from killing frost at this stage: 25-30%

Stage R5.5

1/2 Milk Line

Grain Moist.**~40-45%**

~200 GDUs remaining to maturity

Yield loss from killing frost at this stage: 12-15%

Stage R5.75

3/4 Milk Line

Grain Moist.**~35-40%**

~100 GDUs remaining to maturity

Yield loss from killing frost at this stage: 5-6%

Stage R6

Physiological Maturity

Grain Moist.**~30-35%**

0 GDUs remaining to maturity

Yield loss from killing frost at this stage: 0%

return to table of contents

- Black layer is often used as a visual indicator of physiological maturity, and the two are often considered synonymous. However, this is not actually the case.
  - Black layer formation is triggered when sucrose translocation to the developing kernel stops.
  - This cessation of sucrose flow can be due to the physiological maturity of the kernel but can also be the result of other factors, causing a sharp drop in plant photosynthesis, such as foliar disease, hail, frost, or prolonged cold temperatures.
  - Black layer formation triggered by environmental stress can occur before physiological maturity, effectively shutting down grain fill prematurely.

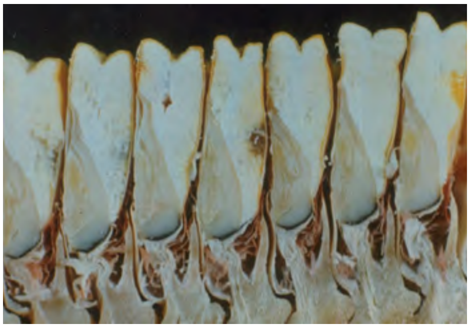


Figure 1. Cross section of kernels following physiological maturity. The black abscission layer is visible at the tip of the kernels.

Dry Down Following Maturity

- Kernel drying that occurs following black layer is entirely due to evaporative moisture loss.
- Corn dry down rate is tightly linked to daily growing degree unit (GDU) accumulation.
  - In general, drying corn from 30% down to 25% moisture requires about 30 GDUs per point.
  - Drying from 25% to 20% requires about 45 GDUs per point (Lauer, 2016).
- GDU accumulation and dry down rates are greatest during the earlier, warmer part of the harvest season and decline as the weather gets colder (Tables 2 and 3).
- By November, GDU accumulation rates are low enough that little further drying will typically occur.

Table 2. Average daily GDU accumulation during early-, mid-, and late-September and October for several Midwestern locations (1981-2010 average, Midwest Regional Climate Center).

	September			October		
	1-10	11-20	21-30	1-10	11-20	21-31
Lincoln, NE	20	17	14	11	8	7
Indianapolis, IN	20	16	13	11	8	6
Bloomington, IL	20	17	13	12	8	6
Ames, IA	18	14	12	10	7	5
Mankato, MN	17	13	10	8	6	4
Madison, WI	16	14	11	9	6	4
Brookings, SD	15	12	9	7	5	3

Table 3. Average daily corn dry down rate for different stages of the harvest season (Hicks, 2004).

Harvest Season Stage	Points of Moisture per Day
Sept. 15 – Sept. 25	¾ to 1
Sept. 26 – Oct. 5	½ to ¾
Oct. 6 – Oct. 15	¼ to ½
Oct. 16 – Oct. 31	0 to ⅓
Nov. 1 and later	~0

Timing of Physiological Maturity

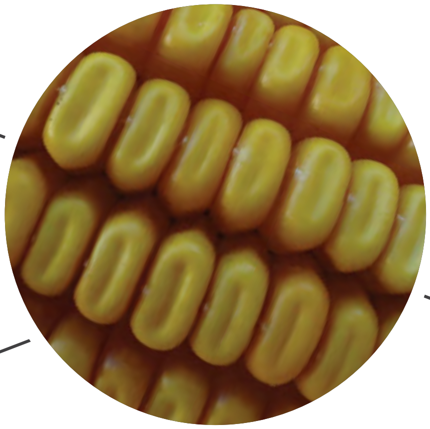
- Corn that matures earlier will dry down faster due to more favorable drying conditions early in the harvest season.
- Later-maturing corn has fewer warm days to aid in drying and will dry down at a slower rate.

Weather Conditions Following Maturity

- Daily GDU accumulation and dry down can vary widely during the harvest season.
- Corn may dry one point of moisture per day or more under favorable conditions.
- Conversely, corn may not dry at all on a cool, rainy day.

Hybrid Characteristics Affecting Dry Down

- **Husk Leaf Coverage:** The more insulated the ear is, the longer it will take to dry down. Leaf number, thickness, and tightness all affect dry down rate.
- **Husk Leaf Senescence:** The sooner these leaves die, the faster the grain will dry down.
- **Ear Angle:** Upright ears are more prone to capture moisture in the husks, which slows dry down.
- **Kernel Pericarp Characteristics:** Thinner or more permeable pericarp layers are associated with a faster dry down rate.



return to table of contents

Extended Diapause in Northern Corn Rootworm

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Northern corn rootworm has adapted to crop rotation in some areas by altering its overwintering dormancy period via a mechanism called extended diapause.
- Populations exhibiting extended diapause have eggs that remain viable in the soil for two or more years before hatching, allowing the insect population to survive until corn returns to the rotation.
- Rotation-resistant northern corn rootworm can now be found throughout much of the northern Corn Belt and continues to expand its range to the south and east.
- Even with the extended diapause adaptation, crop rotation remains a highly effective management tactic.

Corn Rootworm

- Corn rootworm has long been one of the most damaging insect pests of corn in North America.
- The western corn rootworm (*Diabrotica virgifera virgifera*) and northern corn rootworm (*D. barberi*) can both be found throughout much of the Corn Belt, often coexisting in the same fields.
- Both species have a history of adapting to and overcoming control practices, which has increased the complexity and difficulty of successfully managing these pests.

Western Corn Rootworm

- Has three stripes, or one broad stripe, on the wing covers.
- The legs are partially black but not banded.

Northern Corn Rootworm

- Solid green color. Newly emerged adults may be tan or light yellow in coloration.
- No stripes or spots on the wing covers.

Crop Rotation as a Management Strategy

- Crop rotation is the most effective and widely used management strategy for corn rootworm today.
- Crop rotation works by depriving newly-hatched larvae of a food source.
  - Corn rootworm larvae need corn roots within close proximity to feed on in order to survive.
  - A field that has been rotated to a different crop lacks this food source, causing the larvae to starve and die.
- However, both western and northern corn rootworm have developed adaptations that have reduced the effectiveness of crop rotation in many areas.
  - Western corn rootworm began laying eggs in soybean fields, allowing larvae to survive in the subsequent season when the field was rotated back into corn.
  - Northern corn rootworm adapted its life cycle, altering its overwintering dormancy period via a mechanism called **extended diapause.**

Figure 1. Newly-hatched corn rootworm larvae cannot move very far in the soil, only around 18 inches, so corn roots must be in close proximity for them to feed and survive.

What is Diapause?

- Diapause is a delay in development in response to regular and recurring periods of adverse environmental conditions
- Diapause is a common adaptation of insect species in temperate regions to allow populations to survive over the winter.
- Winter dormancy for corn rootworm eggs overwintering in the soil consists of two phases: **obligate diapause** and **facultative quiescence** (Krysan, 1978).
- **Obligate diapause** begins in the fall when embryonic development ceases in eggs that have been deposited in the soil.
- The duration of diapause is genetically determined, hence the term *obligate* diapause.
- Duration of diapause can vary widely across populations and among individuals within a population (Branson, 1976; Krysan, 1982).

- The end of diapause often occurs sometime during the winter. At this point, dormancy enters the **facultative quiescence** phase, during which environmental conditions become the controlling factor in maintaining dormancy.
- Embryonic development remains suspended until soil temperature increases above a threshold at which development can resume.
- This two-phase dormancy allows insects to survive harsh winter conditions while being ready to resume development as soon as conditions turn favorable.

Extended Diapause in Northern Corn Rootworm

- Northern corn rootworm populations exhibiting extended diapause have eggs that remain viable in the soil for two or more years before hatching, allowing the insect population to survive until corn returns to the rotation.
- Selection pressure imposed on corn rootworm populations selects for individuals with a diapause duration that gives them the best chance for survival by timing hatch to correspond with food availability.
- Diapause length in northern corn rootworm is naturally variable, and populations have been able to use this variability to adapt to different crop rotation schemes.
- Repeated use of crop rotation as a means of control selected for individuals with a longer diapause period that allowed eggs to hatch when the field was rotated back to corn.

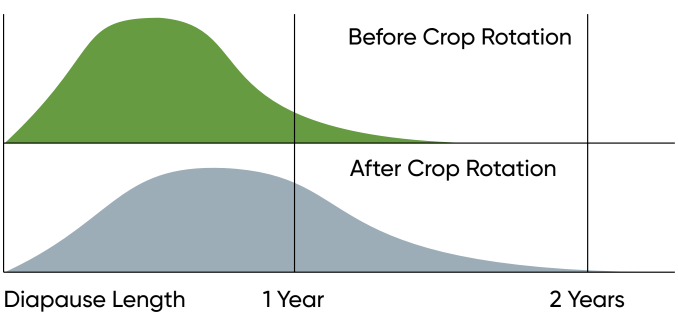


Figure 2. Distribution of diapause length in northern corn rootworm populations under continuous corn and after an extended period of corn-soybean rotation.

- Extended diapause can last up to four years and has shown adaptability to rotation patterns over time; i.e., fields with corn every other year have a relatively high percentage of eggs that hatch in the second year, and fields with corn every third year tend to have more eggs that hatch the third year, etc. (Levine et al., 1992).

Effect of Environmental Conditions

- Diapause in northern corn rootworm is genetically controlled, but the duration of dormancy is also influenced by environmental conditions.
- Exposure to low temperatures has been shown to accelerate dormancy termination in some insect species, including northern corn rootworm.
- Research has shown that northern corn rootworm eggs may need to be exposed to a minimum number of low temperature units before dormancy ends (Fisher et al., 1994).
- The range for these low temperature units appears to be between 37 and 59°F (3-15°C). Temperatures above or below this range do not affect the duration of dormancy.
- Consequently, an overwintering period with a below average number of days falling within this temperature range may extend dormancy and result in a greater proportion of the rootworm population hatching the following year.

Occurrence and Spread of Extended Diapause

- Instances of northern corn rootworm damage to corn grown in rotation with other crops was noted as far back as the 1930s.
- Rotation-resistant northern corn rootworm can now be found throughout much of the northern Corn Belt and continues to expand its range to the south and east.

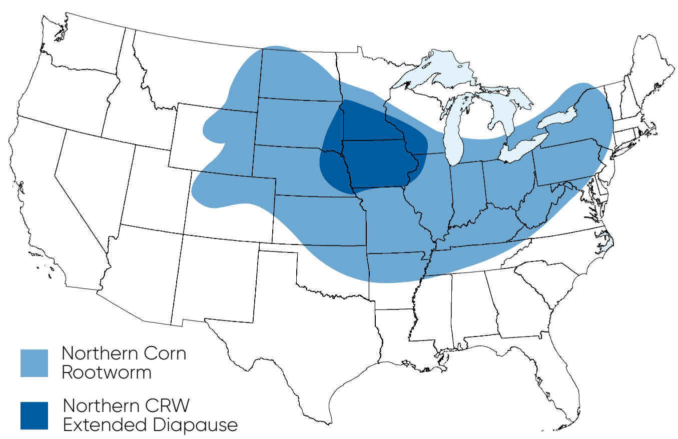


Figure 3. Approximate distribution of northern corn rootworm and extended diapause populations.

Management Considerations

- Corn growers within or near the geographic area where extended diapause has been observed should be on the lookout for rootworm damage in first-year corn fields.
- Employ best management practices for corn rootworm that focus on controlling population levels using an integrated management strategy.
- Crop rotation can still have value in extended diapause areas for reducing rootworm population levels, particularly if western corn rootworm is present as well.

return to table of contents

Corn Rootworm Levels in the Central Corn Belt - 2022

Mary Gumz, Ph.D., Agronomy Manager

Key Findings

- 438 corn and soybean fields were monitored for corn rootworm (CRW) beetles across, Illinois, Indiana, Iowa, Minnesota and Wisconsin in 2022.
- Populations in South Dakota, Iowa and Wisconsin differed from those in Illinois and Indiana with higher maximum weekly counts, higher prevalence of northern corn rootworm (NCR) and peak counts occurring 4 to 5 weeks after initial trap placement.
- All corn growers should monitor for CRW populations and use appropriate control practices and best management practices.

Objectives

- Assess CRW populations across Illinois, Indiana, Iowa, Minnesota, South Dakota and Wisconsin.

Study Description

- **Locations:**
  - 438 corn and soybean field locations across Illinois, Indiana, Wisconsin, Minnesota, Iowa, and South Dakota.
- **Sampling Methods:**
  - Six sticky traps placed per field starting at blister stage (R2). (Figure 1)
  - Northern and western CRW beetles were counted every seven days, with traps replaced every week. (Figure 2)
  - Trapping continued for six consecutive weeks by Pioneer sales professionals and agronomists.

Figure 1. Placement of a new Pherocon® AM/NB sticky trap on a corn plant (left). Arrangement of six traps in the field (right).

Figure 2. Western corn rootworm beetle (left); northern corn rootworm beetle (right).

Results

- Weekly trap counts ranged from zero to 269 average beetles per trap.
- 86% of fields sampled showed some level of CRW pressure.
- Highest average weekly trap counts were found in Wisconsin and Northern Illinois.

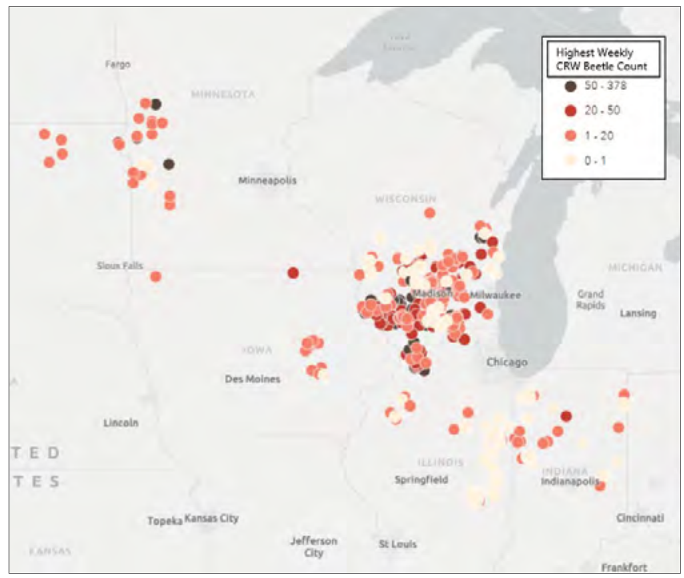


Figure 3. Peak weekly CRW beetle counts by location.

- Corn rootworm populations were characterized at four different levels for each sampling location (Table 1).
  - Zero = no beetles collected
  - Low = <21 beetles/week
  - Moderate = traps averaged 21-50 beetles/week
  - High = traps averaged >50 beetles/week

Table 1. CRW severity across the entire study area and by state.

CRW Level	Locs	Zero	Low	Mod.	High
		% of sample locations			
Overall	438	14	45	23	18
Illinois	57	30	42	21	7
Indiana	29	45	52	3	0
Iowa	14	0	86	14	0
Minnesota	24	4	71	8	0
South Dakota	4	0	100	0	0
Wisconsin	279	6	40	27	24

- Western CRW was found in nearly all sampling locations across all states in the sampling area.
- Northern CRW was prevalent across most of the sampling area except for Eastern Illinois and Indiana.

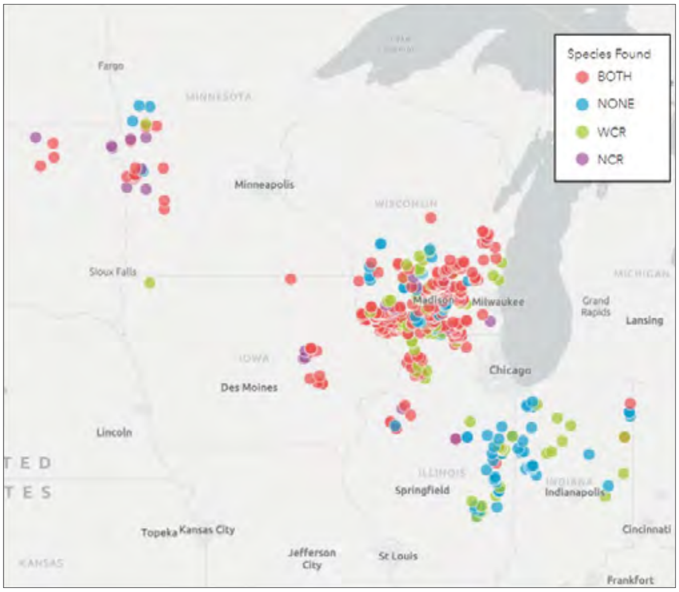


Figure 4. CRW species found at trapping locations in 2022.

- Sticky traps were put in the field at R2 and the first week's counts were taken seven days later and continued on a weekly basis. Since the traps were placed based on crop development rather than a calendar date, traps in the southern part of the study were placed in the field earlier than traps in the northern part of the study.
- Timing of peak beetle trapping (based on weeks following R2) varied depending on geography. Locations in Indiana, Illinois, and Iowa tended to have peak beetle counts during Week 1 or 2 of trapping.
- Locations in Wisconsin and Minnesota tended to have peak beetle counts occur later in trapping.

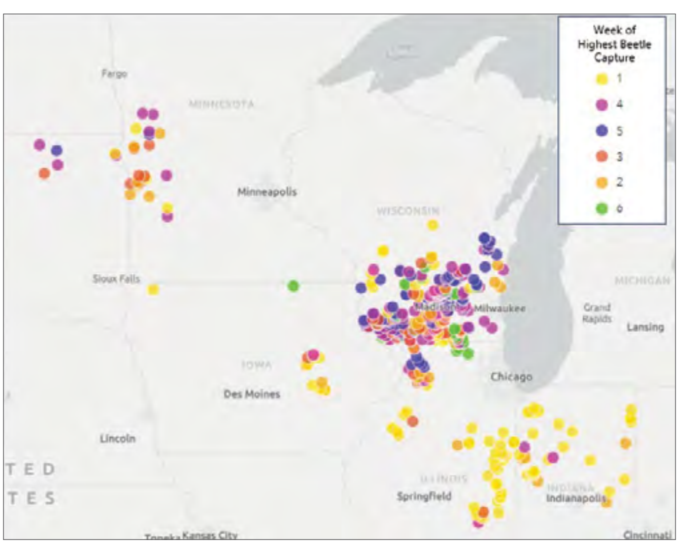


Figure 5. Week of highest CRW beetle count at 2022 trapping locations.

What does this mean in the field?

- Farmers throughout the Central Corn Belt need to be aware of CRW pressure on their farms, especially in continuous corn.
- Northern CRW, and the potential for its extended diapause variant, is a greater concern in Wisconsin, Minnesota, Iowa and South Dakota than in Illinois or Indiana.
- Farmers who are monitoring CRW beetles using sticky traps may be able to make a good population estimate after 1 to 2 weeks of trapping in central Illinois and Indiana. Farmers in the northern and western portions of this study area should trap at least 4 to 5 weeks for more accurate counts.

CRW Best Management Practices

When using CRW beetle trapping to monitor populations:

- If traps average <21 beetles per week:
  - **Low** rootworm populations are anticipated next year
    - Rotate acres to another crop.
    - Plant a corn rootworm Bt corn product.
    - Plant a non-Bt rootworm product with Lumisure® 1250 insecticide treatment OR a soil insecticide for larvae.
- If traps average 21-50 beetles per week:
  - **Moderate** rootworm populations are anticipated next year
    - Rotate acres to another crop.
    - Plant a corn rootworm Bt corn product.
    - Apply a soil insecticide at planting for larvae.
- If traps average >50 beetles per week:
  - **High** rootworm populations are anticipated next year
    - Rotate acres to another crop.
    - Apply foliar insecticide in the current year to control adult beetles prior to egg-laying and use a corn rootworm Bt corn product or soil-applied insecticide the following year.
- Pioneer and university research suggests that continuous, uninterrupted use of the same corn rootworm Bt technology can lead to reduced product efficacy against these insects.
- To maintain efficacy of Bt corn rootworm products, it is essential to develop a rootworm management plan that:
  - Breaks the cycle
  - Manages populations
  - Protects the Bt trait
- Please contact your Pioneer sales professional for more information.

return to table of contents

Estimating Corn Rootworm Populations with Sticky Traps in Ontario

Greg Stopps, Sales Agronomist

Key Findings

- In 2021, 12% of sampled locations had moderate to very high corn rootworm (CRW) pressure, 40% had low or very low pressure, and 48% had no CRW beetles found.
- Predominance of western corn rootworm (WCRW) or northern corn rootworm (NCRW) differed between Southern Ontario and Eastern Ontario. WCRW were predominant at 85% of locations in Southern Ontario where NCRW were predominant at 55% of locations in Eastern Ontario.
- Crop rotation affected CRW pressure levels; all locations with high to very high CRW pressure were planted to corn following corn.

Objectives

- Quantify western and northern corn rootworm populations and categorize them into defined levels of pest pressure across the primary corn growing regions of Ontario using non-baited yellow sticky traps.
- Understand how crop rotation is influencing CRW levels and species dynamics across Ontario.
- Identify best management practices for growers to make informed decisions for the following growing seasons.

Study Description

Year: 2021

Locations: 159 field locations across Ontario including:

- 54 continuous corn
- 64 first year corn in rotation
- 41 soybean following corn fields

Corn Rootworm Sampling Methods:

- Three sticky traps per field were placed starting at blister stage (R2).
- Northern and western CRW beetles were counted every seven days and average counts per trap were recorded. Traps were replaced with new traps upon counting.
- Trapping continued for five consecutive weeks by Pioneer field staff and representatives.

Other Observations:

- Basic soil texture was recorded at each location.
- The number of years in continuous corn was recorded for continuous corn locations.

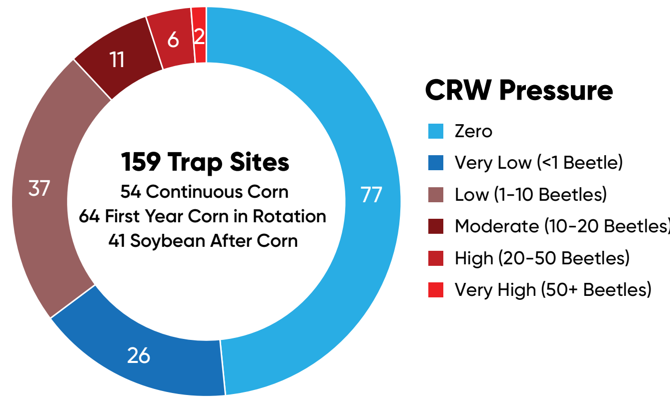


Figure 1. Level of CRW pressure observed at each location as defined by peak weekly trap counts in 2021.

Results

CRW Pressure

- Corn rootworm populations at each sample location were categorized into six levels of pest pressure (Figure 1) previously defined by Stopps and MacDonald (2021), based on the peak populations captured over the course of weekly trapping:
  - Zero Pressure = no beetles collected
  - Very Low = traps averaged <1 beetles/week
  - Low = traps averaged 1-10 beetles/week
  - Moderate = traps averaged 10-20 beetles/week
  - High = traps averaged 20-50 beetles/week
  - Very High = traps averaged >50 beetles/week
- 12% of sampled locations were characterized as moderate to very high CRW pressure, 40% had low or very low pressure, and 48% had no CRW beetles found. The distribution of peak beetle population levels across Ontario is shown in Figure 2.

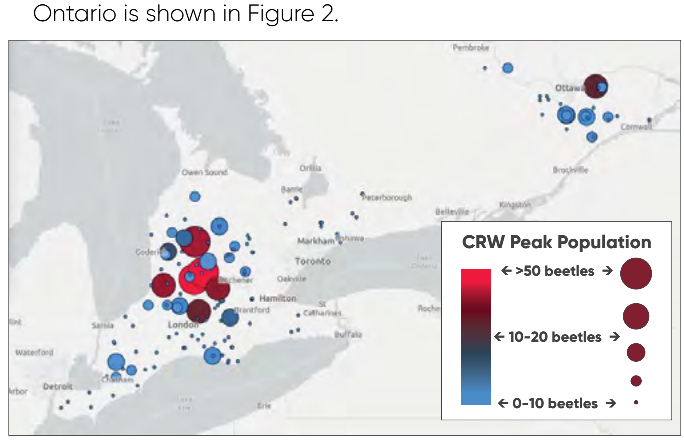


Figure 2. Peak populations observed at corn rootworm beetle trapping locations in 2021.

return to table of contents

CRW Species Composition

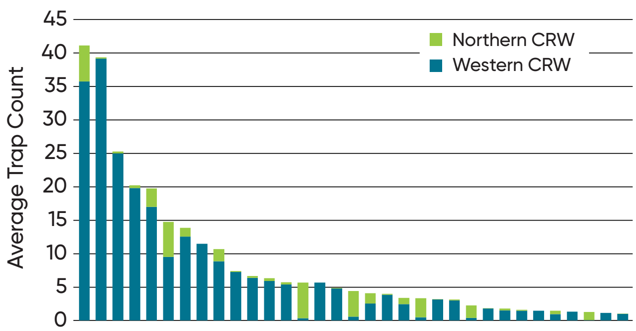


Figure 3. CRW species compositions for very high, high, moderate, and low population locations across Ontario in 2021.

- Western corn rootworm (WCRW) was the predominant species across Ontario, being either the only or the predominant species trapped at 71% of locations (Figure 3). Northern corn rootworm (NCRW) was the only or predominant species trapped at 23% of locations in Ontario. Equal pressure between WCRW and NCRW was observed at 5% of locations.
- Southern Ontario (Durham Region and West) and Eastern Ontario (Ottawa Valley) differed in regard to species composition at trapping locations (Table 1).

Table 1. CRW species predominance in Southern and Eastern Ontario.

	Southern ON	Eastern ON
NCRW Present	50%	85%
NCRW Predominant	15%	55%
Equal NCRW/WCRW	0%	10%
WCRW Present	92%	75%
WCRW Predominant	85%	35%

Crop Rotation Effects

- 100% of the locations that showed high to very high pressure were continuous corn locations.
- Of the 11 locations showing moderate pressure, seven were corn on corn locations while four were first year corn in rotation.
- Of the four first-year corn locations showing moderate pressure, two occurred in Southern Ontario and two in Eastern Ontario. The two Southern Ontario locations predominantly trapped WCRW but also trapped NCRW at low pressure levels. The two locations in Eastern Ontario both showed predominance of NCRW.

Table 2. Distribution of pressure levels based on crop rotation.

	# of Locations by Crop Rotation		
CRW Pressure	Continuous Corn	First Year Corn in Rotation	Soybeans Following Corn
Very High	2	0	0
High	6	0	0
Moderate	7	4	0
Low	19	13	5
Very Low	8	15	3
Zero	12	32	33

- CRW pressure in all soybean locations was characterized as low, very low, or zero.
  - » CRW beetles were trapped at eight of the 41 locations where traps were placed in a soybean crop following corn the previous year.
  - » WCRW were found at six of these eight soybean locations but were only predominant at two locations. NCRW were predominate at six of the eight locations (Figure 4).

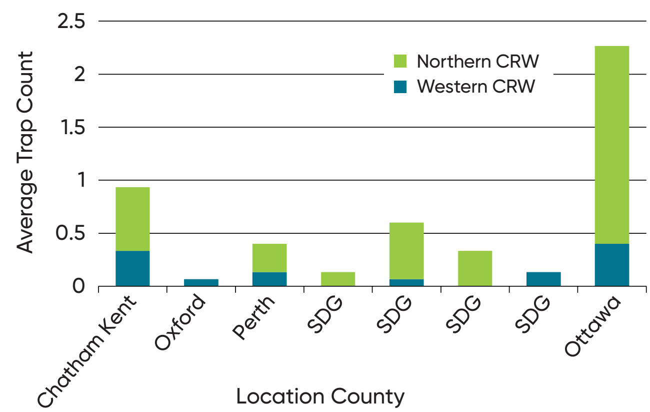


Figure 4. CRW species compositions at soybean locations where CRW were trapped in 2021.

Soil Texture Effects

- Soil texture was classified for all locations. Locations that showed moderate to high CRW pressure ranged in texture from sandy clay to clay loam (including sandy clay loam, silt loam, and loam).
- Six continuous corn locations had been in corn for 10+ years. Three of these locations showed moderate to high pressure, all on silty loam or clay loam soils. The other three long-term continuous corn locations were on sand or sandy loam soils, and showed zero, very low, or low pressure. One location on sandy loam is particularly noteworthy, as it has been in continuous corn for 27+ years and showed very low pressure.

Discussion

Sampling of CRW populations across Ontario in 2021 revealed the variable geographic nature of CRW pressure and effects of crop rotation. All locations characterized as high to very high pressure were continuous corn locations, lending support for the use of rotation out of corn as a critical tool to manage CRW populations.

Continuous corn practices have been shown by university and Pioneer research to increase CRW pressure and can result in the development of resistance to Bt traits. Crop rotation is the best way to reduce CRW populations and selection pressure to keep these valuable Bt traits effective. In this study, the two locations characterized as very high pressure were both located in central Perth County in a geography where investigations of CRW resistance to Bt traits is now underway. Bt resistance has been confirmed by the Canadian Corn Pest Coalition in nearby Huron county, highlighting that CRW Bt resistance can and has happened in Ontario when enough selection pressure is applied under continuous corn practices.

Results from this study indicate that WCRW is the predominant species in Southern Ontario, but that NCRW is narrowly predominant in Eastern Ontario. Species predominance may become important in managing CRW pressure within local geographies as both WCRW and NCRW species have been found capable of expressing different adaptive responses to crop rotation (Jeschke, 2021).

A variant of the WCRW known as the "rotation adapted variant" or the "soybean variant" first discovered by researchers in 1987, can lay its eggs in soybean fields rather than corn, enabling it to maintain its population levels in two-year corn-soybean crop rotation systems (Dunbar and Glassmann 2013). While not yet observed or confirmed in Ontario, this rotation adapted variant of WCRW has been found previously in nearby states of Michigan and Ohio (Prasifka et al., 2006). The observed appearance of WCRW, even at low levels, in six soybean locations across the province could be coincidence with transient adults being trapped as they move from one corn field to another, or it could be indicative of adaptive variants starting to appear. Their mere observation warrants further investigation in coming years to verify the presence or absence of any such variants of WCRW that would be of concern.

NCRW has been documented to adopt a different adaptive strategy with some populations capable of showing 'extended diapause' where eggs can remain viable in a dormant state for two or more years before hatching when a corn crop is back in rotation (Krysan et al., 1984). Similar to the WCRW variant, the NCRW variant exhibiting extended diapause has not been shown to date in Ontario, but likely warrants further examination with predominance of NCRW populations particularly in Eastern Ontario. The observation of four first-year corn locations that showed moderate CRW pressure – an unexpectedly high level for first year corn fields – all four of which trapped NCRW and two in the Ottawa area that showed predominance of NCRW, lends further weight to the need for closer examination of NCRW and the possibility that the extended diapause variant is present in Ontario.

Classification of soil types did not reveal clear correlation with the occurrence of CRW pressure, however observation of three long-term (10+ year) continuous corn locations that showed zero to low pressure on sandy soils lends some anecdotal evidence to the thought that coarse soil textures may have some impact on CRW larval survival and overall population pressure (Jeschke, 2021).

Management Recommendations

If CRW is of concern to for your operation, a yearly scouting program trapping adult beetles to assess population levels can be an effective tool to inform future rotation decisions.

If traps average <20 beetles per week:

- **Low/Moderate** CRW populations are anticipated next year.
- Select a control option for each field:
  - Rotate acres to another crop.
  - Plant a corn rootworm Bt corn product. (If a Bt-rootworm product has already been planted three years in a row or you are in a geography where CRW Bt resistance is already confirmed/suspected, rotate out of corn.)
  - Plant a non-Bt rootworm product with Poncho® 1250/VOTiVO® insecticide treatment.
  - (**PLEASE NOTE** Health Canada's Pest Management Regulatory Agency has removed registered use of Poncho® 1250 for the 2023 growing season and beyond. Other "high rate" seed treatments are being evaluated to assess their utility for use on non-Bt rootworm corn in a first-year corn on corn scenario.)

If traps average >20 beetles per week:

- **High** rootworm populations are anticipated next year
- Select a control option for high populations:
  - Rotate acres to another crop.
  - If corn must be grown, apply foliar insecticide in the current year to control beetles prior to egg-laying. If CRW Bt resistance is suspected in your geography, consider using a non CRW Bt product with application of in furrow insecticide.

To maintain efficacy of Bt corn rootworm products, it is essential to develop a rootworm management plan that:

- **Breaks the cycle**
- **Manages populations**
- **Protects the Bt trait**

Please contact your Pioneer Sales Professional or local Extension professionals to assist you in developing field-specific best management practices for your operation.




return to table of contents

Most affected areas experienced low to moderate tar spot severity in 2022. **Dry summer conditions** across much of the Corn Belt may have helped ***keep tar spot in check.***

Tar Spot of Corn in the U.S. and Canada

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Tar spot *(Phyllachora maydis)* is a relatively new disease of corn in the U.S., first appearing in Illinois and Indiana in 2015 and subsequently spreading to neighboring states.
- In 2018, tar spot established itself as an economic concern for corn production in the Midwest, with severe outbreaks affecting corn yield reported in several states.
- Tar spot gets its name from the fungal fruiting bodies it produces on corn leaves that look like spots of tar.
- Tar spot 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.
- Tar spot can rapidly spread through the corn canopy under favorable conditions, causing premature leaf senescence.
- Commercial corn hybrids vary widely in their susceptibility to tar spot. Hybrid selection should be a primary consideration in managing for tar spot.
- Fungicide treatments have shown some effectiveness in reducing tar spot symptoms; however, application timing can be critical for achieving adequate control and two applications may be needed in some cases.

Tar Spot: An Emerging Disease Of Corn

Tar spot is a foliar disease of corn that has recently emerged as an economic concern for corn production in the Midwestern U.S. It is not a new disease, having been first identified in 1904 in high valleys in Mexico. Historically, tar spot's range was limited to high elevations in cool, humid areas in Latin America, but it has now spread to South American tropics and parts of the U.S. and Canada. It first appeared in the U.S. in 2015. During the first few years of its presence in the U.S., tar spot appeared to be a minor cosmetic disease that was not likely to affect corn yield. However, widespread outbreaks of severe tar spot in multiple states in 2018 and again in 2021 proved that it has the potential to cause a significant economic impact. With its very limited history in the U.S. and Canada, much remains to be learned about the long-term economic importance of this disease and best management practices.

Tar Spot Origins

Tar spot in corn is caused by the fungus *Phyllachora maydis*, which was first observed more than a century ago in high valleys in Mexico. *P. maydis* was subsequently detected in several countries in the Caribbean and Central and South America (Table 1). Despite its decades-long presence in many of these countries, it was not detected in the Continental U.S. until 2015.

Historically, *P. maydis* was not typically associated with yield loss unless a second pathogen, *Monographella maydis*, was also present, the combination of which is referred to

Table 1. Country and year of first detection of *P. maydis* (Valle-Torres et al., 2020).

Region	Country	Year
Caribbean	Dominican Republic	1944
	U.S. Virgin Islands	1951
	Trinidad and Tobago	1951
	Cuba	1968
	Puerto Rico	1973
	Haiti	1994
Central America	Guatemala	1944
	Honduras	1967
	Nicaragua	1967
	Panama	1967
	El Salvador	1994
	Costa Rica	1994
North America	Mexico	1904
	United States	2015
	Canada	2020
South America	Peru	1931
	Bolivia	1949
	Colombia	1969
	Venezuela	1972
	Ecuador	1994

Corn leaves infected with tar spot in a field in Illinois in 2018.

as tar spot complex. In Mexico, the 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 but it has proven capable of causing significant yield losses, even without the presence of an additional pathogen.

Tar Spot Spread To The U.S. and Canada

The first confirmations of tar spot in North America outside of Mexico were in Illinois and Indiana in 2015 (Bissonnette, 2015; Ruhl et al., 2016). It has subsequently spread to Michigan (2016), Wisconsin (2016), Iowa (2016), Ohio (2018), Minnesota (2019), Missouri (2019), Pennsylvania (2020), Ontario (2020), Kentucky (2021), New York (2021), Nebraska (2021), Kansas (2022), and Maryland (2022). Its presence was also confirmed in Florida in 2016 (Miller, 2016) and in Georgia in 2021.

2018 Outbreak

During the first few years of its presence in the U.S., it appeared that tar spot might remain a relatively minor cosmetic disease of little economic impact. In 2018, however, tar spot established itself as an economic concern for corn production in the Midwest, with severe outbreaks reported in Illinois, Indiana, Wisconsin, Iowa, Ohio, and Michigan. Significant corn yield losses associated with tar spot were reported in some areas. University corn hybrid trials conducted in 2018 suggested potential yield losses of up to 39 bu/acre under the most severe infestations (Telenko et al., 2019). Growers in areas severely impacted by tar spot anecdotally reported yield reductions of 30-50% compared to 2016 and 2017 yield levels.

Yield losses specifically attributable to tar spot were often difficult to determine however, because of the presence of other corn diseases due to conditions generally favorable for disease development. Instances of greatest tar spot severity in 2018 were largely concentrated in northern Illinois and southern Wisconsin, where other foliar diseases and stalk rots were also prevalent.

Tar spot made another ***substantial expansion*** westward in 2022, with its presence confirmed for the **first time** in numerous eastern Nebraska counties as well as a few counties in northeastern Kansas.

2019 and 2020 Observations

In 2019, tar spot severity was generally lower across much of the Corn Belt and appeared later and more slowly compared to 2018, although severe infestations were still observed in some areas. There is no clear explanation for why tar spot severity was lower in 2019 in areas where it was severe 2018. Less favorable conditions for disease development during the latter part of the growing season in 2019 may have played a role. Reduced winter survival may have been a factor as well. Winter temperatures in some tar spot-affected areas oscillated between warm periods and extreme cold, which may have affected fungal dormancy and survival (Kleczewski, 2019).

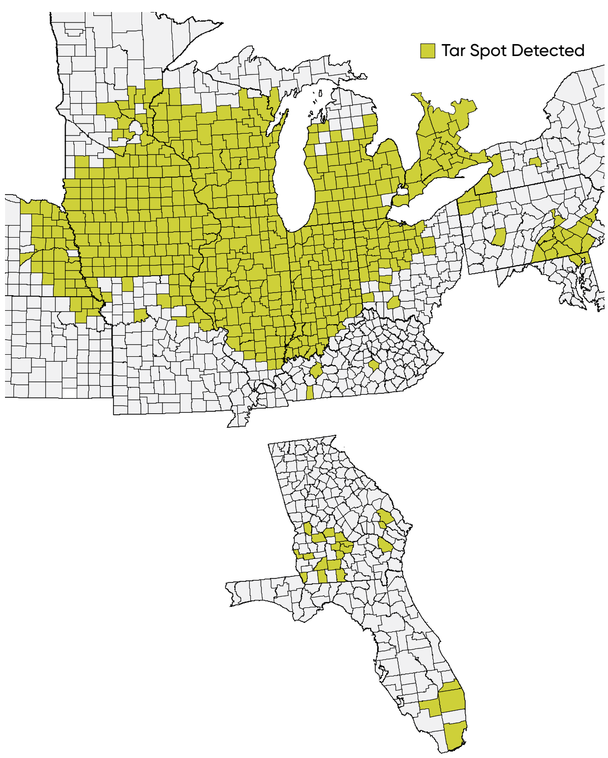


Figure 1. Counties with confirmed incidence of tar spot, as of October 2022. (Corn ipmPIPE, 2022).

Despite the generally lower disease severity, tar spot continued to expand its geographic range in 2019. In Iowa, tar spot presence was limited to around a dozen eastern counties in 2018 but expanded to cover most of the state in 2019 (Figure 1). Tar spot was confirmed in Minnesota for the first time in September of 2019 (Malvick, 2019). Tar spot spread to the south and east as well, with new confirmations in parts of Missouri, Indiana, Ohio, and Michigan.

2020 brought another year of generally lower tar spot severity in the Corn Belt, with severe infestations mostly limited to irrigated corn and areas that received greater than average rainfall or developing late enough in the season that they had minimal impact on yield. Tar spot continued to spread, however, with the first confirmation of tar spot in Pennsylvania. Tar spot was also confirmed to be present in corn in Ontario, marking the first time the disease had been detected in Canada.

2021 Outbreak

The 2021 growing season proved that the 2018 outbreak was not a fluke, with a severe outbreak of tar spot once again impacting corn over a large portion of the Corn Belt. Wet conditions early in the summer appeared to be a key factor in allowing tar spot to get a foothold in the crop. Whereas in 2018, when tar spot appeared to be mainly driven by wet conditions in August and September, in 2021 many impacted areas were relatively dry during the latter portion of the summer. Wet conditions early in the summer were apparently enough to allow the disease to get established in the crop and enabled it to take off quickly when a window

Figure 2. A corn field with almost no visible foliar disease on August 28, 2021 and the same field with extensive tar spot infection on September 23.

of favorable conditions opened up later in the summer. The 2021 season also provided numerous demonstrations of the speed with which tar spot can proliferate, enabled by its rapid reinfection cycle (Figure 2).

The availability of several fungicides labeled for tar spot allowed growers to get a better look at fungicide efficacy. Fungicide application timing proved to be critical for controlling tar spot in 2021. In some cases, two applications were necessary to provide adequate control.

2022: The Tar Spot Story Gets More Complex

2022 was another season with generally low to moderate tar spot severity in most affected areas, similar to the 2019 and 2020 growing seasons. Dry summer conditions experienced in many areas of the Corn Belt may have helped keep tar spot in check. Greater familiarity with the disease following several years of infestation and two major outbreaks may also be driving a more proactive approach to management with foliar fungicides when symptoms begin to develop.

A new study revealed that *P. maydis* infecting corn in the U.S. is **not one species** but is actually ***multiple, related but genetically distinct, species.***

Tar spot made another substantial expansion westward in 2022, with its presence confirmed for the first time in numerous eastern Nebraska counties, as well as a few counties in northeastern Kansas. Eastward spread was more limited, with only a handful of new confirmations in counties in Pennsylvania, New York, and Maryland. Infestation continued to spread in the southern U.S. with several new confirmations in Georgia.

A study published in 2022 (Broders et al., 2022) shed new light on the pathogen that causes tar spot, *Phyllachora maydis*. Previously, it was thought that *P. maydis* was not in the U.S. prior to 2015 and that it was not capable of infecting any species other than corn – results from the new study indicate that both of these hypotheses were wrong. Even more notably, the study revealed that *P. maydis* infecting corn in the U.S. is not one species but is actually multiple, related but genetically distinct, species. In light of these new findings, the authors proposed the term ***P. maydis* species complex** to refer to the causal pathogen for tar spot in corn pending further research.

The study assessed sequence diversity of numerous tar spot specimens from field samples as well as herbarium samples of corn and several other grass species. Results revealed five genetically distinct *Phyllachora* species, three of which are currently found in corn in the U.S.:

Species 1 (In U.S. Corn)

- Found only in corn
- Found only in field samples from Indiana and Ohio

Species 2 (In U.S. Corn)

- Found only in corn
- Found in herbarium samples from Colombia and Puerto Rico and field samples from Puerto Rico, Mexico, Florida, Illinois, and Michigan

Species 3 (In U.S. Corn)

- Widest geographic and host range
- Found in several U.S. states and a dozen other countries around the world
- Found in corn as well as 10 other host species, including monocots and dicots
- Includes first isolate collected from U.S. corn in 2015 and the original specimen collected in Mexico in 1904
- Herbarium samples indicate that Species 3 has been present in the Southwestern U.S. since at least the 1940s in native grass species, but not in corn

Species 4

- Found in herbarium samples of corn from Guatemala and Venezuela
- Found in field samples of other grass species in the U.S. but NOT in corn.

Species 5

- Not found in corn.
- Found in some of the same grass species as Species 4.

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 (Figure 3). 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 3 and 4). 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).

Figure 3. A corn leaf with tar spot symptoms.

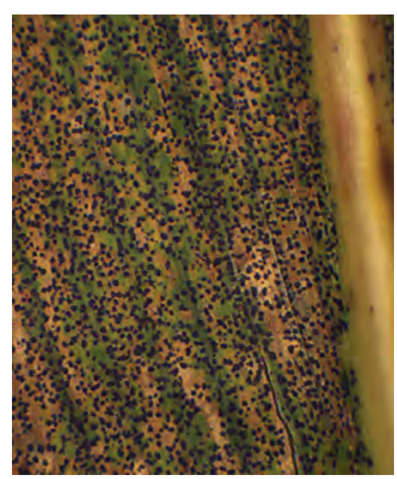


Figure 4. Corn leaf under magnification showing dense coverage with tar spot ascomata.

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 5).

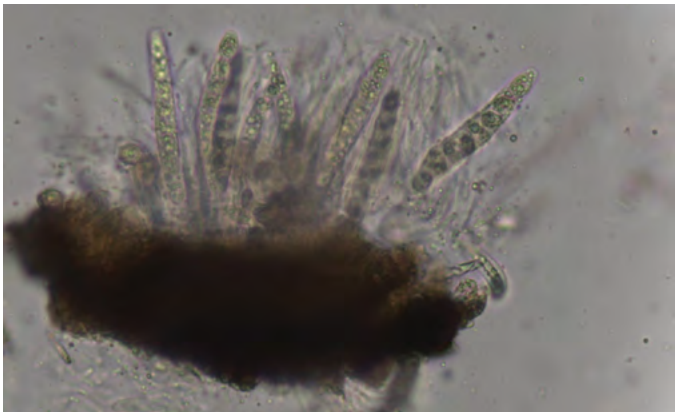


Figure 5. Microscopic view of fungal spores of *P. maydis*.

Tar Spot Look-Alikes

Common rust (*Puccinia sorghi*) and southern rust (*Puccinia polysora*) can both be mistaken for tar spot, particularly late in the growing season when pustules on the leaves produce black teliospores (Figure 6a). Rust pustules can be distinguished from tar spot ascomata by their jagged edges caused by the spores breaking through the epidermis of the leaf (Figure 6b). Rust spores can be scraped off the leaf surface with a fingernail, while tar spot cannot. Saprophytic fungi growing on senesced leaf tissue can also be mistaken for tar spot.

Figure 6a. Southern rust in the teliospore stage late in the season, which can resemble tar spot (left). **Figure 6b.** Corn leaf with common rust spores showing jagged edges around the pustules (right).

Figure 7. Corn leaf with tar spot symptoms.

Tar Spot Arrival and Spread In The U.S.

The mechanism by which tar spot arrived in the Midwestern and Southeastern U.S. and the reason for its recent establishment and proliferation, despite being present in Mexico and several Central American countries for many decades prior, both remain unclear.

Following its initial detection in the U.S. in 2015, numerous reports speculated that *P. maydis* spores may have been carried to the U.S. via air currents associated with a hurricane, the same mechanism believed to have brought Asian soybean rust (*Phakopsora pachyrhizi*) to the U.S. several years earlier. However, Mottaleb et al. (2018) suggested that this scenario was 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.

Shorter and warmer winters may be allowing *P. maydis* to overwinter further north than previously possible and ***greater temperature and precipitation*** could contribute to epidemics during the growing season.

As for the reason for tar spot's establishment and spread as a disease capable of severely reducing corn yield, Broders et al. note two possible contributing factors. The first is that changes in climate have favored the disease. Shorter and warmer winters may be allowing *P. maydis* to overwinter further north than previously possible and greater temperature and precipitation could contribute to epidemics during the growing season. Second, is the overall lack of resistance to *P. maydis* in North American corn genetics, which has made corn in the U.S. and Canada a particularly vulnerable host population. Corn hybrids have been shown to vary in their susceptibility to tar spot. Corn breeding programs in Central and South American – countries where tar spot has long been present – would have selected for more resistant genetics, whereas breeding programs in the U.S. and Canada, until very recently, would not.

return to table of contents

Tar Spot Epidemiology

Much is still being learned about the epidemiology of tar spot, even in its native regions, and especially in the U.S. and Canada. *P. maydis* is part of a large genus of fungal species that cause disease in numerous other species. *P. maydis* is the only *Phyllachora* species known to infect corn, and, until very recently, was believed to only infect corn (Chalkley, 2010). The recent confirmation of the existence of multiple, related *P. maydis* species infecting corn, some of which can infect others hosts as well, has added another layer of complexity to the situation.

P. maydis is an obligate pathogen, which means it needs a living host to grow and reproduce. It is capable of overwintering in the Midwestern U.S. in infected crop residue on the soil surface. Tar spot 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. Tar spot is polycyclic and can continue to produce spores and spread to new plants as long as environmental conditions are favorable. *P. maydis* produces windborne spores that have been shown to disperse up to 800 ft. Spores are released during periods of high humidity.

Management Considerations

Yield Impact

2018 was the first time that corn yield reductions associated with tar spot were documented in the U.S. University corn hybrid trials conducted in 2018 suggested potential yield losses of up to 39 bu/acre under heavy infestations (Telenko et al., 2019). Pioneer on-farm research trials, along with grower reports, showed yield losses of up to 50% under the most extreme infestations during the 2018 season and again in the 2021 growing season.

Differences in Hybrid Response

Observations in hybrid trials have shown that hybrids differ in susceptibility to tar spot (Kleczewski and Smith, 2018). Tar spot affects yield by reducing the photosynthetic capacity of leaves and causing rapid premature leaf senescence. Longer maturity hybrids for a given location have been shown to have a greater risk of yield loss from tar spot than shorter maturity hybrids (Telenko et al., 2019). Pioneer agronomists and sales professionals continue to collect data on disease symptoms and hybrid performance in locations where tar spot is present to assist growers with hybrid management. Pioneer hybrid trials have shown differences in canopy staygreen among Pioneer® brand corn products[1] and competitor products under tar spot disease pressure (Figure 8). Genetic resistance to tar spot should be the number one consideration when seeking to manage this disease, as it appears to have a greater impact on symptoms and yield loss than either cultural or chemical management practices.

Pioneer Agronomy

Evaluating Corn Hybrids for Tar Spot Tolerance
- Ryan Bates, Pioneer Field Agronomist

Figure 8. Pioneer on-farm trial in Knox County, Illinois, with high tar spot pressure showing differences in canopy staygreen among hybrids (September 2022).

Stalk Quality

Severe tar spot infestations have also been associated with reduced stalk quality (Figure 9). Stress factors that reduce the amount of photosynthetically functioning leaf area during grain fill can increase the plant's reliance on resources remobilized from the stalk and roots to complete kernel fill. Remobilizing carbohydrates from the stalk reduces its ability to defend against soil-borne pathogens, which can lead to stalk rots and lodging.

Tar spot seems to be particularly adept at causing stalk quality issues due to the speed with which it can infest the corn canopy, causing the crop to senesce prematurely. If foliar symptoms are present, stalk quality should be monitored carefully to determine harvest timing.

Figure 9. Field with severe tar spot infection and extensive stalk lodging in Wisconsin in 2018.

return to table of contents

Fungicide Treatments

Research has shown that fungicide treatments can be effective against tar spot (Bajet et al., 1994). Specific management recommendations for the use of fungicides in managing tar spot in the Midwestern U.S. are still in development as more research is done.

University trials conducted in 2018 in locations where tar spot was present provided evidence that fungicides can reduce tar spot symptoms and potentially help protect yield. However, initial work also suggested that tar spot may be challenging to control with a single fungicide application due to its rapid reinfection cycle, particularly in irrigated corn.

A 2019 Purdue University study compared single-pass and two-pass treatments for tar spot control using Aproach® (picoxystrobin) and Aproach® Prima (picoxystrobin + cyproconazole) fungicides under moderate to high tar spot severity (Da Silva et al., 2019). Fungicide treatments were applied at the VT (August 8) and R2 stage (August 22), and disease symptoms were assessed on September 30. Results showed that all treatments significantly reduced tar spot symptoms relative to the nontreated check, with Aproach Prima fungicide applied at VT and two-pass treatments at VT and R2 providing the greatest reduction in tar spot stroma and associated chlorosis and necrosis on the ear leaf (Figure 10).

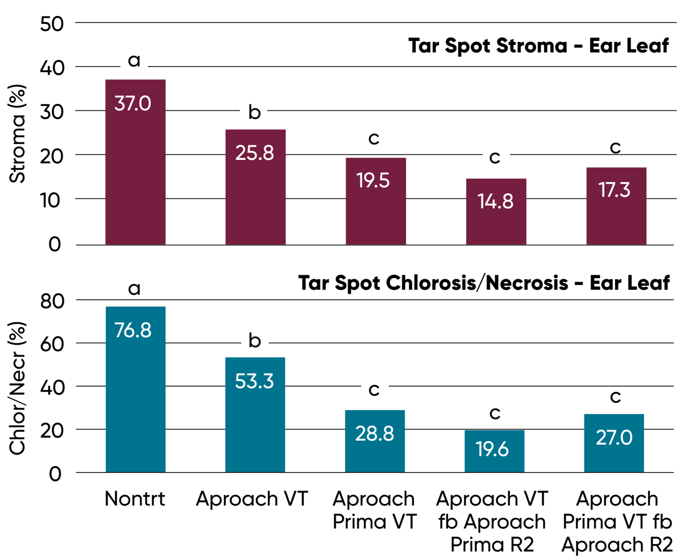


Figure 10. Fungicide treatment effects on tar spot symptoms in a 2019 Purdue University study. Visually assessed tar spot stroma and chlorosis/necrosis (0-100%) on the ear leaf.

Means followed by the same letter are not significantly different based on Fisher's Least Significant Difference test (LSD; α=0.05)

Aproach® Prima fungicide applied at VT and the two-pass treatments all significantly increased yield relative to the nontreated check. Aproach Prima fungicide applied at VT followed by Aproach® fungicide at R2 had the greatest yield, although it was not significantly greater than Aproach followed by Aproach Prima (Figure 11).

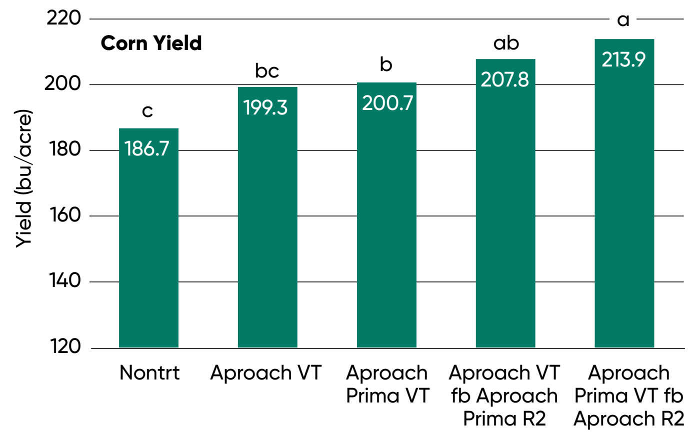


Figure 11. Fungicide treatment effects on corn yield in a 2019 Purdue University study.

Means followed by the same letter are not significantly different based on Fisher's Least Significant Difference test (LSD; α=0.05)

On-farm fungicide trials conducted in 2021 appeared to confirm concerns that the rapid reinfection rate of tar spot would make it difficult to control with a single pass fungicide treatment. Precise application timing was often critical, and two applications were necessary in some cases to provide adequate tar spot control. Disease forecasting models such as Tarspotter, developed at the University of Wisconsin, may be helpful in optimizing timing of fungicide applications. Tarspotter uses several variables, including weather, to forecast the risk of tar spot fungus being present in a corn field.

https://ipcm.wisc.edu/apps/tarspotter/

Several foliar fungicide products are available for management of tar spot in corn. (Table 2). Aproach® and Aproach® Prima fungicides have both received FIFRA 2(ee) recommendations for control/suppression of tar spot of corn.

Agronomic Practices

The pathogen that causes tar spot overwinters 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. Spores are known to disperse up to 800 ft, so any benefit from rotation or tillage practices that reduce corn residue, in a field may be negated by spores moving in from neighboring fields. Evidence so far suggests that rotation and tillage probably have little effect on tar spot severity. Agronomists have noted that infestation may occur earlier in corn following corn fields, where infection proceeds in a "bottom-up" manner from inoculum present in the soil, in contrast to rotated fields that more commonly exhibit "top-down" pattern of infection from spores blowing in from other fields.

Pioneer Agronomy

Tips for Scouting and Managing Tar Spot
- Kevin Fry,
Pioneer Field Agronomist

return to table of contents

Duration of leaf surface wetness appears to be a key factor in the development and spread of tar spot. Farmers with irrigated corn in areas affected by tar spot have experimented with irrigating at night to reduce the duration of leaf wetness, although the potential effectiveness of this practice to reduce tar spot has not yet been determined.

Yield potential of a field appears to be positively correlated with tar spot risk, with high productivity, high nitrogen fertility fields seeming to experience the greatest disease severity in affected areas. Research on *P. maydis* in Latin America has also suggested a correlation between high nitrogen application rates and tar spot severity (Kleczewski et al., 2019).

Mycotoxins

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

How Far Will Tar Spot Spread?

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 forecasts indicated the areas beyond the then-current range of infestation at highest risk for spread of tar spot were central Iowa and northwest Ohio. Observations in recent growing seasons have been consistent with model predictions, with further spread of tar spot to the east in Ohio, Ontario, and Pennsylvania and a dramatic expansion of tar spot across Iowa and into parts of Minnesota and Missouri. Results indicated the potential for further expansion to the north and south but primarily to the east and west, including corn production areas of New York, Pennsylvania, Ohio, Missouri, Nebraska, South Dakota, eastern Kansas, and southern Minnesota.

Table 2. Efficacy of fungicides labeled for tar spot in corn (Wise, 2021).

Product Name	Tar Spot Efficacy	Harvest Restriction
Aproach® 2.08 SC	G*	7 days
Aproach® Prima 2.34 SC	G-VG*	30 days
Affiance® 1.5 SC	G*	7 days
Delaro® Complete 3.83 SC	G-VG	35 days
Delaro® 325 SC	G-VG	14 days
Domark® 230 ME	G-VG*	R3
Fortix® 3.22 SC Preemptor™ 3.22 SC	G-VG*	R4
Headline® AMP 1.68 SC	G-VG	20 days
Lucento®	G*	R4
Miravis® Neo 2.5 SE	G-VG	30 days
Priaxor® 4.17 SC	G-VG*	21 days
Quilt® Xcel 2.2 SE	G-VG*	30 days
Revytek®	G-VG	21 days
TopGuard® EQ	G-VG*	7 days
Trivapro® 2.21 SE	G-VG	30 days
Veltyma®	G-VG	21 days

G = good, VG = very good

* A 2ee label is available for several fungicides for control of tar spot, however efficacy data are limited. Check 2ee labels carefully, as not all products have 2ee labels in all states. Always read and follow product label guidelines.

return to table of contents

Corn Yield Response to Fungicides in Eastern Ontario

Paul Hermans, *Pioneer Area Agronomist, and* ***Liam Bracken,*** *Sales Associate - Eastern Canada*

Key Findings

- Corn yield response to foliar fungicide treatment in Eastern Ontario was low in 2021, averaging only 2.7 bu/acre.
- Precipitation during grain fill was below average across all trial locations, resulting in minimal foliar disease pressure.

Study Description

- On-farm trials were conducted at nine locations in Eastern Ontario in 2021 comparing corn yields with and without foliar fungicide treatment.
- Each location included between two and seven Pioneer® brand corn products ranging in maturity from 91 to 95 CRM. Pioneer brand P9301AM™ (AM,LL,RR2) and P9535AM™ (AM,LL,RR2) were included at the majority of locations (7 and 6 locations, respectively).

Results

- Leaf disease pressure was minimal during grain fill due to dry conditions. Total rainfall in August averaged 50 mm (1.97 inches) across trial locations.
- The average yield response to foliar fungicide treatment across all hybrids and locations was 2.7 bu/acre (Figure 1).
  - Similar results have been observed in other Pioneer studies that had dry weather during grain fill.
- The average fungicide yield response of P9535AM™ was slightly greater than that of P9301AM™; however, both were below the level likely to cover the cost of treatment in most scenarios (Figure 2).

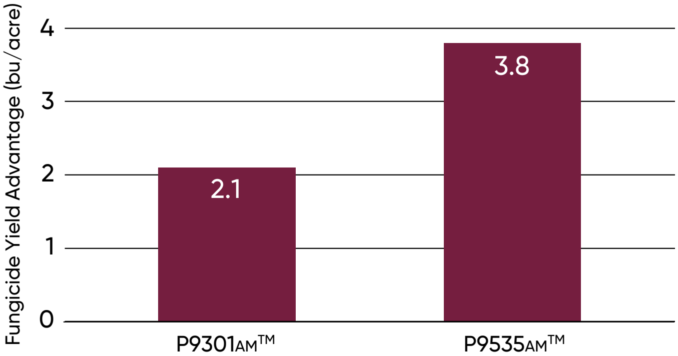


Figure 2. Average yield response to fungicide of the two Pioneer brand corn products included at most trial locations.

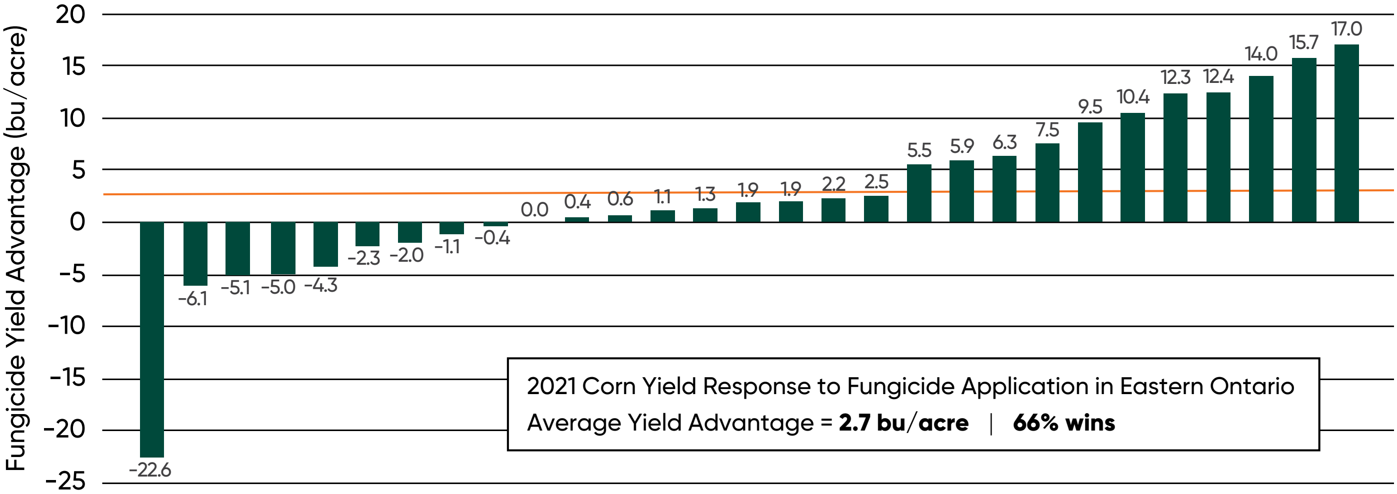
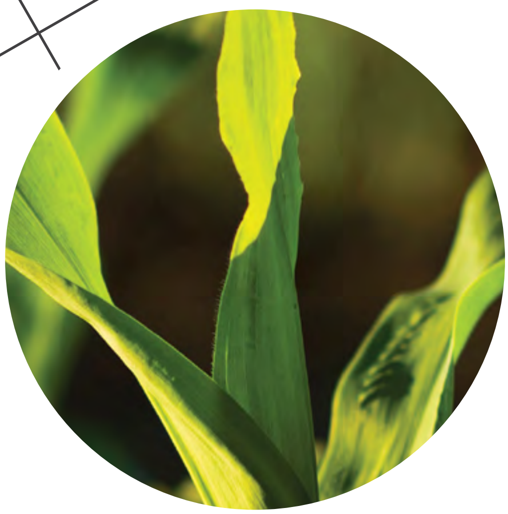


Figure 1. Corn yield response to foliar fungicide in Eastern Ontario in 2021. All paired comparisons across nine on-farm trial locations are shown.

return to table of contents



Seed and Seedling Diseases of Corn

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Corn planted into cold, wet soil can be susceptible to injury from soilborne pathogens.
- Soilborne pathogens may attack seeds and seedlings both before and after plant emergence, as well as the roots and mesocotyl of emerging or established plants.
- Corn seedling disease is caused by a complex of fungal pathogens that often occur together.
- Injury may be subtle or severe enough to require replanting. Surviving stands may have reduced yields due to low plant population, uneven plant growth and reduced plant fitness.
- Managing corn seedling diseases begins with utilizing an effective fungicide seed treatment package and avoiding planting when soil temperatures are likely to remain low for an extended period of time.
- Corn planted following a rye cover crop can be at greater risk of seedling disease, as rye can serve as an alternate host for soilborne pathogens that attack corn.

Corn planted into a **well-prepared seedbed** with **warm conditions** can generally outgrow the effects of ***pathogen attack.***

Seed and Seedling Diseases

Corn fields can contain numerous pathogens in the soil that are capable of infecting corn seeds and seedlings. Corn planted into a well-prepared seedbed with warm conditions that allow it to emerge quickly, can generally outgrow the effects of pathogen attack. However, corn planted into cold, wet soils that emerges more slowly can be susceptible to injury from soilborne pathogens. Soilborne pathogens may attack seeds and seedlings both before and after plant emergence, as well as the roots and mesocotyl of emerging or established plants.

The effect of soilborne diseases on stand establishment and plant development depends largely on the duration of adverse weather and the prevalence of other factors that affect overall plant health, emergence, and early growth. Soil compaction, heavy crop residues, crusting, herbicide or fertilizer injury, and excessive planting depth can all weaken the plant, delay emergence, and increase the susceptibility of corn seedlings to diseases.

When a **corn plant** succumbs to seedling disease, ***multiple pathogens*** are usually involved.

Conditions That Favor Disease

The ideal environment for most soilborne diseases that attack corn seeds and seedlings is wet and cool (50-60°F, 10-16°C). Under these conditions, corn develops very slowly. For example, when the soil temperature averages only 55°F (13°C), corn seedlings require over 20 days to emerge. Fungicide seed treatments applied at label rates to protect the seed during germination and emergence can provide protection for six weeks after planting. However, extended delays in emergence can stretch the limits of fungicide seed treatments and make seeds vulnerable to attack. Soil temperature during emergence is determined by geography, soil type, soil moisture, residue cover, tillage, planting date and weather patterns.

A corn plant infected with seedling disease. This field experienced cold conditions and saturated soils after planting.

Weather conditions are the most important determinant of growing environment in any year. Cold, wet conditions that favor seed and seedling disease development will occur periodically in all fields and frequently in some fields. The amount of inoculum in the soil also affects disease development. Soilborne pathogens that attack corn seedlings survive in both corn residue and in the soil. They are both saprophytic and parasitic, able to attack dead and living plant tissue. Pathogens have alternative hosts, sometimes including previous crops and weeds – both corn residue and that of other crops and weeds can be important to inoculum load. If a field has a history of seedling disease problems, inoculum load is likely to be high. Knowing the history of each field with respect to problem areas and related causes is important to successful management of seedling diseases.

Common Pathogens

Soil-inhabiting disease organisms that attack corn seeds and seedlings include *Pythium*, *Fusarium*, *Rhizoctonia*, *Penicillium*, *Colletotrichum*, *Diplodia*, and others (Table 1). Each of these fungal genera includes multiple species capable of infecting corn that can differ in pathogenicity and environmental influences.

Pythium, a water mold that survives in soil and plant debris, is an otherwise weak pathogen that tends to predominate under very wet soil conditions. This is because high soil moisture levels promote germination of the overwintering oospores. Soil water also provides a medium for the swimming of zoospores, the germinated motile spores that infect the corn root system. *Pythium* is one of the first groups of fungi to attack corn in the spring, due to the low temperature optimum of some species. Cool soil temperatures of 50-60°F (10-16°C) favor several *Pythium* species that are common in northern areas, particularly in early-planted fields, but the various species of *Pythium* are active over a wide range of temperatures.

Table 1. Symptoms and favorable environmental conditions for the most common pathogens affecting corn seedlings.

Pathogen	Symptoms	Favorable Environment
Pythium	Seminal roots and mesocotyl tissue are soft, water soaked and dark colored. Rotted surface can be peeled off roots.	Favored by very wet soil conditions. Several species favored by cold temperatures.
Fusarium	Small, discolored roots and/or rotted root tips. Mesocotyl firm or shriveled; may be tan/pink.	Wet soil, cold temperatures, compacted soil, nutrient deficiency, and herbicide injury.
Rhizoctonia	Sunken brown to reddish-brown lesions on roots and mesocotyl with white tissue that may remain mostly firm.	Rainfall followed by cool then warm, humid conditions. Infection is enhanced in well-aerated soil.

Other seedling pathogens like *Fusarium* and *Rhizoctonia* do not require extremely wet conditions in order to cause disease. *Fusarium* is a ubiquitous soilborne group of fungi that can be found to some degree on the majority of corn plants suffering from seedling diseases. *Rhizoctonia* is another very prevalent fungal group with a wide range of plant hosts.

When a corn plant succumbs to seedling disease, multiple pathogens are usually involved. Dying seed or seedling tissues below ground are rapidly colonized by a variety of fungi, all of which contribute to the decay, making it difficult to determine the primary pathogen. Consequently, it is useful to think of corn seedling disease as a complex of fungi that must be controlled as a group. Management strategies to reduce the risk of injury from soilborne pathogens are largely the same, regardless of the pathogen involved.

Diagnosing Seedling Diseases

Field Level Symptoms

At the field level, seedling disease may be slight to severe. Early symptoms of slow growth, chlorosis, stunting, and missing plants may be followed by near complete recovery if favorable conditions allow corn to outgrow the injury. But if cold, wet conditions continue, symptoms often worsen and stands decline. Missing plants may be in patches or scattered among other plants. Often, a chlorotic, stunted plant will appear next to a healthy one (Figure 1). Symptoms may be more noticeable in low-lying areas of the field. These are not typical symptoms associated with other seedling problems such as fertilizer or herbicide injury, nutrient deficiency, or restricted growth due to compaction or crusting.

Figure 1. Corn plant that succumbed to seedling disease neighbored by two healthy plants.

In extreme cases, replanting the entire field or affected field areas may be necessary. Even when replanting is not required, diseased fields may have reduced yields due to low plant population, uneven plant growth, and reduced plant health and fitness. Stunted plants surrounded by healthy plants may be uncompetitive and fail to produce an ear. Rotted roots seldom recover entirely, resulting in plants that are less able to withstand later stresses such as drought, storms, insect feeding, and stalk rot development.

Seed and Plant Symptoms

Soilborne pathogens may attack seeds and seedlings both before and after plant emergence, as well as the roots and mesocotyl of emerging or established plants.

Seeds: In some cases, seeds may rot prior to germination. Affected seeds are often soft, discolored, and overgrown with fungi. Rotted seeds decompose very rapidly and may be difficult to find. Soil adhering tightly to the decomposing seed may help to obscure it.

Pre-emerged seedlings: Oftentimes, the seed germinates but the seedling is killed before it emerges from the soil. The coleoptile and primary roots may be discolored and have a wet, rotted appearance.

Post-emerged seedlings: Seedlings may emerge through the soil surface before developing symptoms. Plants affected at this stage may grow more slowly than surrounding, healthy plants and appear chlorotic (yellow), stunted or wilted. In severe cases, damping off of seedlings may occur. Damping off generally refers to rapid wilting and death of seedlings as soft rot collapses the stem, often at the soil line. *Pythium* and *Fusarium* are the most common fungi associated with seed rot and damping off of corn.

Roots and mesocotyl: Discolored, sunken lesions may be evident on the mesocotyl, which eventually becomes soft and water soaked. The root system is usually poorly developed and discolored, and water-soaked roots may slough off. If the primary root system and mesocotyl are severely affected before the nodal or permanent root system has developed, the plants have little chance of survival.

For further diagnosis of plants with aboveground symptoms, carefully dig up living plants, wash the soil from the roots, and look for rotted tissue and discolored lesions on the plant stem, crown, and roots. Discoloration may range from whitish pink to gray, to dark brown or black, or even greenish blue, depending on the array of pathogens involved.

Several corn plants in a row dead from seedling disease in a field that experienced cold and wet conditions after planting.

Distinguishing Seedling Diseases

Subtle differences exist between the various soil fungi that attack corn seeds and seedlings. For example, *Pythium* thrives in cool, wet soils and is among the first plant pathogens active in the spring. In spite of subtle differences, it is difficult or impossible to distinguish these pathogens based on symptoms alone. Many symptoms are similar, and more than one fungus invariably attacks the plant. Distinguishing among pathogens has little value anyway, as management practices are similar across soil diseases. The important distinction is between diseases and other seedling problems, including insect feeding, fertilizer or herbicide injury, or restricted growth due to compaction or crusting.

Reducing the Risk of Seedling Disease

Managing corn seedling diseases begins with an effective fungicide seed treatment package. Additionally, growers can help to minimize the effects of seedling diseases by avoiding planting when soil temperatures are likely to remain low for an extended period of time. Management practices that minimize soil compaction, crusting, dense crop residue over the row, herbicide injury, or fertilizer injury will help maintain seedling health and reduce susceptibility to soilborne pathogens.

Seed Treatments

The LumiGEN® fungicide seed treatment package on Pioneer® brand corn products includes five different active ingredients, providing multiple modes of action against each of the three primary seedling disease pathogens, *Pythium*, *Fusarium*, and *Rhizoctonia* (Table 2).

Table 2. Activity of the fungicide components of the LumiGEN® seed treatment package on corn products against primary corn seedling diseases.

Trade Name	Active Ingredient	*Pythium*	*Rhizoctonia*	*Fusarium*
Lumiscend™ Pro seed treatment	Metalaxyl	●		
	Ethaboxam	●		
	Inpyrfluxam		●	●
Lumiflex™ seed treatment fungicide	Ipconazole		●	●
L-2012 R biofungicide	*Bacillus amyloliquefaciens* strain MBI 600		●	●

Like all pesticides, seed-applied fungicides break down in the soil. Applied at label rates, these products can provide protection against seedling diseases for six weeks after planting. The benefits of this early protection can extend all season though, as the establishment of a strong and healthy root system can make the plant better able to fend of pathogens later in the season.

Insecticide seed treatments have no direct activity against diseases but may contribute to disease control in a secondary way. By reducing insect feeding on roots and plants, insecticide seed treatments reduce the points of entry into the seedling by pathogenic fungi.

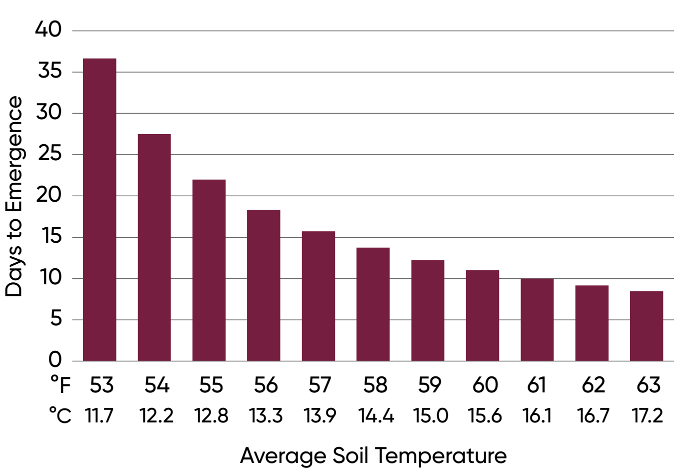


Figure 2. Estimated days to corn emergence by average soil temperature, based on 110 GDUs to emergence.

Soil Temperature at Planting

Most soilborne pathogens are ineffective against a treated corn seed and a healthy, growing corn seedling. But at soil temperatures below 55°F (13°C), corn germination and emergence require three weeks or more (Figure 2). During this time in the soil, the corn seed and seedling are vulnerable to a myriad of stresses that can weaken the plant and increase its susceptibility to seedling diseases that often thrive in cool, wet conditions. Primary stresses include excessive herbicide uptake, fertilizer burn, and insect feeding.

Growers should begin their corn planting in fields with lighter soils, good drainage, and minimum residue over the row. In heavy-textured, low-lying, or high-residue fields, especially those with a history of seedling diseases, early planting in cold soils is not recommended. Generally, growers should wait until soil temperatures rise above 50°F (10°C) and are likely to remain there before planting corn in those fields.

Corn growing in killed rye stubble. Rye can serve as a green bridge for soilborne pathogens that attack corn seedlings.

Residue Management

A seedbed that is well-drained with little or no crop residue over the row will reduce the risk of corn seedling diseases. Compaction, crusting and dense residue in the row are barriers to seedling emergence and are often a primary contributor to seedling disease development.

Cover Crop Systems

Corn planted following a rye cover crop can be at greater risk of seedling disease, as rye can serve as an alternate host for soilborne pathogens that attack corn. Soilborne pathogen populations that would normally decline during the fallow period over the winter when no host crop is present are instead sustained by the rye cover crop. When the rye is terminated, the dying roots release pathogens back into the soil. Corn planted before or immediately following termination can consequently be subject to a higher inoculum load. Iowa State University pathologists recommend waiting at least 10-14 days to plant corn following termination of a rye cover crop to reduce the risk of corn seedling diseases.

return to table of contents

Field Performance of Lumiscend™ Pro Fungicide Seed Treatment

Mark Jeschke, Ph.D., Agronomy Manager, Ron Sabatka, Farm Manager Coordinator,
Paul Gaspar, Ph.D., Field Scientist, and Brad Van Kooten, Seed Applied Technologies Marketing Leader

Key Findings

- Lumiscend™ Pro fungicide seed treatment increased corn yield compared to the former standard fungicide seed treatment package in field research studies.
- Lumiscend Pro fungicide seed treatment increased corn stand establishment compared to a competitor seed treatment in inoculated field plots, particularly in plots inoculated with *Rhizoctonia* and metalaxyl-resistant *Pythium ultimum*.

Lumiscend™ Pro Fungicide Seed Treatment

- Lumiscend™ Pro is a fungicide seed treatment formulated to protect against damping off and seedling blight, as well as seed and root rot caused by *Pythium* spp., *Fusarium* spp., and *Rhizoctonia solani.*
- Lumiscend Pro includes three active ingredients: ethaboxam, metalaxyl, and inpyrfluxam.
- Ethaboxam and metalaxyl provide two robust modes of action against *Pythium* spp., including metalaxyl- and mefenoxam-resistant strains.
- Inpyrfluxam is a new active ingredient (FRAC Group 7) that protects against *Fusarium* spp., as well as providing industry-leading protection from *Rhizoctonia* seed and soil-borne diseases.

Field Research

- Field experiments were conducted in 2020, 2021, and 2022 to evaluate the performance of Lumiscend Pro fungicide seed treatment for stand establishment and yield in corn.
- Replicated experiments conducted at 50 locations in 2020 and 2021 compared yield of corn treated with Lumiscend Pro to corn treated with the previous standard fungicide seed treatment package for Pioneer® brand corn products (2022 FST).
- A replicated field experiment conducted near Valdosta, GA, in 2022 compared stand establishment of corn seed treated with Lumiscend Pro fungicide seed treatment to seed treated with a competitor FST and seed with no FST in plots inoculated with common corn seedling pathogens.
  - Plots were inoculated with *Rhizoctonia, Fusarium graminearum, Fusarium oxysporum, Pythium ultimum,* or metalaxyl-resistant *P. ultimum*.
  - Plots were all planted at a seeding rate of 29,000 seeds/acre and plant stand was evaluated at 14, 21, and 28 days after planting (DAP).

Replicated seed treatment trial near Valdosta, Georgia, in 2022 inoculated with *Fusarium graminearum*. Seeding rate in the trial was 29,000 seeds/acre. Photo shows stand establishment 28 days after planting.

Results

2020-2021 Field Experiments

- At 16 field research locations that experienced high early season stress and disease pressure, corn seed treated with Lumiscend Pro fungicide seed treatment averaged 3 bu/acre more than that of seed treated with the previous standard fungicide seed treatment (Figure 1).
- Across all 2020 and 2021 field research locations, yield of corn seed treated with Lumiscend Pro fungicide seed treatment was similar to that of seed treated with the previous standard fungicide seed treatment, averaging 1 bu/acre higher (Figure 2).

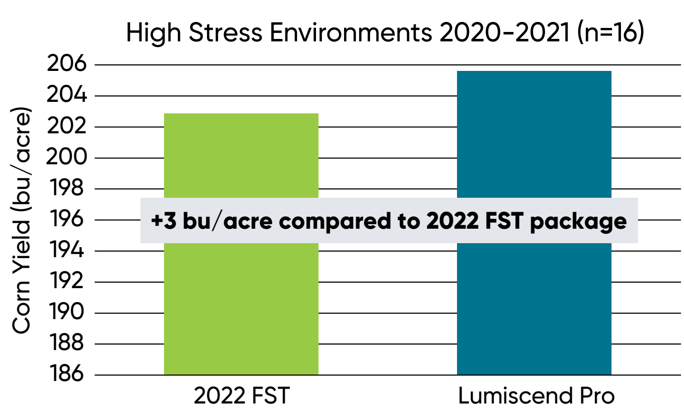


Figure 1. Average yield of corn seed treated with Lumiscend Pro fungicide seed treatment and seed treated with the previous standard fungicide seed treatment across 16 replicated field experiments with high early season stress and disease pressure in 2020 and 2021.

return to table of contents

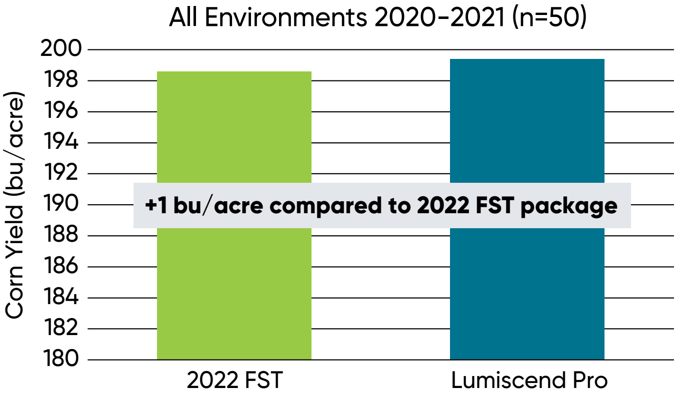
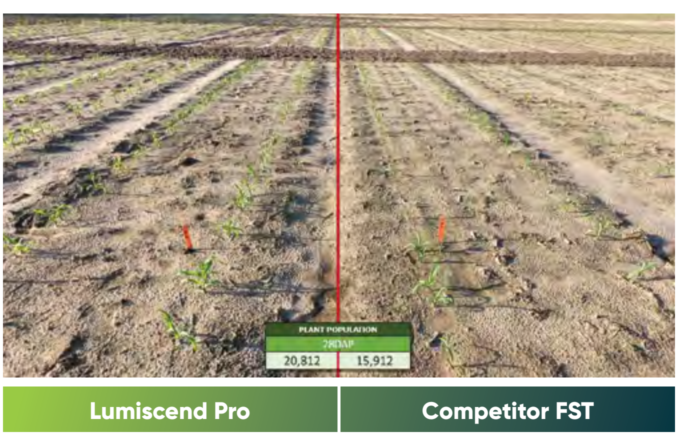


Figure 2. Average yield of corn seed treated with Lumiscend™ Pro fungicide seed treatment and seed treated with the previous standard fungicide seed treatment across 50 replicated field experiments in 2020 and 2021.

2022 Stand Establishment Experiment

- High levels of disease pressure were successfully induced in all inoculated plots, as demonstrated by the extremely poor stand establishment of corn seed with no fungicide seed treatment (Figure 3).
- Lumiscend Pro fungicide seed treatment provided a clear advantage in stand establishment compared to the competitor FST in plots inoculated with *Rhizoctonia,* averaging nearly 5,000 plants/acre more at 28 days after planting.
- In plots inoculated with *Fusarium* or *Pythium* spp., stand establishment was often comparable between Lumiscend Pro fungicide seed treatment and the competitor FST at 14 days after planting.
- Beyond 14 days after planting, the competitor FST experienced continued attrition in plant stand as measured at 21 and 28 DAP; however, corn treated with Lumiscend Pro fungicide seed treatment did not.



Replicated seed treatment trial near Valdosta, Georgia, in 2022 inoculated with *Rhizoctonia.* Seeding rate in the trial was 29,000 seeds/acre. Photo shows stand establishment 28 days after planting.

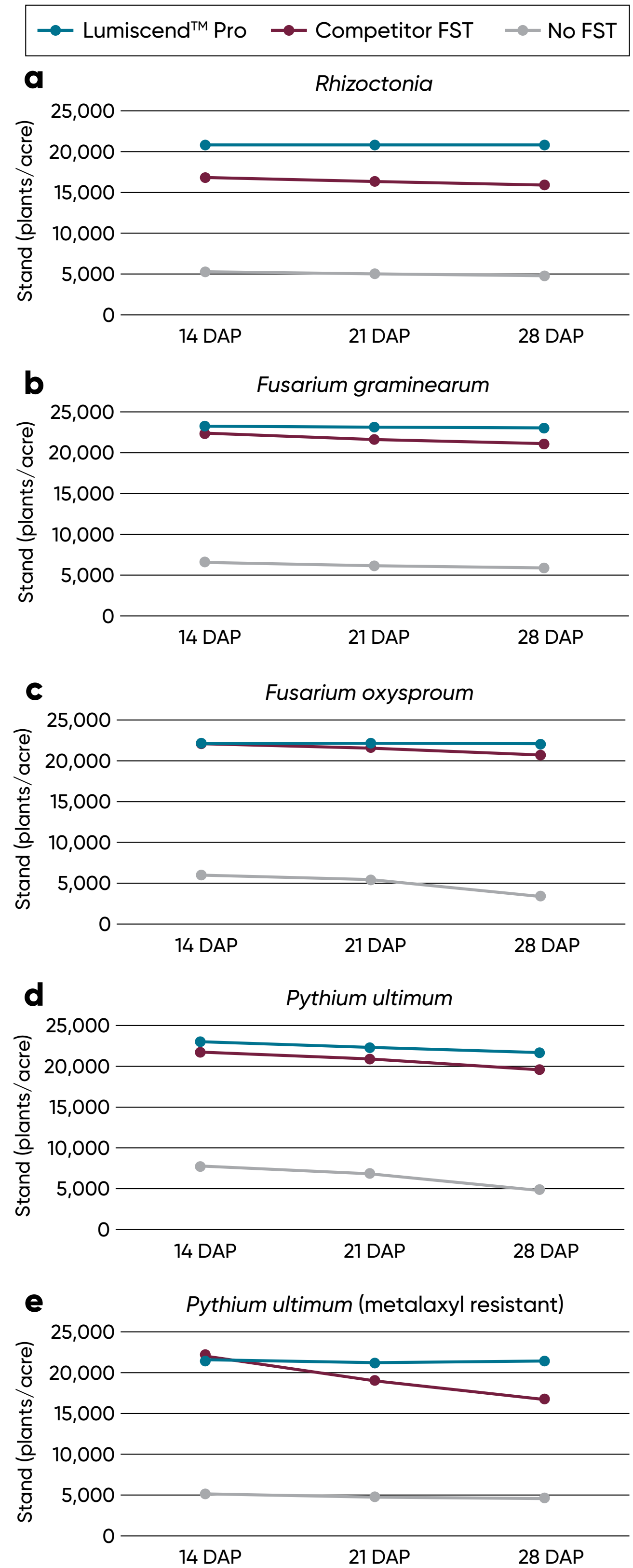


Figure 3(a-e). Plant stand 14, 21, and 28 days after planting in 2022 field plots inoculated with common corn seedling pathogens.

return to table of contents

Seedcorn Maggot

Cori Lee, Agronomy Sciences Intern

Key Points

- Seedcorn maggot *(Delia platura)* larvae damage corn and soybeans by feeding on germinating seeds or seedlings.
- Pest pressure is common in fields with a history of infestation, or that have been recently tilled or have high organic matter, including manure, cover crops, or weeds.
- Insecticide seed treatments can provide effective protection against seedcorn maggot in both corn and soybeans.

Pest Facts

- Seedcorn maggot *(Delia platura)* was introduced from Europe and was first found in the United States in the mid-1800s. It is now present across the U.S. and in Canada.
- It feeds on germinating seeds or seedlings of corn and soybeans and decaying organic matter.
- Unlike many other insect pests, seedcorn maggot tends to affect whole fields rather than just localized patches.

Figure 1. Seedcorn maggot feeding on soybean cotyledons.

Figure 2. Mature seedcorn maggot larvae found in the soil.

Impact on Corn and Soybean

- This pest is damaging in the larval stage when it feeds on germinating seeds or emerging seedlings.
- Seeds and seedlings attacked by seedcorn maggot can have a range of symptoms and severity. Damage may include destroyed seed or cotyledons from feeding. Fields severely impacted by seedcorn maggot may need to be replanted.
- Injury from seedcorn maggot may also serve as an entry point for pathogens. In combination with other conditions that delay germination, damage can slow plant growth in the early vegetative stages or cause additional stand loss.

Figure 3. Poor stand establishment in a soybean field due to seedcorn maggot damage.

Life Cycle

- Overwintering in the soil as pupae, seedcorn maggot is difficult to detect in the fall before it causes damage.
- Adults emerge in the spring after the ground thaws and enough heat units have been accumulated. Females will then mate and lay eggs in freshly plowed fields at the soil surface.
- The eggs will hatch within a few days and develop into their larval stage.
- In the upper Midwestern United States, seedcorn maggot will complete three to four generations in the growing season, with each life cycle taking three to four weeks. However, they are only a pest during planting season and later generations are not a concern.

Figure 4. Pupae of seedcorn maggot found in a soybean field.

Key Characteristics

Egg

- Eggs are elongated and white; however, they are generally not visible on the soil surface.
- Eggs will hatch a few days after being laid.

Larvae

- Seedcorn maggot larvae have a pale, yellowish color and are ¼ inch long when fully grown.
- They have a long, narrow, cylindrical, tapered body with no head or legs. Maggots have a small black mouth with hook-shaped mouth parts.

Pupae

- The pupa stage has a wheat seed-like appearance, with a caramel brown color and a hard, football shaped casing.

Adult

- Like the larva, the adult is ¼ inch in length and is similar to a house fly in shape with a grey-brown color and red eyes.

Figure 5. Adult seedcorn maggot.

Scouting

- Scouting should be done in freshly planted fields from emergence to early seedling stages.
- Scouting should be prioritized on fields that are at higher risk of have a history of infestation.
- Seedcorn maggots are most prevalent in fields with high organic matter and decaying vegetation. Populations are also generally higher following soybeans than following corn.
- Because infestation is likely to occur across the whole field, it is important to check multiple places when scouting.
- If seedlings are damaged, check for the presence of maggots by digging around plants and looking for larvae or damage to the seed.

Figure 6. Seedcorn maggot larvae feeding on a kernel of corn.

Management Considerations

- There are no effective rescue treatments available for control of seedcorn maggot, making prevention and minimizing risk critical.
- Insecticide seed treatments can provide effective protection against seedcorn maggot in both corn and soybeans.
  - LumiGEN® premium seed treatment packages available for Pioneer® brand corn provide above average protection against seedcorn maggot.
  - LumiGEN® premium seed treatments for Pioneer® brand soybeans include two available insecticide modes of action against seedcorn maggot.
- In-furrow insecticides may also be considered in fields with a high risk of infestation.
- Replanting is the only management option after damage has occurred.
- Replant decisions should consider the remaining stand, date, and potential yield.
- Cultural practices that may be helpful in reducing the severity of seedcorn maggot damage include:
  - Delay planting until the soil is warmer to promote rapid germination and emergence.
  - Higher seeding rates.
  - Earlier termination of cover crops.
  - Wait two weeks following tillage or manure application to plant.
  - Avoid planting during peak fly emergence.
  - Avoid planting before cool and wet periods.

return to table of contents

Fall vs. Spring Strip-Till in Indiana

Lauren Schwarck, M.S., and Tony J. Vyn, Ph.D., Agronomy Department, Purdue University

Key Findings

- A five site-year field-scale experiment compared corn growth and yield between fall and spring strip-tillage.
- Whole-plant biomass at the V6 development stage was greater with fall strip-till in four out of five site years.
- Strip-till timing had little impact on corn yield, with fall strip-till slightly outyielding spring strip-till in only one of the five site years.

Fall vs. Spring Strip-Till

- Whether to strip-till in the fall or the spring is an important consideration for farmers using strip-till systems, and the best approach for a given farm can depend on a number of factors, including the type of strip-till machine being used, the texture and erodibility of the soil, nutrients being applied and labor availability.
- Fall strip-till can help avoid wet soil conditions more common in the spring and allow the tilled soil to mellow over the winter, but it can increase the risk of erosion in the strips during the winter and spring.
- Spring strip-till can provide a freshly aerated seedbed at planting and reduces soil erosion risk but can create clods and poor seed to soil contact if soils are wetter than ideal.

Purdue University Research

- A five site-year field-scale experiment was conducted at the Agronomy Center for Research and Education (ACRE Farm) near West Lafayette, IN, and Pinney Purdue Agriculture Center (PPAC Farm) near Wanatah, IN, to evaluate effects of strip-till timing on corn growth and development.
- This research was led by Dr. Tony Vyn and Lauren Schwarck of Purdue University and partially supported by the Pioneer Crop Management Research Awards (CMRA) Program.

Study Description

- Strip-tillage was done in either the spring or fall using an Environmental Tillage Systems 6-row SoilWarrior coulter-type strip-till unit.
- Potassium and boron fertilizer (Aspire®, 0-0-58-0.5B) was banded in the strips at rates of 0, 58, or 116 lbs K_2O/acre, representing non-treated, half-rate, and full rate treatments, respectively.
- Soil samples were taken shortly after planting each year to measure levels of plant-available potassium.
- Whole-plant tissue samples were taken at V6 and ear leaf samples at R1 to evaluate differences in potassium concentration among treatments.
- Research at the ACRE farm alternated between two fields from 2016 to 2019; the study repeated following the soybean year with the treatment positions fixed for data collection during corn years.
- Research at the PPAC farm was conducted in one field in 2019.

Results

- Whole plant tissue samples taken at the V6 stage showed that the concentration of K was similar for all site years between the two timings (data not shown) but fall strip-tillage frequently had more biomass compared to spring strip-till (Figure 1).
- Ear leaf K concentrations at R1 showed no consistent difference between fall and spring strip-till timings, with fall strip-till higher in one site year, spring strip-till higher in one site year, and no significant difference in three site years (Figure 2).
- Ear leaf K concentrations increased with Aspire™ potassium and boron fertilizer application (data not shown).
- Corn yield showed little difference between fall and spring strip-till (Figure 3), with a small but significant difference detected in only one of the five site years. Fall strip-till averaged 7 bu/acre more than spring strip-till in this site year.

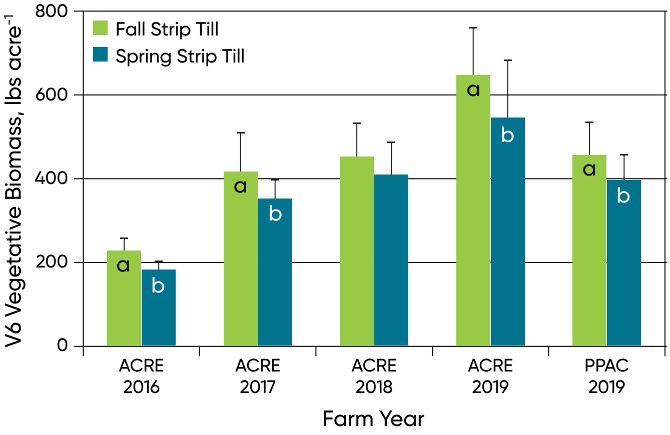
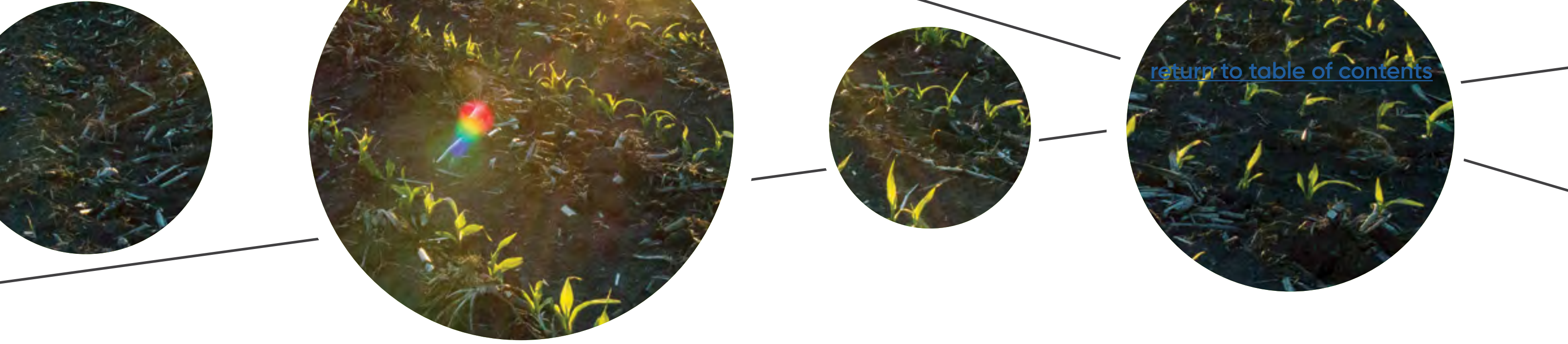


Figure 1. Aboveground plant biomass at the V6 development stage for fall and spring strip-till, averaged across all K application rates. Letters indicate a significant difference between fall and spring strip-till ($p<0.05$).



return to table of contents

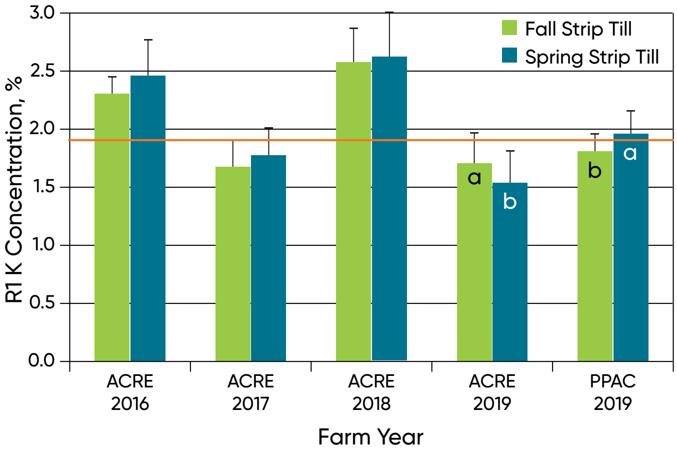


Figure 2. Ear leaf K concentration at the R1 development stage for fall and spring strip-till, averaged across all K application rates. The orange line represents the critical K concentration recommended at R1 by the Tri-State Fertilizer Recommendation Guide (1.9%) (Vitosh et al., 1995). Letters indicate a significant difference between fall and spring strip-till ($p<0.05$).

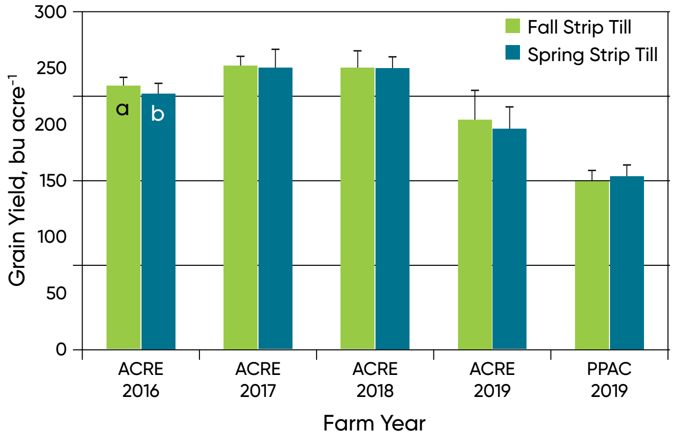


Figure 3. Corn grain yield for fall and spring strip-till, averaged across all K application rates. Letters indicate a significant difference between fall and spring strip-till ($p<0.05$).

Discussion

- With little difference among strip-till timings both in-season and at harvest, there was no apparent advantage to one timing over another when planting dates were the same. However, it is well known that a potential benefit with fall strip-tillage is that it enables earlier planting in spring on finer-textured soils.
- An important consideration from this Purdue research (and other strip-till timing studies) is that tillage was performed in optimal conditions. Because optimal conditions were achieved in both the fall and spring, there were no plant population differences and only small growth differences due to strip-till timing.
- Whenever performing strip-till, it is essential to consider the soil condition (moisture, residue, topography, etc.). The soil surface may seem as though the soil is at the ideal moisture for tillage but digging down several inches may reveal that the soil is too wet (Figure 4). If conditions are not conducive for effective strip-till, farmers could potentially be causing damage that could limit future corn growth and development.
- Wet soil conditions during strip-till will lead to clods, causing poor seed to soil contact and smearing of sidewalls limiting root growth (Demander et al., 2013).
- Wet soil conditions are commonly prevalent in the spring, leading North Dakota specialists to generally recommend fall strip-tillage, with spring strip-tillage only advised on coarse-textured soils with low organic matter (Nowatzki et al., 2017).

Figure 4. Excessive moisture conditions not ideal for tillage.

return to table of contents

Effects of Potassium Fertilizer Placement on Availability and Uptake

Lauren Schwarck, M.S., and Tony J. Vyn, Ph.D., Agronomy Department, Purdue University

Key Findings

- A five site-year field-scale experiment evaluated effects of potassium (K) fertilizer placement and tillage on K availability and uptake, and corn yield.
- Patterns of K stratification within the top 8 inches of the soil profile differed among tillage systems.
- Plant K concentration tended to be higher at V6 when fertilizer was incorporated with tillage, but no significant differences were detected at the R1 stage or in grain.

Advantage to Banded K in Strip-Till?

- Research has suggested a potential advantage to placement of potassium (K) fertilizer at depth in the soil rather than applying to the surface in conventional broadcasting (Bordoli and Mallarino, 1998; Mallarino et al., 1999).
- This conceptual benefit is in response to the significant stratification of plant-available K in the soil commonly observed in conservation tillage systems.
- However, it is important to acknowledge the variability in response to K placement due to subsequent soil conditions (precipitation, reduced tillage, etc.) following application as well as inherent soil test K levels (Randall and Hoeft, 1988).
- Even when not banding, some researchers suggest that incorporation of K fertilizers into a greater amount of soil volume may benefit corn (Bell et al., 2017; Ebelhar and Varsa, 2000; Kovar and Barber, 1987; Randall and Hoeft, 1988).

Purdue University Research

- A five site-year field-scale experiment was conducted at the Agronomy Center for Research and Education (ACRE Farm) near West Lafayette, IN, and Pinney Purdue Agriculture Center (PPAC Farm) near Wanatah, IN, to evaluate effects of K fertilizer placement and tillage practices on K availability, uptake, and corn yield.
- This research was led by Dr. Tony Vyn and Lauren Schwarck of Purdue University and partially supported by the Pioneer Crop Management Research Awards (CMRA) Program.

Study Description

- Research at the ACRE farm alternated between two fields from 2016 to 2019; the study repeated following the soybean year with treatment positions fixed for data collection during corn years. Research at the PPAC farm was done in one field in 2019.
- Four K placement and tillage systems were compared:
  1. (NT) No-till with broadcast K
  2. (FST) Fall strip-till with banded K
  3. (SST) Spring strip-till with banded K
  4. (FC) Fall chisel + spring field cultivation with broadcast K
- Tillage systems were compared with and without application of potassium and boron fertilizer (Aspire®, 0-0-58-0.5B) at a rate of 116 lbs K_2O/acre.
- Strip-tillage was done in either the spring or fall using an Environmental Tillage Systems 6-row SoilWarrior coulter-type strip-till unit.
- Soil samples were taken shortly after planting each year to measure levels of plant-available potassium.
- Whole-plant tissue samples were taken at V6 and ear leaf samples at R1 to evaluate differences in potassium concentration among treatments.

Results

- Stratification of soil test K was evident in this experiment; an example from one site year of the study is shown in Figure 1.
- The strategic incorporation of fertilizer into the crop row within the strip-till systems led to what appears to be more stratification compared to FC and NT because the latter had fertilizer spread across the surface (between-row and in-row).
- The FC system had less evident stratification compared to NT due to mixing from tillage (Figure 1).

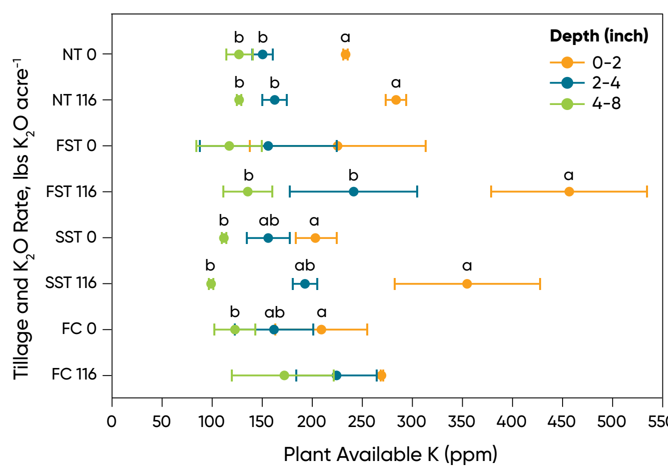


Figure 1. Example of K stratification in the soil profile. Concentration of K decreased with soil depth, but degree of stratification differed among tillage and K treatment systems. Letters indicate significant differences among the sampling depths at $p<0.05$.

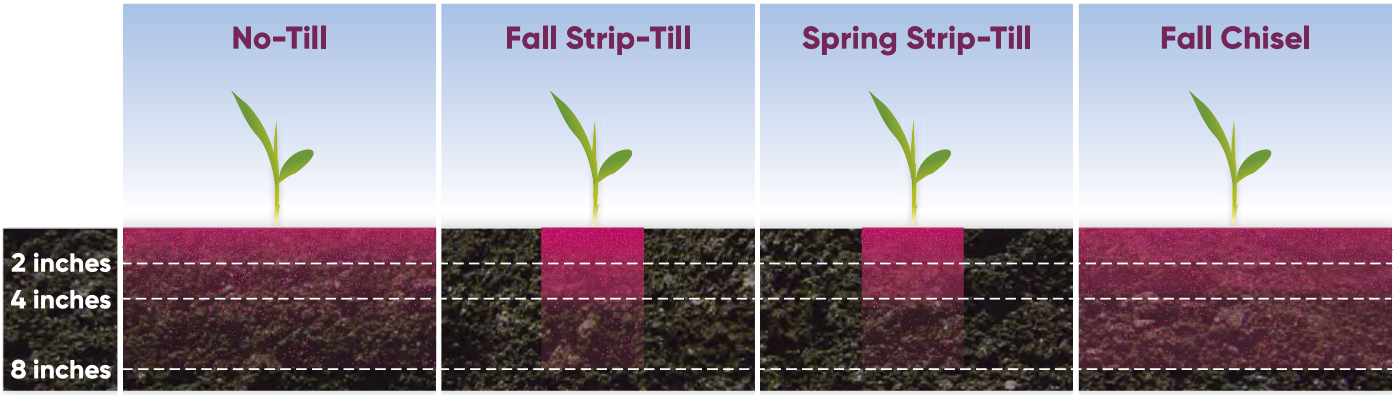


Figure 2. Visual representation of differences in K stratification among tillage systems with 116 lbs K_2O/acre applied based on data shown in Figure 1. The fall chisel system had a more even distribution of K in the top 8 inches of soil than the no-till and strip-till systems. Banded application in the strip-till systems greatly increased K concentration in the top 2 inches of soil in the row relative to broadcast application.

- Because of fertilizer placement in the crop row zones, FST and SST had the highest concentrations of K in the crop row. However, most of the increase in K concentration from fertilizer application was in the 0 to 2-inch depth, suggesting that coulter-based strip-till implements with above-surface delivery tubes may have difficulty placing fertilizer deeper than 2 inches. A visual representation of the differences in K stratification and application zones among tillage systems is shown in Figure 2.
- Early season samples collected at the V6 stage showed differences among tillage systems in K content (Figure 3).
- Corn in the NT treatment commonly had the lowest K content, with concentrations significantly lower than one or more of the tillage treatments observed in four out of five site years.
- Although V6 K content tended to be higher when fertilizer was incorporated with tillage, no significant differences among tillage systems in K concentration were detected with ear leaves at the R1 stage or in grain at maturity.

Conclusions

- Stratification of K in the soil could limit K availability to corn during the growing season if near-surface moisture is scarce during periods of high plant K demand.
- Ensuring adequate K availability to corn plant can benefit the plant by helping with water regulation, improved tolerance to low temperatures (at the beginning of the growing season), disease/pest tolerance (corn can better avoid infection and tolerate higher levels of foliar damage), and improved N use efficiency (corn plants can better utilize N with better K fertility).
- More remains to be learned about how K nutrition can influence plant health in modern corn production systems and how farmers can maximize efficiency of K fertilizer applications.
- The efficient use of K fertilizer is difficult to measure because of the influence a K fertilizer application can have over multiple years and the inability to detect all the K present in the soil.

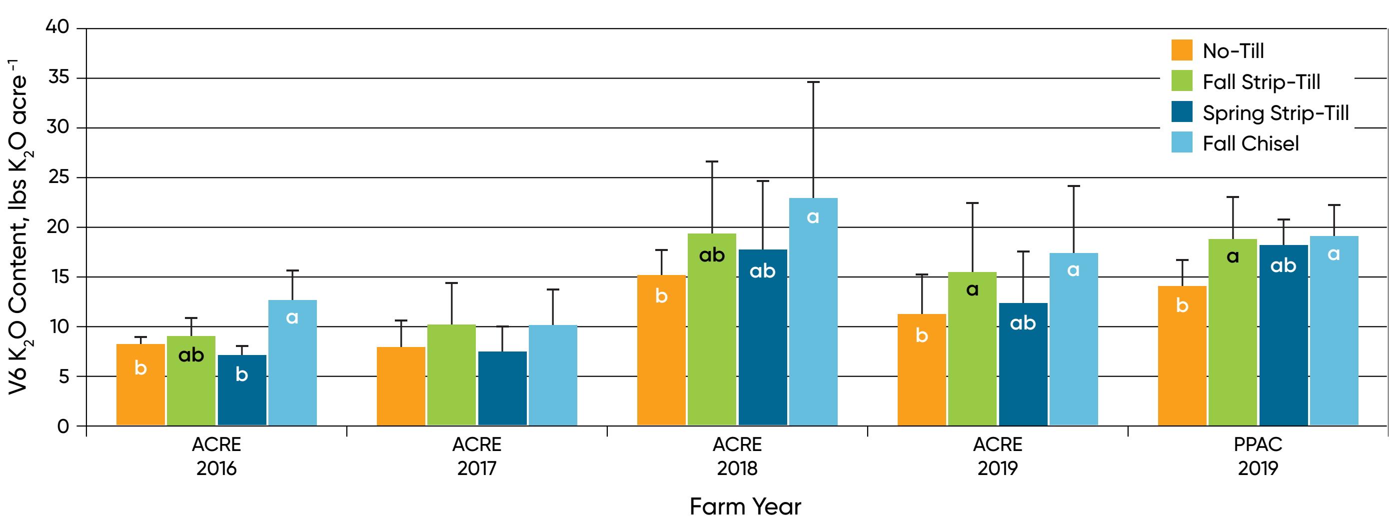


Figure 3. Average K_20 content at V6 for the 116 lbs K_2O/acre treatment within each tillage system. Letters represent significant differences among tillage systems at $p<0.05$ within a farm year.

return to table of contents

Can Potassium Fertilizer Rates Be Reduced in Strip-Till?

Lauren Schwarck, M.S., and Tony J. Vyn, Ph.D., Agronomy Department, Purdue University

Key Findings

- A field-scale experiment was conducted to evaluate potassium (K) uptake and corn yield with banded application in a strip-till system.
- Tissue samples taken at the V6 stage showed differences in K concentration between full- and half-rates of K, but not until the second year of corn in the rotation.
- Results suggest the possibility of longer-term negative consequences if a reduced rate is maintained over several years.

Objectives

- The ability to band fertilizer into the tilled strip where most corn roots are located has led some adopters of strip-till to question if potassium (K) fertilizer rates could be reduced.
- Previous research has suggested rate can interact with placement; i.e., lower rates in a band generally have greater nutrient uptake efficiency than a higher rate broadcast (Randall and Hoeft, 1988), but some research has not found rate differences in maize response to K placement (Bordoli and Mallarino, 1998).
- There are concerns that reduced rates used over an extended period of time may negatively impact grain yield and plant health.

Purdue University Research

- A four site-year, field-scale experiment was conducted at the Agronomy Center for Research and Education (ACRE Farm) near West Lafayette, IN, to evaluate K uptake and corn yield with full and reduced rates of K fertilizer with banded application in a strip-till system.
- This research was led by Dr. Tony Vyn and Lauren Schwarck of Purdue University and partially supported by the Pioneer Crop Management Research Awards (CMRA) Program.

Study Description

- Strip-tillage was done in either the spring or fall using an Environmental Tillage Systems 6-row SoilWarrior® coulter-type strip-till unit.
- Potassium and boron fertilizer (Aspire®, 0-0-58-0.5B) was banded in the strips at rates of 0, 58, or 116 lbs K_2O/acre, representing non-treated, half-rate, and full-rate treatments, respectively.
- Research alternated between two fields planted in a corn-soybean rotation, with one field in corn in 2016 and 2018 and the other in 2017 and 2019.
- Treatments were only imposed before corn in the corn-soybean rotation and applied in the same location in the fields during the corn years of the rotation. This methodology allowed responses to K rates to be observed for both first- and second-year corn.
- Whole-plant tissue samples were taken at V6 and ear leaf samples at R1 to evaluate differences in potassium concentration among treatments.
- The distribution of plant-available K for each site-year and the critical level based on the average cation exchange capacity (CEC) for the area currently recommended in the Tri-State Fertilizer Recommendations (Vitosh et al., 1995) is shown in Figure 1. All study locations were close to meeting the recommended critical level based on the CEC; however, a majority of locations had portions of the field area that were considered insufficient.

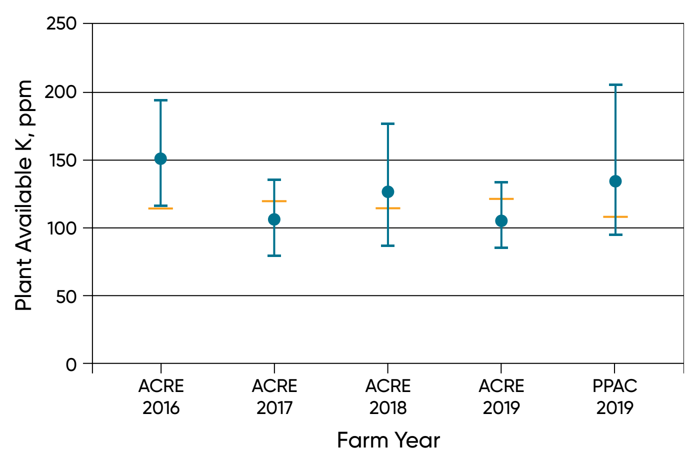


Figure 1. Distribution of plant available K (parts per million, or ppm) to a depth of eight inches for each site year (minimum, maximum, and average). Orange bars indicate critical values calculated using the Tri-State Fertilizer Recommendation Guide based on the average CEC for the control plots.

- Grain yield also did not show a significant difference between the 58 and 116 lbs K_2O/acre rates for either field-year, but in the second year, 58 lbs K_2O/acre did not significantly differ from either the 0 or 116 lbs K_2O/acre (Figure 3).
- Results from this experiment suggest that, initially, there may be few negative consequences (possibly lower initial K concentration at the beginning of the growing season) to cutting K fertilizer rates when utilizing strip-till in soils that are already near the soil test K critical level.
- However, results also suggest the possibility of longer-term negative consequences if a reduced rate is maintained for several years.
- Reducing fertilizer rates with strip-till incorporation (and particularly at rates below actual crop removal) should only be considered when soils are well above the critical levels and when soil and tissue K concentrations are monitored closely to prevent considerable mining of exchangeable soil K supplies.

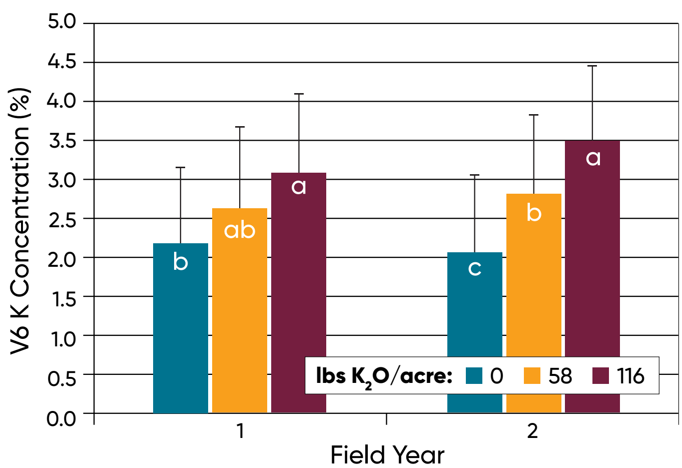


Figure 2. Average concentration of K in whole-plant tissue samples taken at V6 in the first and second year of corn in the rotation with zero, half and full rates of K fertilizer. Letters indicate significant differences in rate for strip-till (average of fall and spring) treatments within a specific field year at $p<0.05$.

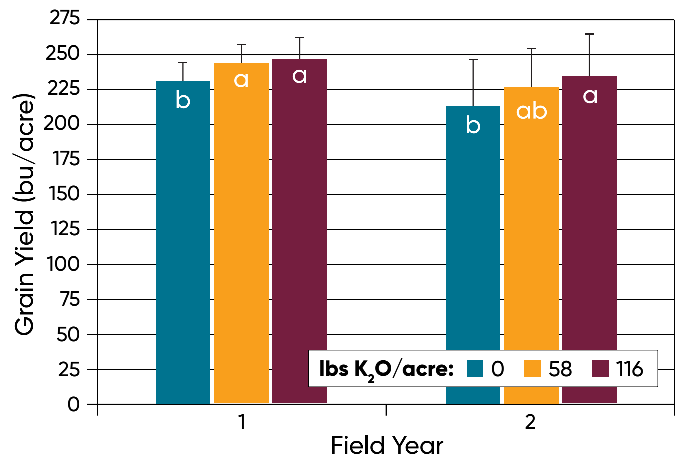


Figure 3. Corn grain yield for the first and second year of corn in the rotation with zero, half, and full rates of K fertilizer. Letters indicate significant differences in rate for strip-till (average of fall and spring) treatments within a specific field year at $p<0.05$.

Conclusions

- Strip-till is growing in adoption across the Midwest, and research to identify optimal management using strip-till is ongoing.
- As with any tillage operation, strip-till needs to be completed under the correct soil conditions to prevent short- and possibly long-term damage to soil structure.
- Reduction of K fertilizer rates when utilizing strip-till showed signs of reducing early-season uptake but did not negatively affect grain yield in the short term.
- However, repeated use of that practice, especially at rates well below crop removal (for a rotation cycle) on moderate K testing soils, may still be negative.
- More research is needed to better understand the long-term impacts of fertilizer rate reduction with placement in the intended crop row.

return to table of contents

Factors Affecting Soybean Nodulation

Dan Berning, Agronomy Manager

Key Points

- The process of nodulation requires that the bacteria, *Bradyrhizobium japonicum,* and the soybean form a mutually beneficial or "symbiotic" partnership.
- Rhizobia growth, health, and activity depend on the initial population of bacteria and soil conditions that can favor or hinder their development
- Reduced nodulation can lead to nitrogen deficiency symptoms in soybeans if residual nitrogen is not available.

Figure 1. Healthy nodules on soybean root.

Biology of Soybean Nodulation

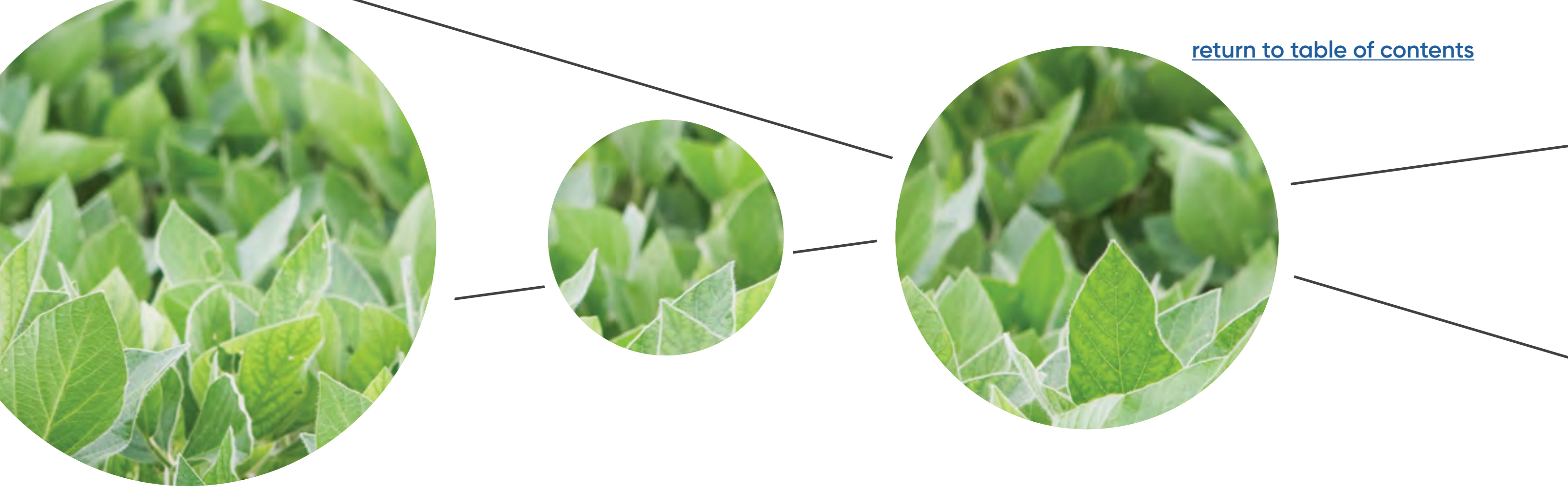
- Soybean nodulation is initiated in the early vegetative stages, within 2-4 weeks of germination, and usually begins Nitrogen fixation around V2.
- The process of nodulation requires that the bacteria, *Bradyrhizobium japonicum*, and the soybean form a mutually beneficial or "symbiotic" partnership.
- The bacteria adhere to the roots and create a chemical bond, forming root tissue (nodules) around the bacteria.
- The bacteria reside in these root nodules, where they use a nitrogenase enzyme to convert atmospheric nitrogen (N_2) to ammonium (NH_4^+), a form of nitrogen available to the plant. The plant provides photosynthates or sugars to feed the bacteria in return.
- For this relationship to develop, rhizobia bacteria must be present in the root initiation area.

Factors That Affect Rhizobia Health

Rhizobia growth, health, and activity depend on the initial population of bacteria and soil conditions that can favor or hinder their development. Several factors can reduce activity of these bacteria:

- Oxygen-limiting environments, like fully saturated soils, can reduce rhizobia activity. The bacteria are living organisms and require ample oxygen to be active.
- Soil pH can also affect the nitrogen production and health of the bacteria, as it does the soybeans. Soil pH < 5.6 or >8.0 creates a difficult environment for the bacteria to function efficiently.
- Survival in soils with low organic matter can be reduced due to insufficient food sources for the bacteria to live on until they adhere to the developing root hairs.
- Activity and health of bacteria can deteriorate in storage as well. Be sure the rhizobia inoculant and treated seed is stored in a cool, dry area, preferably below 77°F (25°C), to avoid heat or water damage.
- Nitrogen fixation is sensitive to soil drying. Dry conditions can lead to excess sodium in the root zone, restricting water availability to the bacteria. Use caution when applying talc seed amendments that can dry seed as well as the bacteria in the inoculant.
- Soil temperatures in the range of 40-80°F (4-27°C) are optimum for survival of rhizobia bacteria.
- Some fertilizers applied with the seed or in-furrow can be toxic to the rhizobia bacteria.
- Nitrogen availability in the soil will also reduce the soybean-to-bacteria relationship. The plant may not initially need the bacteria due to excess residual nitrogen in the soil. In such cases the soybean plant will not recognize the bacteria chemical reaction, and thus will not initiate nodular tissue formation.

Figure 2. Soybean field not previously planted to soybeans. Dark green strips were inoculated with rhizobia.



Symptoms of Reduced Nodulation

Reduced nodulation can lead to nitrogen deficiency symptoms in soybeans if residual nitrogen is not available.

- Yellow and stunted soybeans will be evident in those situations.
- The areas of yellowing may vary based on the soil conditions and issues noted on the previous page.
- Soybean fields with excessive moisture early in the season may have more extensive yellowing.
- Soil compaction limits rooting and root hair development. Chemical signals from the roots that invite the bacteria to colonize can be reduced with limited rooting.

Figure 3. Field not previously planted to soybeans shows symptoms of nitrogen deficiency.

Other Field-Specific Issues May Lead to Yellowing

Yellowing is not always due to reduced nodulation. Other possible causes of soybean yellowing include:

- Soybean cyst nematode activity will lead to yellow, stunted soybeans.
- Other nutrient deficiencies may appear similar to nitrogen deficiency. Iron chlorosis due to high soil pH may be able to be corrected using an EDDHA iron chelate in-furrow or foliar treatment.
- Herbicide applications can yellow leaves and, in some cases, stunt plants.
- General environmental factors such as drought, compaction, soil pH conditions, and excessive rainfall may lead to yellowing.

Management Information

- Check first year soybean fields for nodulation around V2 to V3. Adequate nodulation is 7 to 14 nodules per plant.
- If less than five nodules are present, wait about a week and take another assessment.
- The number of nodules formed on the roots along with the amount of nitrogen fixed continues to increase until the R5 stage of crop development.
- Nodules that are fixing nitrogen are pink or red inside. Green, brown, or white indicates that little or no fixation is occurring.
- If the number and quality of the nodules is not sufficient, supplemental N can be applied.
- Applications of a nitrogen source at less than 44 pounds of actual N per acre can be made.
- Avoid 28% solution as a broadcast application.
- Follow best management practices if using urea-type products; apply at early flowering, when foliage is dry.
- Leaf burn or “shot-holes” from the applications may occur.
- Higher rates of N can be applied but are usually not profitable.

Figure 4. Field areas show N deficiency due to poor nodulation.

return to table of contents

Early Season Soybean Pests and Diseases

Laura Sharpe, Agronomy Information Consultant

Key Points

- Pests like seed corn maggot, wireworms and white grub, as well as diseases like *Pythium* and *Phytophthora,* can reduce soybean stands early in the season.
- Cover crops or heavy crop residue keep soils cooler and can delay emergence, which can increase the vulnerability of seeds and seedlings to pests.
- LumiGEN® seed treatments provide advanced protection against pests, disease and uncertain soil conditions during the critical early growth period.

Early Season Insect Pests in Soybeans

White Grub

- Often found in lighter textured soils, or near lawns, golf courses, and pasture/hay fields.
- White grubs are white in color with brownish red heads and will curl up in a C shape. They feed on root hairs causing stunted, low-vigor plants.

Seed corn maggot

- Potentially problematic in early-planted fields or in cool wet periods when germination is delayed. More prevalent in manured fields.
- Maggots are cream or tan in color, headless and legless and feed on germinating soybean seeds or seedlings.

Wireworm

- Often found in well-manured fields or fields with sod in the rotation.
- Pale yellow to reddish brown in color, shiny, slender and about an inch long. They bore into the germinating seed or into the base of the seedling plant, killing or weakening it.

Figure 1. Soybean field showing stand reduction due to *Fusarium* root rot.

Early Season Diseases in Soybeans

- Damping off – the rotting and death of seeds and seedlings – can affect soybean plants prior to or just after emergence.
- Pathogens that can cause damping off, such as *Pythium*, *Fusarium*, *Phytophthora*, and *Rhizoctonia,* are generally favored by wet soils following planting.

Fusarium

- Infection is caused by a complex of different species that prefer different conditions; some prefer warm and dry soils, while others prefer cool and wet soils.
- Some species attack corn, wheat and other host plants.
- Causes light- to dark-brown lesions on soybean roots that may spread over much of the root system.
- May attack the taproot and promote adventitious root growth near the soil surface, and may also degrade lateral roots, but usually does not cause seed rot.

Pythium

- Prefers cold soil temperatures of <59°F (15°C); may be the first soybean disease found in a growing season.
- High-residue fields and heavy or compacted soils are at higher risk because of cooler, wetter conditions.
- Pathogen may attack seeds before or after germination; seeds killed before germination are soft and rotted with soil adhering to them.
- Plants may be killed by "damping off" before or after emergence. On infected plants, the hypocotyl becomes narrow and is commonly "pinched off" by the disease.

return to table of contents

Figure 2. Soybean seedlings with damping off symptoms due to *Pythium* seedling blight.

Figure 3. Symptoms of *Rhizoctonia* root rot. Note the red discoloration.

Rhizoctonia Root and Stem Rot

- More common in wet soils or moderately wet soils where germination is slow, or emergence is delayed.
- Infection is characterized by a shrunken, reddish-brown lesion on the hypocotyl at or near the soil line.
- Normally appears as the weather becomes warm, around 81°F (27°C); more often seen in late-planted soybean fields.
- Causes loss of seedlings (damping-off) in small patches or within rows; is usually restricted to the seedling stage.

Phytophthora Root and Stem Rot

- Associated with wet soil conditions, commonly occurs on heavy, poorly drained or compacted soils.
- The seedling blight phase occurs at emergence or soon after and is characterized by rapid decay, wilting, and plant death.
- The root and stem rot phase can occur later in development. Symptoms begin in the roots and may spread to the stem.
- Dark-brown to red-brown lesions that may progress up the stem are a key diagnostic feature of the stem rot phase.
- Diseased tissues quickly become soft and water-soaked, and wilting and plant death may soon follow, especially during stress periods.

Figure 4. Soybean plants wilting due to *Phytophthora* root and stem rot.

Influence of Cover Crops and Tillage

- Cover crops can potentially host insect pest species that may damage the subsequent crop. Insect pests that can be associated with cover crops include Japanese beetle, bean leaf beetle, stink bugs, true armyworm, black cutworm, seed corn maggot, and wireworms.
- Reduced tillage and or excess residue on the soil surface can cause soils to be cooler and wetter which slows crop emergence leaving it vulnerable to early season pests.
- Seed treatments are especially important in this kind of seedbed environment to protect seedlings and help ensure that stands are sufficient for highest yields.

Protecting Your Soybean Stand

Variety Selection

- Choose varieties with genetic resistance to *Phytophthora* root and stem rot and strong field tolerance ratings. This information is available in your seed guide and from your local Sales Representative.

Seed Treatments

- LumiGEN® seed treatments provide advanced protection against pests, disease and uncertain soil conditions during the critical early growth period.
- Lumisena® fungicide seed treatment provides best-in-class protection against *Phytophthora*, the number one soybean disease.
- Lumiderm® insecticide seed treatment contains a novel Group 28 insecticide mode of action that protects soybean seedlings against several insect pests.

Directed Scouting from Granular

- Scouting soybean fields for early season pests and disease is easier using Granular Insights Directed Scouting.
- The figure to the right shows a field vegetation index map in the Granular Insights app. The blue/green are areas of the field that are good, whereas the yellow indicates that some scouting is necessary to determine what is hampering the growth in those areas.
- Soybean growers can use this app to walk to these areas of the field, then take photos or notes about the area.

return to table of contents

Soybean Cyst Nematode Populations Across the Midwest

Mary Gumz, Ph.D., Agronomy Manager

Key Findings

- Potentially damaging levels of soybean cyst nematode were found in soybean fields in several Midwestern states.
- 27% of fields sampled had SCN population levels capable of causing heavy to severe crop damage.
- Farmers can reduce the risk of soybean cyst nematode damage by planting resistant varieties, rotating between PI 88788 and Peking resistance sources and using a nematode protectant seed treatment such as ILEVO®.

Strips of SCN-resistant and non-resistant soybean varieties in a SCN-infested field showing damage to the non-resistant varieties.

Study Description

- 439 soybean fields in Iowa, Minnesota, Missouri, Indiana, Illinois, Michigan, Wisconsin, Kansas, and Ohio were sampled to determine soybean cyst nematode (SCN) pressure in 2021.
- Sampling was concentrated in a total of 55 sampling areas (shown in Figure 1), with samples collected from multiple soybean fields within each sampling area.
- Soybean fields were sampled during the growing season at a depth of approximately 6 inches. Subsamples from across the field were blended into a composite soil sample and submitted to a nematode testing laboratory.
- Samples were analyzed using a sugar-flotation method and sieved through a 120-mesh sieve for adult cysts and a 500-mesh sieve for cyst larva not yet in the root system.
- Potential for SCN damage describes the likely damage to a SCN-susceptible soybean variety with no SCN management taken and is based primarily on the number of eggs per 100 cc of soil. Some samples with very high adult or larva counts may be rated as a higher potential damage class than they would have been if based on egg counts alone.

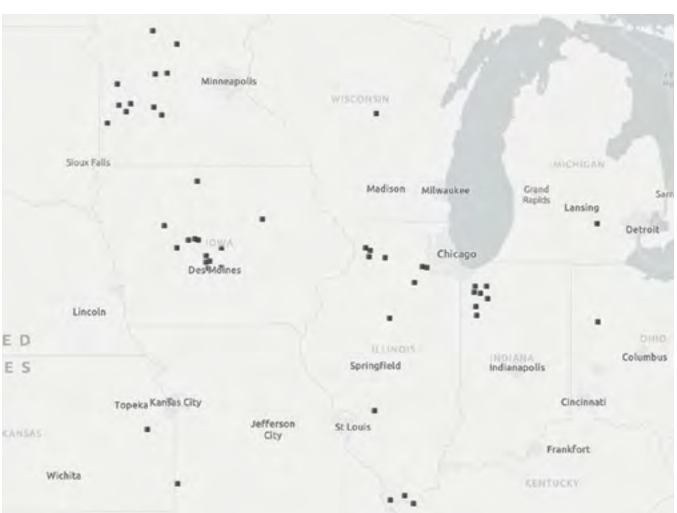


Figure 1. Sampling areas for SCN populations in 2021. Multiple fields were sampled in the vicinity of each point shown on the map.

Results

- SCN infestations were found throughout the study area, with over 80% of fields sampled having some level of SCN infestation (Figure 2).

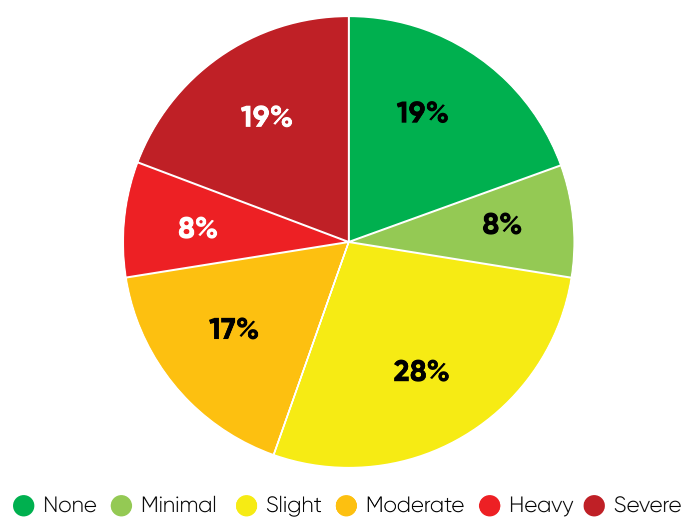


Figure 2. Soybean cyst nematode pressure levels across all 439 soybean fields sampled in 2021.

Table 1. Number of sampling areas and total fields sampled for each state, and sampling results showing the percent of SCN samples in each of six potential crop damage categories.

State	Sampling Areas	Fields Sampled	% of Samples Categorized in Each Potential Damage Category					
			None	Minimal	Slight	Moderate	Heavy	Severe
IA	15	121	22	7	31	23	1	15
MN	13	96	17	8	31	16	11	17
MO	2	93	19	6	23	17	5	29
IN	8	87	11	8	28	15	15	23
IL	13	22	19	14	24	10	19	14
MI	1	6	17	0	17	0	50	17
WI	1	6	50	33	17	0	0	0
KS	1	5	60	0	40	0	0	0
OH	1	3	100	0	0	0	0	0

- 27% of fields sampled had SCN population levels capable of causing heavy to severe crop damage (Figure 2).
- All areas sampled in this study were within the known geographic range of SCN in the U.S. (Tylka and Marett, 2021).
  - Iowa, Minnesota, Missouri, Indiana, and Illinois were the most extensively sampled states in the study. The percentage of fields with heavy to severe SCN pressure in these states ranged from 16% to 38% (Table 1).
  - Wisconsin, Kansas, and Ohio had no fields with more than a slight potential for SCN damage but had a very small number of fields sampled. Conversely, Michigan had a high percent of fields with heavy to severe SCN pressure, but also had a very limited number of samples (Table 1).

SCN on soybean roots.

SCN Management Recommendations

- Test soybean fields for SCN.
- If no infestation is found, use good management practices and rotate a combination of resistant or susceptible varieties in the field.
- If SCN is found:
  - Plant SCN resistant soybeans. Rotate between varieties with PI 88788 resistance and Peking source resistance.
  - Consider using a nematode protectant seed treatment such as ILEVO® seed treatment. The LumiGEN® seed treatment offering includes ILEVO® 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)[8].
  - Rotate to non-host crops such as corn.
  - Control alternate weed hosts such as henbit, purple deadnettle, field pennycress, shepherd's purse, small-flowered bittercress and common chickweed.

return to table of contents

Red Crown Rot in Soybeans

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Red crown rot is a fungal disease of soybeans that has been common in the southern U.S. for years but is now spreading in the Midwest.
- Red crown rot causes deterioration of the stem and roots and premature senescence and can result in significant reductions in yield.
- Later planting in infested fields, improved soil drainage, and management of root-feeding insects and nematodes can help reduce the impact of red crown rot.

New To The Midwest, But Not New

- Red crown rot is a fungal disease of soybeans caused by the soilborne pathogen *Calonectria ilicicola* (anamorph: *Cylindrocladium parasiticum*) and characterized by fungal structures on the stem and root that give it a reddish appearance (Figure 1).
- Red crown rot is a new disease of soybeans in the Midwestern U.S., having first been detected in Pike County, Illinois, in 2017 (Kleczewski, 2020).
- In the years since its initial detection, red crown rot has spread through central Illinois and into Kentucky (Bradley, 2021).
- *C. ilicicola* was first identified in 1950 and has been a pathogen of soybeans in the southern U.S. since the 1970s and in Japan since the 1960s.
- *C. ilicicola* has a broad host range and is a disease in several other crops, including peanut, ginger, and blueberry. Red crown rot is common in areas of the south and southeast where soybeans are grown in rotation with peanuts.

Figure 1. The key identifying characteristic of red crown rot in soybean is the presence of tiny red balls on the crown and stem near the soil line.

Figure 2. Foliar symptoms of red crown rot – interveinal chlorosis and necrosis – are indistinguishable from those caused by SDS, so inspection of the stem and crown is necessary to determine the causal pathogen.

Infection and Spread in Soybeans

- *C. ilicicola* is soilborne and causes deterioration of the root and stem in soybeans.
- Infection is favored by wet conditions following planting and will often show up in low-lying and poorly drained areas of a field.
- Disease progression is favored by warm, wet conditions during the growing season.
- Warm soil temperatures between approximately 77°F and 86°F favor disease development, with infection decreasing when soil temperatures exceed 86°F.
- Secondary spread during the growing season can be caused by the ejection of mature ascospores from the perithecia on the stem, which are distributed by splashing and runoff from rainfall.
- Later in the season, the fungus can produce a toxin that accumulates in the leaves, causing interveinal chlorosis followed by necrosis (Figure 2).

return to table of contents

Figure 3. Soybean plant with senesced leaves caused by red crown rot infection.

- Severely affected plants will senesce prematurely, with the leaves staying attached to the plant (Figure 3).
- *C. ilicicola* overwinters in soils as microsclerotia, which can survive for several years without the presence of a host crop.
- Microsclerotia are spread by the movement of plant debris and infested soil particles, which can be carried by wind or transported between fields by equipment or livestock.

Symptoms and Identification

- Red crown rot infection is often detected after the R3 stage with the appearance of yellowing on the leaves, although root and stem rot can occur without producing foliar symptoms.
- Foliar symptoms can be very similar to those of other common soybean disease such as sudden death syndrome, brown stem rot, and southern stem canker, so inspection of the stems and roots is necessary to determine the causal pathogen.
- Foliar symptoms typically do not appear uniformly across a field, often showing up as single plants or small patches of infected plants randomly throughout the field.
- The key distinguishing characteristic of red crown rot is the presence of perithecia on the crown and roots just below the soil line, which look like tiny red balls and will give the crown a reddish coloration.
- Under wet conditions, the perithecia can extend above the soil line on the lower stem.
- Other factors can cause a reddish coloration of the lower stem, so it is important to look closely to confirm the presence of fungal tissues.
- White fungal hyphae can also appear on infected tissue.
- The pith in the crown of an infected plant may have a gray discoloration.
- Plants with severely rotted roots can be easily pulled from the soil. Diseased plants may have more than one pathogen present.

Management Considerations

- Yield losses of 25% to 30% have been documented for red crown rot infections in soybeans in Louisiana and Mississippi, where the disease has been present for years.
- Severely infected areas can be significantly impacted; however, red crown rot usually only affects patches within a field.
- Management options for red crown rot are limited and no rescue treatments are available to mitigate plant damage and yield impact once infection has been detected.
- Delaying soybean planting in fields known to be infested with *C. ilicicola* can help reduce the severity of infection.
- Management of pathogenic nematodes can help reduce the severity of red crown rot. Nematode damage to the roots can create access points for infection by soilborne pathogens.
- Crop rotation into a non-host crop can help reduce inoculum load in the soil.

Figure 4. Perithecia on a soybean plant with red crown rot.

return to table of contents

Two-Spotted Spider Mites in Soybeans

Jim Boersma, Product Agronomist, and Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Two-spotted spider mites are a pest of soybeans that show up during extended periods of drought.
- Spider mites damage soybeans by piercing plant leaves and feeding on the plant juices.
- There are no established economic thresholds for two-spotted spider mites.
- Effective chemical control of spider mites is challenging due to the limited efficacy of treatments, short residual period, and detrimental effect on natural predators.

Spider Mites – A Problem in Drought Years

Two-spotted spider mite *(Tetranychus urticae)* is a pest of soybeans that proliferates during extended periods of drought. Drought conditions accelerate spider mite movement and reproduction and inhibit fungal pathogens that normally help keep spider mite populations in check. Economically damaging outbreaks of spider mites are relatively rare, but populations can grow rapidly when conditions are favorable.

Figure 1. Two-spotted spider mite adult.

Two-Spotted Spider Mite Life Cycle

Two-spotted spider mites have four stages of development: egg, larva, nymph and adult. Spider mites overwinter as adults in field edges and roadsides bordering fields, feeding on weeds until spring. After early spring mating, female spider mites lay eggs on weeds that usually hatch to the larval stage in three to five days. Unlike most damaging insects in soybeans, spider mites do little feeding during the larval stage of development.

Nymphs are young eight-legged mites that resemble full-size adults but do not yet have reproduction capability. Adults are very small at only 1/60 (female) to 1/80 (male) inch in size when fully developed, with females laying an average of 50 to 100 eggs during their lifetime.

The entire life cycle of this pest can be completed within 5 to 14 days, depending on environmental conditions. Fastest reproduction occurs when temperatures are over 85°F (29°C) and weather conditions are dry. During heavy outbreak years, all stages of mites may be present in the field at one time. Two-spotted spider mites have the potential for up to 10 generations per year during the growing season.

Figure 2. Soybean leaves showing spider mite feeding symptoms.

Spider Mite Damage to Soybeans

Two-spotted spider mites damage crops by piercing plant leaves and feeding on the plant juices with their mouth parts. Mites suck on the bottom sides of soybean leaves and remove moisture and nutrient contents from plant cells, resulting in a yellow or whitish spotting on the top side of the leaf surface. In heavy infestations, a common visual symptom of spider mite feeding is leaf burning and stippling.

Hot spots will typically be noticed first on field margins, as infested plants take on a wilted appearance. Drought-prone fields or field areas that contain lighter soils or sands are often affected first by spider mites. As populations increase, spider mites will move out across the entire field if left unchecked. Fields heavily infested by mites can cause premature leaf drop and significant reductions in yield.

Populations of spider mites increase significantly during extended hot, dry conditions. This is due to a reduction in predators and naturally occurring pathogenic fungi that keep populations at non-economic levels in normal years.

Figure 3. Spider mite eggs on underside of soybean leaf. Spider mite infestations are more common under hot, dry, drought stressed conditions.

Spider Mite Scouting and Economic Thresholds

Look on the undersides of affected soybean plants and leaves for mites, eggs and webbing in the lower canopy. Mites are almost impossible to see with the naked eye, so doing a simple "paper test" is a quick and easy way to confirm their presence. Shaking the plant onto a white piece of paper should allow you to see the tiny orange- to yellow-colored mites slowly moving on the paper.

There is currently limited information regarding potential economic threshold for two-spotted spider mite infestations in soybeans, which makes treatment decisions challenging. Some extension sources suggest treating for spider mites if 20% to 50% of the leaves are discolored before pod set. After pod set has begun, the suggested treatment threshold is 10% to 15% of the leaves discolored.

Figure 4. Soybean leaves showing spider mite feeding symptoms.

Consideration for treatment of two-spotted spider mite should take several factors into account:

- Are there other insect pests present that cause economic injury (such as soybean aphids, bean leaf beetles, and grasshoppers)?
- What are the weather trends? If heavy rains and moderating temperatures occur, mite populations may be reduced or contained in the short term.
- Are there thrips, pirate bugs, mite destroyer beetles, and/or naturally occurring fungi in the field? Under proper conditions these beneficials can significantly reduce or limit populations of two-spotted spider mites.
- Is the outbreak confined to field edges or borders? If mite outbreaks are caught on outside field edges before they have a chance to move across the entire field, spot treatments or treating field margins might head off the need for whole field treatments. If scouting reveals that mites have spread across the field, then whole field protection will be necessary.

If hot and dry weather persists, spider mites will continue to build, and it will be important to control them. Field scouting is necessary for detection of early outbreaks and for effective early treatments and control.

Treatment and Control

Chemical control of spider mites is challenging. While some pyrethroid products may suppress activity of spider mite, nearly all the synthetic pyrethroid products have a detrimental effect on spider mite predators. The lack of full control by pyrethroids allows mite numbers to increase unchecked or "flare up" when conditions are favorable.

Spider mites, like other soybean insects, are found on the undersides of soybean leaves. For optimal control of spider mite populations, use high pressure and a high volume of carrier to achieve thorough coverage and penetration of the crop canopy. Using higher pressures, (40 to 60 psi) and increased carrier volume (15 to 25 gpa) will improve overall performance.

Unfortunately, residual control of most treatments is short-lived, and applications will only control adults and nymphs. Treated fields need to be re-scouted five to ten days following application. It is possible that a second application might be necessary to pick up any newly hatched spider mites, so be sure to scout treated fields about a week after application.

Conditions can change quickly depending on environmental conditions. Heavy rainfall, or changes in temperature, humidity or crop conditions may warrant a re-evaluation of mite populations before treatments are made.

return to table of contents

Effects of Cold Temperatures Following Soybean Planting

Mark Jeschke, Ph.D., Agronomy Manager, Adam Gaspar, Ph.D., Global Biology Leader - Seed Applied Technologies, and Ryan Van Roekel, Ph.D., Pioneer Field Agronomist

Key Points

- Imbibitional chilling injury can occur when cold water is imbibed by the seed within 24 hours of planting.
- Emerged soybeans are more susceptible to damage from freezing temperatures than corn because their growing points are above the soil surface.
- The use of a fungicide seed treatment is important in early-planted soybean when development can be delayed by poor conditions.

Benefits and Risks of Early Planting

- Trends toward larger farms and planting equipment size along with the availability of effective seed treatments and proven yield benefits have prompted a shift toward earlier planting of soybeans.
- Several Pioneer agronomy research studies have shown the benefits of early planting with a full-season soybean variety for maximizing soybean yield.
- Early planted soybeans generally reach canopy closure sooner, intercept more sunlight, and spend a longer duration in reproductive growth.
- However, it is possible to plant too early every year, and several management factors as well as risks associated with early planting must be considered.
- Cold and wet conditions at and after planting can injure developing seedlings; delay germination and emergence; and reduce stand establishment.

Figure 1. Pioneer® brand soybean varieties are rated for field emergence, which is based on speed and strength of emergence in suboptimal temperatures.

Soil Temperature

- Like corn, soybeans are typically planted into soils well below their optimum temperature for germination, making early growth conditions inherently stressful. The optimum temperature for soybean germination is around 70°F (21°C).
- A minimum soil temperature of 50°F (10°C) during the 24 hours following planting is recommended. At soil temperatures below 50°F (10°C), the risk of slow germination, infection of seedling diseases, and reduced stand establishment increases.
- Soybeans typically require between 90 and 130 GDUs to emerge, depending upon soil type.
- The GDU requirement of soybean is similar to corn with a base temperature of 50°F (10°C). Thus, planting ahead of a cold spell often does not result in accumulation of additional GDUs or gain any early growth.

Imbibitional Chilling Injury

- The initial uptake of water into the seed following planting is referred to as the imbibitional phase. A soybean seed imbibes approximately 50% of its weight in water during germination.
- The imbibitional phase occurs very rapidly after planting, typically not lasting more than 24 hours.
- Imbibitional chilling injury and stand loss can occur when very cold soil water (<40°F, 4°C) is imbibed by the seed during this time. A damaged seed coat can increase the likelihood of imbibitional chilling injury. Care should be taken when handling/treating seed.
- Once the imbibitional phase is completed, the risk of chilling injury associated with cold soil temperature or rain declines.

Risk of Freezing Injury

- Emerged soybeans are more susceptible to damage from freezing temperatures than corn because their growing points are above the soil surface as soon as the plants emerge.
- Temperatures below 32°F (0°C) can cause frost damage to emerged soybean plants, while temperatures below 28°F (-2°C) for an extended period of time (>4 hrs) can be lethal, especially on lighter-textured soils.
- Heavier-textured soil can better store and release previously accumulated heat near the soil surface when air temperatures drop, helping to protect recently emerged soybean plants.
- High levels of residue on the soil surface can increase the risk of freezing injury by reducing the transfer of heat from the soil to the plants.
- A soybean plant at the cotyledon stage has three growing points – the main shoot and two axillary buds at the base of the cotyledons. Recovery from freezing injury is possible as long as at least one of these buds survives.
- Soybean seedlings that have just cracked the soil surface will be more tolerant to freezing temperatures than plants at the cotyledon or unifoliate stages.
- The cotyledons are full of solutes, which makes them good buffers to protect the three potential growing points between them, and causes them to be more resistant to injury.
- Freezing damage that extends below the cotyledons will result in the death of the plant.

Figure 2. Just-emerged soybean plants damaged by frost. The cotyledons are still green and look healthy, but the region of the hypocotyl just below the cotyledonary node is turning brown and is becoming soft and shrunken.

Disease Risk

- Cold, wet soils following planting increase the risk of seed rots and seedling blights in soybeans.
- The use of a fungicide seed treatment is important in early planted soybean when development can be delayed by poor conditions.
- Pythium is favored by cold and wet soils. In fields where the disease is present, infection is likely when soils are cold and heavy rains occur soon after planting.
- Cold, wet conditions early in the growing season can also result in higher incidence of sudden death syndrome (SDS).
- SDS is caused by a virulent strain of the common soil-inhabiting fungus *Fusarium virguliforme*, which infects soybean plants very early in the growing season, often as early as germination to just after crop emergence.
- The use of resistant soybean varieties and ILeVO® fungicide seed treatment (active ingredient: fluopyram) provides protection of seedlings against *Fusarium virguliforme* infection and can reduce the incidence of SDS in early planted soybean.

Figure 3. Soybean seedlings with damping-off symptoms due to Pythium seedling blight, a soil-borne fungal pathogen that is favored by wet soil conditions and cool temperatures just after planting. Damping-off occurs when germinating seedlings are infected prior to or just after emergence. Diseased seedlings collapse when the infection girdles the hypocotyl.

Management Considerations

- Early soybean planting is a consistently proven management practice for high-yield soybean production.
- Imbibitional chilling injury can occur when very cold soil water is imbibed by the seed within 24 hrs after planting. However, if the soil is fit, soil temperatures are near 50°F (10°C), and the weather forecast for the next 24 to 48 hours is favorable, soybean planting should begin.
- Predicting a frost event 10 or more days after planting when soybeans are beginning to emerge is a difficult task. Many factors affect the potential for freezing injury to emerged soybean plants – growth stage; air temperature and duration; soil temperature; soil texture; residue; and field topography.
- If temperatures drop below freezing after soybeans have emerged, allow approximately five days before assessing any potential stand loss and replant considerations.
- Planting soybean seed treated with a fungicide seed treatment can help protect against elevated disease risks associated with early planting, particularly when development is delayed by poor conditions.

return to table of contents

Sudden Death Syndrome of Soybeans

Mark Jeschke, Ph.D., Agronomy Manager

Disease Facts

- Fungal disease caused by *Fusarium virguliforme.*
- Has spread to most soybean-growing states and Ontario, Canada.
- Continues to spread to new fields and larger areas of infected fields.
- Ranked second only to soybean cyst nematode (SCN) in damage to soybean crop.
- Fungus colonizes only crown and roots of the plant.
- Above-ground symptoms are caused by a toxin produced by the fungus and translocated throughout the plant.
- Severity varies from area to area and field to field.

Figure 1. Soybean leaf showing classic symptoms of sudden death syndrome infection, with yellow and brown areas contrasted against a green midvein and green lateral veins.

Conditions Favoring Disease Development

- Cool, moist conditions early in the growing season often result in higher disease incidence.
- Favorable disease conditions may result from early planting, high rainfall and/or low-lying, poorly drained or compacted field areas.
- If SCN is also a problem in the field, disease may be more severe.
- Infection occurs early in the season, but symptoms usually do not appear until mid-summer.
- Appearance of symptoms often associated with weather patterns of cooler temperatures and high rainfall during flowering or pod-fill.

Fusarium virguliforme Disease Cycle

- Fungus survives in crop debris and as mycelia in the soil.
  - Survives best in wet areas such as poorly drained or compacted field areas.
- Fungus enters roots early in the growing season.
  - Infection may be facilitated by wounds from SCN, insects or mechanical injury.
- Fungus colonizes the root system.
- Fungus overwinters in diseased soybean residue.

Impact on Crop

- Soybean seed yield is reduced as:
  - Plants lose leaf area and leaves drop prematurely.
  - Roots deteriorate, reducing water/nutrient uptake.
  - Flowers and pods abort, resulting in fewer pods and seeds.
  - Seeds may be smaller, and late-forming pods may not fill or mature.

Root Symptoms

- A blue coloration may be found on the outer surface of taproots due to the large number of spores produced.
- These fungal colonies may not appear if the soil is too dry or too wet.

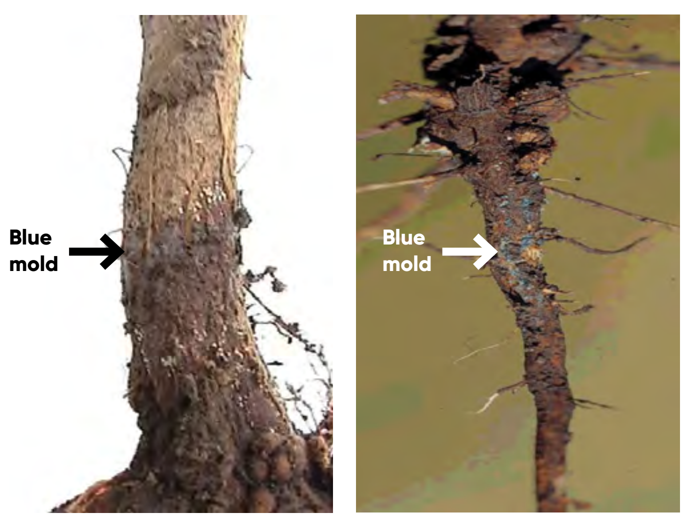


Figure 2. Root and stem of soybean plants with blue *Fusarium virguliforme* fungal colonies present at soil surface line.

- Splitting the root reveals cortical cells have turned a milky gray-brown color while the inner core, or pith, remains white.
- General discoloration of the outer cortex can extend several nodes into the stem, but its pith also remains white.

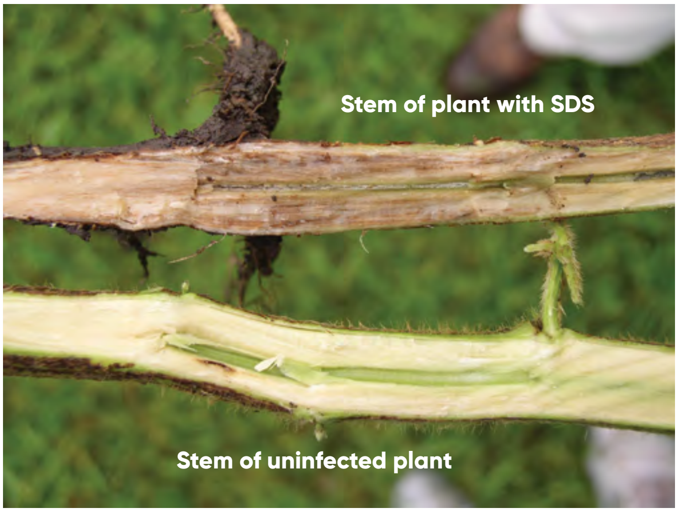


Figure 3. Split soybean stem on top shows stem symptoms of sudden death syndrome infection. Split stem on bottom is healthy.

Leaf and Plant Symptoms

- Leaf symptoms first appear as yellow spots (usually on the upper leaves) in a mosaic pattern.
- Yellow spots coalesce to form chlorotic blotches between the leaf veins.
- As chlorotic areas die, leaves show yellow and brown areas contrasted against green veins.
- Affected leaves twist and curl and fall from plants prematurely.
- Flowers and pods abort, and seeds are smaller.
- Later-developing pods may not fill, and seeds may not mature.

Figure 4. Soybean plants infected with sudden death syndrome. Necrotic areas of leaves dry rapidly. Leaves drop from the plant prematurely, but leaf petioles remain firmly attached to the stem.

Figure 5. Soybean leaf showing symptoms of sudden death syndrome infection. Drying of necrotic areas can cause curling of affected leaves.

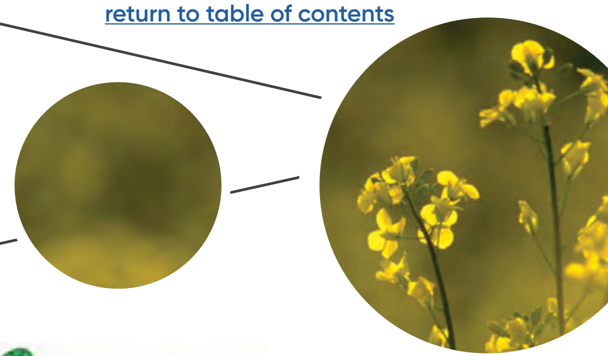
Management

Use a combination of practices:

- Select SDS-resistant varieties.
  - Pioneer has developed elite soybean varieties with improved SDS resistance.
  - Soybean breeders have selected for genetic resistance in multiple environments with high levels of natural SDS infection.
  - Pioneer rates its varieties and makes ratings available to customers.
  - Ratings range from 4 to 8 (9 = resistant), indicating very good resistance is available in elite soybean varieties.
  - Your Pioneer representative can help you select suitable varieties.
- Manage soybean cyst nematode (SCN).
  - Plant varieties resistant to both SDS and SCN.
- Improve field drainage and reduce compaction.
- Evaluate tillage systems. Where possible, some tillage may be needed to bury infected residue.
- Reduce other stresses on the crop.
- Plant the most problematic fields last in your planting sequence.
- Foliar fungicide cannot protect plants from SDS.

Figure 6. Soybean leaf showing early symptoms of sudden death syndrome infection

return to table of contents



Sclerotinia Stem Rot of Canola

Kristin Hacault, Agronomy Information Consultant

Disease Facts

- Sclerotinia stem rot is a soil borne pathogen, also known as white mould. It is a disease that affects western Canadian crops on a yearly basis including canola, sunflowers, peas, soybeans, dry beans, lentils, and chickpeas.
- A challenging aspect of managing Sclerotinia stem rot is diagnosing the threat before it appears, as most fungicide control options are protective and not curative.
- Incidence and severity of infection can be sporadic, but in high rainfall/humidity regions the disease can cause significant yield loss.
- Yield loss can vary from year to year and field to field but generally the yield loss is estimated to be half the level of infection (i.e., 50% infection = estimated 25% yield loss).

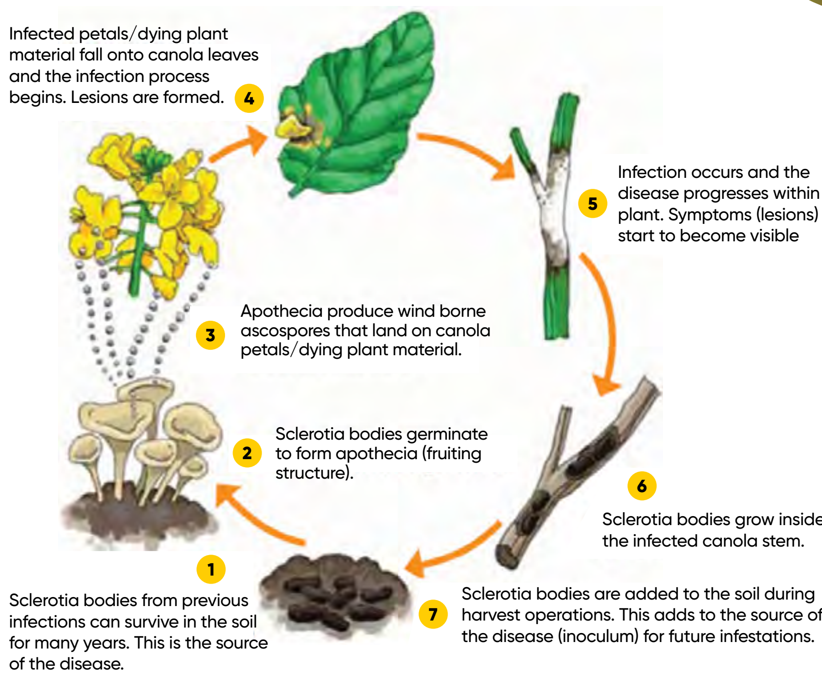


Figure 1. Sclerotinia life cycle.

Disease Life Cycle

- Infection occurs during the flowering period of canola from airborne spores and is highly dependent upon moisture conditions prior to and during canola flowering.
  - Temperatures between 20-25°C (68-77°F) and prolonged soil moisture/high humidity favor disease development.
- Spores can persist for years in soil via structures of hardened mycelial masses, called sclerotia, which function like seeds.
- Apothecia germinate from the sclerotia and produce millions of spores that are wind blown and land on canola petals. These spores begin to colonize dead plant tissue, particularly senescing canola flower petals.
- Infection is favored in dense canopies with minimal airflow and high moisture.
- Petal drop generally starts between 6-9 days after flowering begins.
- This coincides with a plant that is approximately at the 30% bloom stage.
- When infected petals fall off the floret and land on the leaf or stem axels of a plant and stick, the sclerotinia can then flourish and infect the stem and branches.
- Infection results in premature ripening and yield loss.

Disease Identification & Symptomology

- Infection begins as a soft, watery rot on infected leaves or stems.
- Lesions can completely girdle the main stem, resulting in plant wilting, lodging, and eventual death.
- The infected area dries up and becomes bleached.
- During harvest, the diseased tissues shred and sclerotia bodies are released from the infected stems, contributing inoculum to the soil for successive years.

Figure 2. Symptoms of sclerotinia stem rot within canola crop canopy.

Figure 3. Canola stems infected with sclerotinia stem rot.

Disease Risk and Forecasting

- Determining if fungicide control is warranted can be difficult due to the sporadic nature of the disease. Growers often ask, "How do I manage risk of a disease I cannot see?"
- Practical risk factors growers should consider prior to applying fungicides include:
  1. Level of disease infection in their own and neighboring canola fields over the past several years.
  2. Amount of precipitation and humidity 10-14 days prior to first flower and during flowering (soil at field capacity).
  3. Plant density.
  4. Crop rotation.
  5. Long-range precipitation forecast.
  6. Proper fungicide timing.
- Various predictive tools exist to aid in measuring the presence of the disease in fields such as petal tests, spore traps and scouting for the presence of apothecia.
- The Canola Council of Canada publishes a Sclerotinia Stem Rot Checklist (www.canolacouncil.org)
- The checklist assigns numeric risk factors to variables affecting the presence of sclerotinia (i.e., weather forecast, crop rotation, etc.)
- Once a score of >40 points is achieved, a fungicide may be warranted.
- It is important to note that fungicide costs and commodity prices are not factored into the checklist and must be taken into account.

Disease Management

1. Fungicides

- Fungicides are the most effective management tool in combating sclerotinia when disease risk is high.
- However, due to disease variability within a field and on plants (incidence and severity), prophylactic applications are often uneconomical.
- Forecasting models are available. Although not perfect, they do provide directional guidance on whether a fungicide application is warranted (See Canola Council of Canada Sclerotinia Checklist)
- Most fungicides are protective – aim to protect the flower petals which are the food source for the disease.
- Generally, most fungicides are applied between 20-50% bloom with optimal being 30% bloom (when most petals are open).
- Refer to individual product labels for complete details on application, timing, and staging.

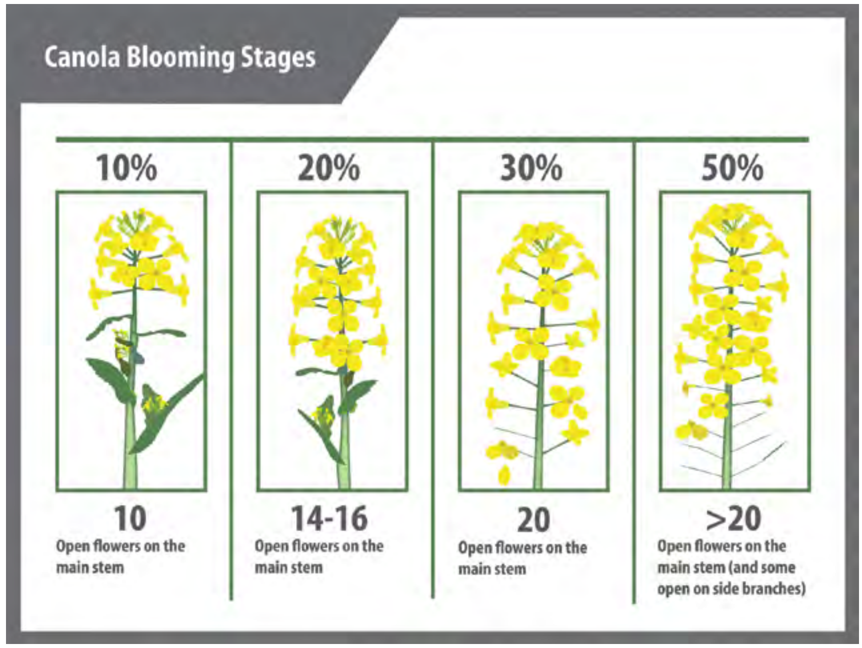


Figure 4. Canola bloom stage assessment. *Courtesy of the Canola Council of Canada.*

2. Genetic Resistance

- Pioneer® brand canola offers hybrids with built in resistance to sclerotinia. This genetic resistance confers the ability of the plant of overcome the pathogen's ability to infect.
- These resistant hybrids have been shown to reduce sclerotinia incidence by over 60%, as well as reducing overall disease severity.
- Utilizing genetic resistance provides season long protection from sclerotinia and convenience, as the protection is planted with the seed.

Pioneer Agronomy

Pioneer® Protector Sclerotinia Tolerance Trait Mode of Action

- Resistant genetics also aid in managing disease risk over large geographies and acres.
- Resistant hybrids offer growers peace of mind in providing protection under low to moderate disease infection levels and increased flexibility when timing fungicide applications to proactively managing sclerotia.
- Both resistant canola hybrids and/or fungicides work to reduce the amount of sclerotinia inoculum returned to the soil.

3. Cultural Controls

- This would include management strategies such as crop rotation, management of host weed species, etc.

Figure 5. Sclerotia bodies in infected canola stem. *Photo courtesy of the Canola Council of Canada.*

return to table of contents

Critical Period of Weed Control in Canola

Kristin Hacault, *Agronomy Information Consultant*

Why Control Weeds Early?

- Early season weed control helps protect crop yield potential, especially during the canola seedling stage when the crop is a poor competitor.
- Weeds and canola compete for the same resources (water, sunlight and nutrients).
- Small weeds are easier to control and can absorb and translocate herbicide better.
- Herbicides can be less effective during times of heat and drought stress, which often occurs with later applications. Additionally, there is greater risk of crop injury with later/out of stage applications.
- Generally, a combination of both pre-seed and in-crop herbicide applications have the greatest potential to protect canola crop yield.
- New glyphosate herbicide tolerant canola traits allow for a wider in-crop application window; however, it is important to keep in mind the critical weed free period (CWFP) for canola and to maximize yield potential by controlling weeds early.

Critical Weed Free Period (CWFP)

- Defined as the stages in a crop's life cycle during which weeds must be controlled to prevent yield loss from weed competition in the crop.
- Studies from Western Canada have found that the CWFP in canola is from emergence to the 4-leaf stage of the plant. (Martin et al., 2001; Harker et al., 2008).
- In one study in Western Canada examining the timing of weed removal in canola, it was found that delaying weed control until the 6- to 7-leaf stage of canola resulted in a 20% yield loss (Harker et al. 2008; Figure 1).
- Another benefit of early season weed removal is the prevention of weed seed production.

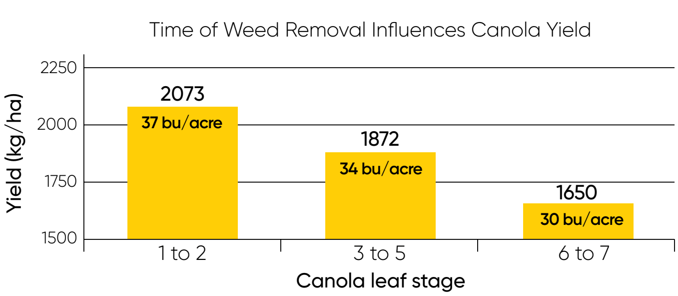


Figure 1. Influence of time of weed control on canola yield (Harker et al. 2008).

Pre-Seed Application

- Applying recommended, labeled herbicides prior to seeding reduces overall risk of yield loss due to weed competition, especially if an in-crop herbicide application is delayed.
- A pre-seed herbicide application is highly recommended, especially for fields with an abundance of winter annual and perennial weeds.
- If a pre-seed application is not an option, consider applying control measures immediately after seeding prior to crop emergence. Keep in mind that this can be a very narrow application window.

Postemergence Applications

- The best time to apply in-crop herbicide applications to canola is from the 1- to 4-leaf stage.
- After the 4-leaf stage, canola plants are much more competitive and emerging weeds have less effect on yield.
- As the crop canopy closes, late emerging weeds have a reduced effect on yield. Second in-crop applications may produce a smaller ROI but can help manage weed escapes from the first herbicide pass or crops with low plant populations.
- In some cases, a pre-harvest or post-harvest herbicide application is more effective at controlling weed escapes than a second in-crop herbicide application – especially in the case of perennial weeds.
- Tank mix options are available for both pre-seed and in-crop applications to enhance weed control. Always read and follow label directions.
- However, all situations are unique and need to be evaluated on a field-by-field basis. Your local Pioneer sales representative or agronomist can provide a specific field recommendation.

Figure 2. Grassy weed pressure in herbicide tolerant canola near the end of the CWFP.

Figure 3. Kochia competition in canola. July 2019. Saltcoats, SK.

return to table of contents

Herbicide Tolerant Canola Systems from Corteva Agriscience

Table 1. List of herbicide tolerant canola system options available from Corteva Agriscience.

HT System	Active(s)	Product*	Group	Application Rate	Crop Stage	Water Volume	Max Passes/ Year
Roundup Ready®	Glyphosate	VP480	9	2 apps. up to 0.5 REL/ac** each or a single app. Ip to 0.75 REL/ac	Cotyledon to 6-leaf	5-10 US gal/ac	2
LibertyLink®	Glufosinate	Interline®	10	1st app: 1.62L/ac; 2nd app: 1.37L/ac; do not exceed 2.97L/ac per season	Cotyledon to early bolting	10 US gal/ac	2
Clearfield®	Imazamox/ Imazapyr	Ares™ SN***	2	244ml/ac	2- to 7-leaf	5-10 US gal/ac	1
Optimum® GLY[t]	Glyphosate	VP480	9	2 apps. up to 1.0 REL/ac each	Cotyledon to first flower	5-10 US gal/ac	2
				Single app. up to 2.0 REL/ac.	Cotyledon to 6-leaf		1

* Refer to individual product labels for complete instructions on rates, tank mix partners, staging, application timing, rainfastness, etc. **REL = Roundup Equivalent Litre.
***Requires Surjet Surfactant. [t]Availability subject to regulatory approval.

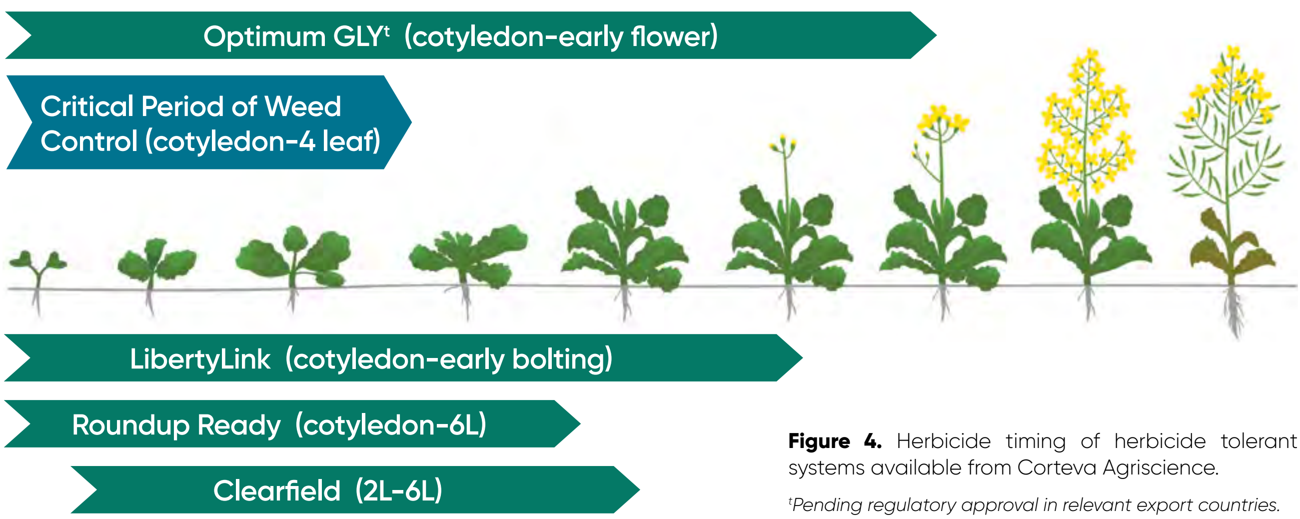


Figure 4. Herbicide timing of herbicide tolerant systems available from Corteva Agriscience.

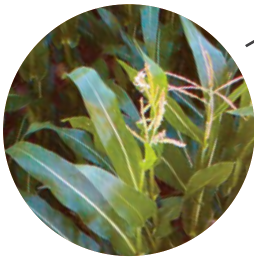
[t]Pending regulatory approval in relevant export countries.

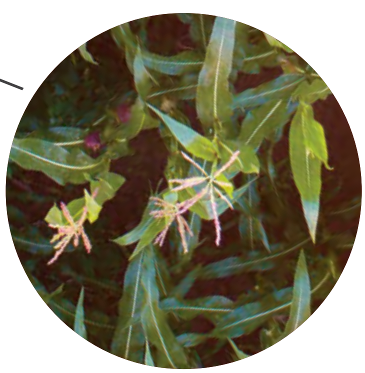
Weeds of Concern

- Weed surveys are conducted in the Prairie provinces on a recurring basis. The latest prairie weed survey (2014-2017) listed the following as the top 10 weeds in canola (Canola Digest, 2019)
  1. Wild buckwheat (annual)
  2. Wild oats (annual)
  3. Green foxtail (annual)
  4. Volunteer wheat (annual)
  5. Cleavers (annual)
  6. Chickweed (annual)
  7. Volunteer canola (annual)
  8. Spiny annual sow thistle (annual)
  9. Lamb's quarters (annual)
  10. Canada thistle (perennial)

Future Research

- The majority of research regarding the critical period of weed control in canola was conducted over 15 years ago.
- There is ongoing research in Western Canada, specifically at the University of Manitoba, investigating the CWFP in canola given the myriad new herbicide technologies (pre-emerge and in-crop), improved hybrid competitiveness, and changes to recommended seeding rates in canola.





Nitrogen Fertilizers and Stabilizers for Corn Production

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- A central challenge in managing nitrogen fertility in corn production is the susceptibility of nitrogen to loss through volatilization, leaching, or denitrification.
- The most commonly used nitrogen fertilizers for corn production in North America are anhydrous ammonia, urea, and urea-ammonium nitrate solutions.
- Urea is hydrolyzed by soil bacteria releasing two ammonia molecules (NH_3) which can be lost to the atmosphere if this reaction takes place on the soil surface.
- Ammonium ions (NH_4^+) in the soil are converted to the nitrate form (NO_3^-) by the action of soil bacteria in a process known as nitrification.
- Nitrate is at risk of loss through leaching or denitrification, a series of reactions that convert nitrate into N_2 gas.
- When nitrate is not completely converted to N_2, the resulting byproduct is nitrous oxide (N_2O), a greenhouse gas.
- Nitrogen stabilizers are additives that can be used with nitrogen fertilizers to reduce the risk of nitrogen loss by slowing the rate of chemical reactions that occur in soil.
- Nitrogen stabilizers have proven effective at increasing soil nitrogen retention and reducing nitrous oxide emissions.

...**nitrogen can be lost by leaching** *– the downward movement of nitrates below the root zone,* **or denitrification** *– loss to the atmosphere caused by reactions in the soil under anaerobic conditions.*

return to table of contents

Nitrogen – A Critical Input for Corn

Nitrogen (N) fertilizer is a critical input in corn production. One of the most challenging aspects of successfully managing nitrogen is the fact that nitrogen from fertilizer can be lost from the soil before the corn crop is able to take it up. Under prolonged wet field conditions and warm temperatures, nitrogen can be lost either by leaching – the downward movement of nitrates below the root zone, or denitrification – loss to the atmosphere caused by reactions in the soil under anaerobic conditions. Surface-applied nitrogen can also be lost through ammonia volatilization if not incorporated into the soil by tillage or rainfall. Nitrogen loss is not only a waste of resources, it also can have negative environmental impacts. Nitrogen stabilizers are additives used with nitrogen fertilizers that can help reduce nitrogen losses from the soil.

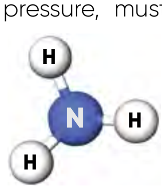
Nitrogen Fertilizers

The most commonly used forms of nitrogen fertilizer in corn production in North America are anhydrous ammonia, urea, and urea-ammonium nitrate (UAN) solutions.

Table 1. Nitrogen fertilizers most commonly used for corn production in North America.

Fertilizer	Form	% N
Anhydrous Ammonia	Gas, applied as liquid from pressurized tank	82
Urea	Solid	46
UAN solutions	Liquid	28 - 32

Anhydrous ammonia (NH_3) is the most basic form of N fertilizer. Ammonia, a gas at atmospheric pressure, must be compressed into a liquid for transport, storage, and application. Consequently, it is applied from a pressurized tank and must be injected into the soil to prevent its escape into the air. When applied, ammonia reacts with soil water and changes to the ammonium form, NH_4^+.



NH_3

Most other common N fertilizers are derivatives of ammonia transformed by additional processing, which increases their cost. Due to its lower production costs, high N content (82%) that minimizes transportation costs, and relative stability in soils, anhydrous ammonia is the most widely used source of N fertilizer for corn production in North America.

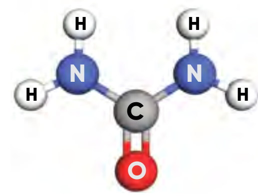
Urea is a solid fertilizer with high nitrogen content (46%) that can be easily applied to many types of crops and turf. Its ease of handling, storage and transport; convenience of application by many types of equipment; and ability to blend with other solid fertilizers has made it the most widely used source of N fertilizer in the world.

Urea is manufactured by reacting CO_2 with NH_3 in two equilibrium reactions:

$2NH_3 + CO_2 \rightarrow [NH_4]NH_2CO_2$ (ammonium carbamate)

$[NH_4]NH_2CO_2 \rightarrow CO(NH_2)_2 + H_2O$ (urea + water)

The urea molecule has two amide (NH_2) groups joined by a carbonyl (C=O) functional group.



Urea

$CO(NH_2)_2$

Urea-ammonium nitrate (UAN) solutions are liquid fertilizers made by dissolving urea and ammonium nitrate (NH_4NO_3) in water. The composition of common N solutions is shown in Tables 2 and 3.

Table 2. Total N content and quantities of urea, ammonium nitrate, and water in 100 lbs of common UAN solutions.

	UAN-28	UAN-30	UAN-32
Total N	28%	30%	32%
	– approx. lbs in 100 lbs of solution –		
Urea	30	32	35
NH_4NO_3	40	43	45
Water	30	25	20

As Table 3 indicates, ½ of the total N in UAN solutions is amide N (NH_2^-) derived from urea; ¼ is ammonium N (NH_4^+) derived from ammonium nitrate, and ¼ is nitrate N (NO_3^-) derived from ammonium nitrate.

Table 3. Percent of nitrogen by type in UAN solutions.

	UAN-28	UAN-30	UAN-32
Total N Content	28%	30%	32%
		%	
Amide (NH_2^-)	14	15	16
Ammonium (NH_4^+)	7	7.5	8
Nitrate (NO_3^-)	7	7.5	8

Although there are several other forms of nitrogen fertilizers such as ammonium sulfate, calcium nitrate, and diammonium phosphate, over 80% of the N needs of corn in North America are met by anhydrous ammonia, urea, and UAN solutions.

Nitrogen Fertilizers and Soil Reactions

Anhydrous Ammonia

Anhydrous ammonia is applied by injection 6 to 8 inches below the soil surface to minimize escape of gaseous NH_3 into the air. NH_3 is a very hygroscopic compound and, once in the soil, reacts quickly with water and changes to the ammonium

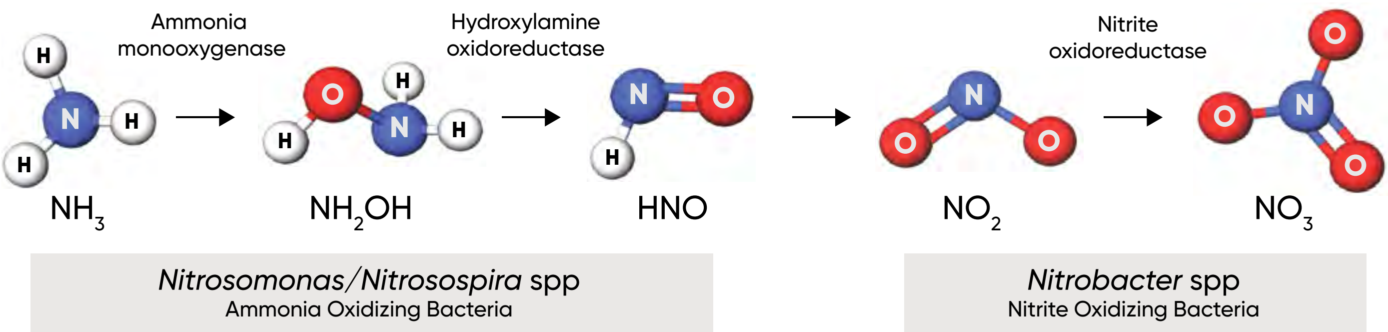


Figure 1. Nitrification process, showing key bacterial species and enzymes.

(NH_4^+) form. As a positively charged ion, ammonium binds with negatively charged soil constituents including clay and organic matter. Nitrogen in the ammonium form is held on the soil exchange complex and is not subject to movement with water.

Soil reactions – Ammonium ions are converted to the nitrate (NO_3^-) form by the action of soil bacteria in a process known as **nitrification** (Figure 1). Nitrification is a two-step process: 1) oxidation of ammonia (NH_3) into nitrite (NO_2^-), and 2) oxidation of nitrite into nitrate (NO_3^-). Both steps are carried out by chemoautotrophic bacteria in the soil that use oxidation of chemical compounds as a source of energy for themselves. These bacteria are ubiquitous in most agricultural, pastoral, natural grassland, and forested geographies worldwide (Rajendran 2011). There are numerous species of ammonia-oxidizing bacteria; the most documented of which in agricultural systems are those belonging to the genera *Nitrosomonas* and *Nitrosospira*. Oxidation of nitrite to nitrate is carried out by bacteria in the genus *Nitrobacter*.

As with nearly all biological reactions, the rate of nitrification is greatly influenced by soil temperature. In soils above 75°F, (24°C) nitrification is not limited by temperature. Cold soil temperatures slow nitrification, with the process essentially ceasing at soil temperatures below 40°F (4°C).

Soil pH, water content, and oxygen availability are also major factors influencing the rate of nitrification. The optimal pH range for nitrification is between 6.5 and 8.8. Nitrification rates are reduced in more acidic soils. High pH soils are limiting for the second step of the process (oxidation of nitrite to nitrate), which can lead to a buildup of nitrite in the soil. Since both water and oxygen are required for nitrification, adequate but not excessive soil moisture is ideal. Nitrification is limited when saturation of soil pore space with water exceeds 60%.

Only after the nitrification process has converted ammonium to negatively charged nitrate ions (that are repelled by clay and organic matter in the soil complex) can nitrogen be lost from most soils by leaching or denitrification. Plants can take up nitrogen in both the ammonium and nitrate forms. If nitrogen can be held in the ammonium form until it is taken up by plants, it is at little risk of loss. (Sandy soils with a very low cation exchange capacity (CEC) are an exception, as they lack enough exchange sites to bind much ammonium.)

Urea

Urea readily dissolves in water, including soil water; consequently, it can be incorporated into the soil by sufficient rainfall or irrigation (½ inch is typically suggested). Otherwise, it should be incorporated by tillage to reduce losses.

Soil Reactions – Urea is hydrolyzed into one carbon dioxide and two ammonia molecules (Figure 2).

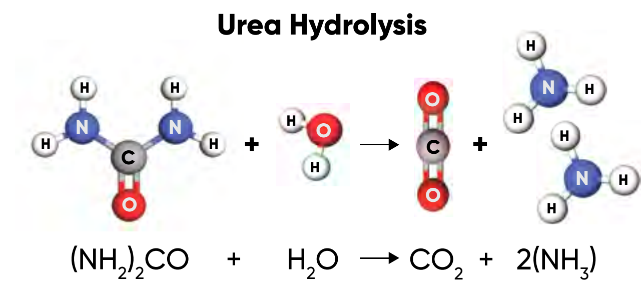


Figure 2. Urea is hydrolyzed by soil bacteria producing one molecule of CO_2 and two NH_3 (ammonia) molecules.

Urea hydrolysis is catalyzed by urease, an enzyme that is produced by many types of bacteria and some plants and is ubiquitous in soils. The biological degradation of urea by urease that releases the N for plant use also makes it subject to volatilization (as NH_3) depending on whether the reaction occurs in the soil or on the soil surface. If it occurs within the soil, the ammonia quickly reacts with soil water to form NH_4^+, which is then bound to the soil. If it occurs at the soil surface, the gaseous ammonia can easily be lost into the air. If plant residue is abundant on the soil surface, it increases bacterial populations, concentration of urease, and volatilization losses of urea.

UAN Solutions

Urea-ammonium nitrate (UAN) solutions are mixtures of urea, ammonium nitrate, and water in various proportions. All common UAN solutions (28%, 30% and 32%) are formulated to contain 50% of actual N as amide, (from urea), 25% as ammonium (from ammonium nitrate), and 25% as nitrate (from ammonium nitrate).

Soil Reactions – The urea portion of UAN solutions reacts just as dry urea does (see previous section on urea). If applied on the surface, the amide-N in the solution may incur losses due to volatilization when urease hydrolysis releases NH_3. But if UAN is incorporated by tillage or sufficient water, the NH_3,

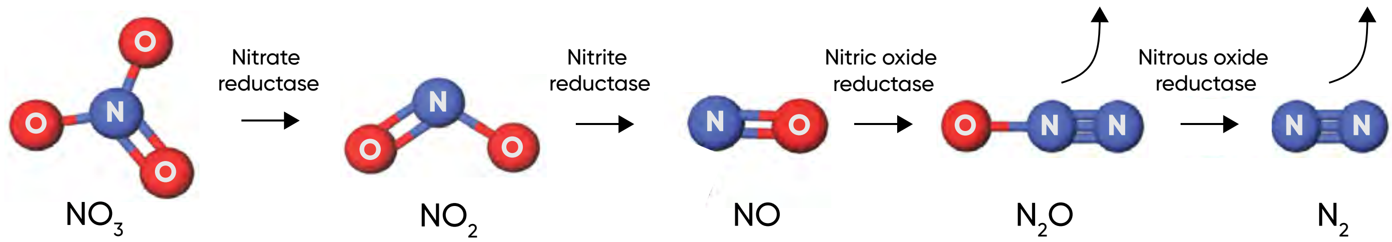


Figure 3. Denitrification process, showing steps and key enzymes.

quickly reacts with soil water to form NH_4^+. This ammonium, as well as the ammonium N derived from ammonium nitrate in the solution, adheres to soil components at the application site and is not subject to loss in the short term. Like N applied as anhydrous ammonia, this N will eventually be taken up by plants in the ammonium form, or if not, eventually converted to nitrate by soil bacteria.

The remaining 25% of nitrogen in UAN solutions is in the nitrate (NO_3^-) form. Because it is negatively charged, it will not adhere to clay and organic matter particles (which are also negatively charged) but rather, will exist as an anion in the soil solution. Because it moves with water, it is easily taken up by plant roots, but is also subject to losses by leaching and denitrification.

Nitrogen Losses

Nitrogen loss constitutes a major challenge to agricultural efficiency and sustainability. Globally, less than half of nitrogen applied to crop land is taken up by the crop (Zhang et al., 2015). Not only is this economically wasteful, the loss of reactive nitrogen from agricultural soils is associated with several adverse environmental consequences, including contamination of ground and surface water, algal blooms in lakes and rivers, hypoxic dead zones in coastal waters, and nitrous oxide emissions into the atmosphere.

Globally, ***less than half of nitrogen applied*** to crop land is **taken up** by the crop.

Nitrous oxide from soil is the largest contributor to agricultural greenhouse gas emissions (U.S. EPA, 2021). The majority of nitrous oxide emissions from soils are produced during denitrification. **Denitrification** is a microbially facilitated process where nitrate (NO_3^-) is reduced and converted to N_2 gas through a series of intermediate steps (Figure 3). When nitrate is not completely converted to N_2 gas, the resulting byproduct is nitrous oxide (N_2O).

Denitrification occurs when nitrogen in the nitrate form is present in the soil and oxygen availability is limited in the soil due to water saturation. When oxygen in the soil is limited, a variety of bacteria will use the oxygen atoms from nitrate molecules for respiration. Denitrification is triggered by rainfall events of sufficient volume to saturate at least 60% of soil pore space. The greatest nitrogen losses through denitrification generally occur in the spring when rainfall events are most frequent and crop uptake of nitrogen from the soil is relatively low.

Denitrification occurs when water saturation limits the availability of oxygen to bacteria in the soil.

Nitrogen Stabilizers

Nitrification Inhibitors

Nitrification inhibitors are compounds that slow the conversion of ammonium to nitrate, prolonging the period of time that nitrogen is in the ammonium form and reducing nitrogen loss from the soil. Several compounds have proven effective for this purpose, including nitrapyrin, dicyandiamide (DCD), and ammonium thiosulfate.

Nitrapyrin, or 2-chloro-6-(trichloromethyl) pyridine, works by inhibiting and depressing the activity of *Nitrosomonas* bacteria; specifically, it inhibits the activity of ammonia monooxygenase (AMO), the enzyme that oxidizes NH4 into NH_2OH in the first step of nitrification (Figure 4). When used in agricultural soils at labeled rates, nitrapyrin exhibits bacteriostatic activity on the *Nitrosomonas* population in the zone of application (Rodgers and Ashworth 1982). Inhibition of the AMO enzyme by nitrapyrin delays nitrification activity for several weeks to months following application.

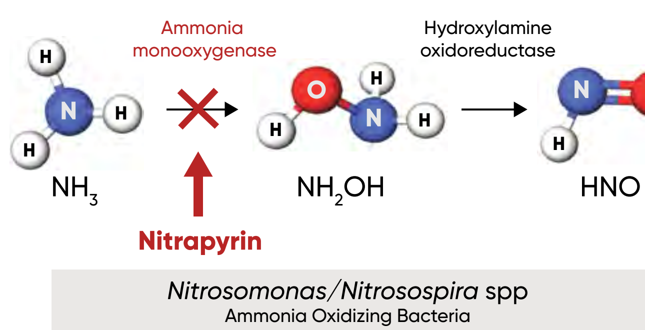


Figure 4. Nitrapyrin delays nitrification by inhibiting ammonia monooxygenase in *Nitrosomonas* bacteria, the enzyme that catalyzes the first step of the nitrification process.

As the nitrapyrin degrades over time, AMO is no longer inhibited and *Nitrosomonas* populations resume the nitrification process converting available ammonia to nitrate. In warm soils, nitrapyrin can degrade in 30 to 40 days. However, it is very persistent in cool soils, which contributes to its effectiveness for fall and winter applications. Measurable activity against *Nitrosomonas* often occurs for about six to eight weeks in warm soils conducive to crop growth, and 30 weeks or more in cool soils typical of late fall and winter in the midwestern U.S. (Trenkel, 2010).

Nitrification inhibitors can be a ***valuable tactic*** for **reducing** agricultural greenhouse gas emissions.

Nitrapyrin products for delaying nitrification of ammoniacal and urea fertilizers include N-Serve® and Instinct NXTGEN®. N-Serve nitrogen stabilizer is an oil-soluble formulation of nitrapyrin for use with anhydrous ammonia. Instinct NXTGEN nitrogen stabilizer is a water-based micro-encapsulated formulation of nitrapyrin that may be used with urea, UAN solutions, ammonium sulfate, liquid manure, aqua ammonia, liquid fertilizers containing N, and ammonium-containing dry fertilizers (MAP or DAP).

DCD (dicyandiamide) - Following extensive use in western Europe and Japan, DCD became more commonly used in the US in the late 1990s. Products containing only DCD are generally used with nitrogen solutions and liquid manure. The rate of DCD used is relative to the amount of fertilizer N applied, rather than the area of application. This may limit its efficacy at low fertilizer application rates (e.g., split applications, side-dress applications, or crops that require low nitrogen rates).

DCD inhibits nitrification in the same way as nitrapyrin, by inhibiting the activity of ammonia monooxygenase in *Nitrosomonas* bacteria. However, DCD is a significantly less potent inhibitor, requiring higher field use rates to be effective and inhibiting nitrification for a shorter period of time. Depending on the amount of mineral N applied and the moisture and temperature of the soil, DCD may stabilize ammonium-N for 4 to 10 weeks.

Value of Nitrification Inhibitors

Nitrification inhibitors have proven very effective in increasing soil nitrogen retention and reducing losses through leaching and denitrification. A 2004 meta-analysis of hundreds of comparisons across a diversity of environments found that the use of nitrification inhibitors increased soil nitrogen retention by an average of 28% and reduced leaching by 16% (Wolt, 2004). Nitrous oxide emissions were reduced by over 50% on average in this study, indicating that nitrification inhibitors can be a valuable tactic for reducing agricultural greenhouse gas emissions.

Corteva Agriscience field trials conducted over several years found that the use of nitrification inhibitors increased corn yield by an average of around 6 bu/acre. The highest value of nitrification inhibitors should be realized in scenarios with a high risk of nitrate losses from leaching or denitrification, including the following conditions (Ruark, 2012):

- Tile-drained soils when leaching potential is high
- Wet or poorly drained soils
- Fields with nitrogen applied in the fall or spring prior to planting

Urease Inhibitors

Urease inhibitors are compounds that reduce volatilization losses of urea applied to the soil surface by slowing down urea hydrolysis. For the nitrogen in urea to be available to plants, it must undergo hydrolysis, a chemical reaction that transforms the amide groups of the urea molecule to ammonia (NH_3). The urease enzyme, ubiquitous in soils, catalyzes this hydrolysis reaction. If this process occurs at the soil surface, ammonia can be lost to the air. However, if this reaction is delayed until surface-applied urea is incorporated into the soil by tillage, rainfall, or irrigation, the risk of ammonia loss is greatly reduced.

Urea granules on the soil surface next to corn plants at V4 growth stage. Urea that is not incorporated can be lost to volatilization without the use of a urease inhibitor.

Urease activity increases as temperature increases. Hydrolysis is normally completed within 10 days at a temperature of 40°F (4°C) and within two days at a temperature of 85°F (29°C). Hydrolysis is also highly correlated with the organic matter, total N and cation exchange capacity (CEC) of the soil; increasing as any of these factors increase.

Certain compounds are known to inhibit the hydrolytic action of the urease enzyme, delaying urea hydrolysis. The most widely used urease inhibitor in agriculture is N-butyl-thiophosphoric triamide, (NBPT). NBPT is a structural analog of urea and, as such, inhibits urease by blocking the active site of the enzyme. NBPT is the active ingredient in PinnitMax® TG nitrogen stabilizer.

PinnitMax TG is an additive for use with urea and urea-ammonium nitrate solutions. Research shows that N loss from surface-applied urea can be significant. The amount of loss depends on weather conditions; loss is greatest with warm, windy weather and a moist soil surface. NBPT protects urea and UAN applications from volatilization for up to 14 days, helping ensure nitrogen gets to the plant root zone. Eventually, NBPT degrades in the soil, allowing urea hydrolysis to resume. This is necessary so that plants can take up and use the nitrogen from urea. However, once in the NH_4^+ form, this nitrogen is subject to nitrification to NO_3^- a form that may be lost from the soil.

Performance of Nitrogen Stabilizers

Nitrogen stabilizers/additives have been widely tested over many years and have proven effective at increasing soil nitrogen retention. However, corn yield increases can vary from 0-20%. This is not surprising; when conditions favor nitrogen losses for a period, and a stabilizer is applied and effective during that period, a large benefit is predictable. On the other hand, under conditions not conducive to nitrogen losses, little advantage would be expected.

Because the risk of nitrogen loss is always present, growers should take appropriate precautions to reduce loss of this important crop nutrient. This can be accomplished by picking an appropriate nitrogen source and applying it as closely as possible to the time of crop uptake or by using a nitrogen stabilizer when application timing is farther removed from the period of crop need. Nitrogen management decisions should take into account all factors that influence the risk of loss for a particular field, including local climatic conditions, topography, soil type, residue level, form of nitrogen fertilizer applied, and timing of application relative to crop growth. Nitrogen stabilizers can provide insurance against the risk of nitrogen losses in many susceptible fields.

Forward-Thinking Farming Webinar

Managing for Improved Nitrogen Utilization in Corn

- Dr. Daniel J. Quinn, Purdue University and Dr. Jason DeBruin, Corteva

Join **Dr. Daniel Quinn,** and **Dr. Jason DeBruin** as they discuss hybrid interactions with nitrogen uptake, application methods, sources, environmental factors, and other insights on nitrogen management strategies to optimize return on investment.

return to table of contents

Micronutrients for Crop Production

Steve Butzen, M.S., *Former Agronomy Information Consultant,*
and ***Mark Jeschke, Ph.D.,*** *Agronomy Manager*

Key Points

- Micronutrients are seven elements essential for crop growth in very low quantities – boron, chlorine, copper, iron, manganese, molybdenum, and zinc.
- In the major crops and production areas of North America, the micronutrients most often supplied by fertilization include zinc, manganese, boron, and iron.
- Micronutrient deficiencies can be detected by visual symptoms on crops and by testing soils and plant tissues.
- The most reliable micronutrient soil tests are for zinc, boron, copper, and manganese. Though useful, these tests are not as precise as those for soil pH, potassium and phosphorus.
- Plant tissue analysis is more reliable than soil testing for identifying many micronutrient problems and can also supplement soil test information.
- Most often, micronutrients are soil-applied in a band at planting, or foliar-applied, as these methods allow lower use rates of sometimes expensive materials.

Critical plant functions can be limited if micronutrients are deficient, resulting in ***plant abnormalities***, ***reduced growth***, and ***lower yield.***

return to table of contents

Micronutrients are Essential

Micronutrients are essential elements that are used by plants in small quantities. For most micronutrients, crop uptake is less than one pound per acre. Despite this low requirement, critical plant functions can be limited if micronutrients are deficient, resulting in plant abnormalities, reduced growth and lower yield. In such cases, expensive, high-requirement crop inputs such as nitrogen and water may be wasted if yield potential is being limited by a micronutrient deficiency. This article will discuss general micronutrient requirements, deficiency symptoms, soil and plant sampling, and fertilization practices.

Corn leaves showing zinc deficiency. Interveinal striping in center of leaf is surrounded by green borders/margins.

Plant Requirements and Soil Availability

There are 16 elements essential to growth of crop plants (Figure 1). Two of these nutrients, carbon and oxygen, are extracted from the air. Hydrogen is extracted from soil water. The remaining thirteen nutrients are all extracted from soil and are classified as primary macronutrients, secondary macronutrients, or micronutrients based on the quantities taken up and utilized for plant growth. The seven micronutrients – boron, chlorine, copper, iron, manganese, molybdenum, and zinc – are used in very low quantities for crop production (Figure 2).

Figure 1. Sources of the sixteen nutrients essential for crop production.

Atmosphere	Carbon	Oxygen
Water	Hydrogen	
Soil	**Primary Macronutrients**	**Secondary Macronutrients**
	Nitrogen Phosphorus Potassium	Sulfur Calcium Magnesium
	Micronutrients	
	Boron Chlorine Copper Iron	Manganese Molybdenum Zinc

The seven micronutrients are sufficient in most soils to meet crop needs. However, some sandy soils and other low-organic matter soils are naturally low in micronutrients, and high pH soils may make some micronutrients less available and therefore deficient. In the major crops and production areas of North America, the micronutrients most often supplied by fertilization include zinc, manganese, boron, and iron. Basic chemical properties of micronutrients help determine their availability in soils (Table 1).

Table 1. Chemical properties of micronutrients.

Cations	
Copper **Iron** **Manganese** **Zinc**	Positively charged - bind to soil particles Solubility is greatest under acid conditions Most likely deficient on calcareous soils or soils extremely high in organic matter where strong chelation decreases availability
Anions	
Boron **Chlorine** **Molybdenum**	Negatively charged – subject to leaching In short supply in areas where they are readily leached and not being replenished by organic matter decomposition

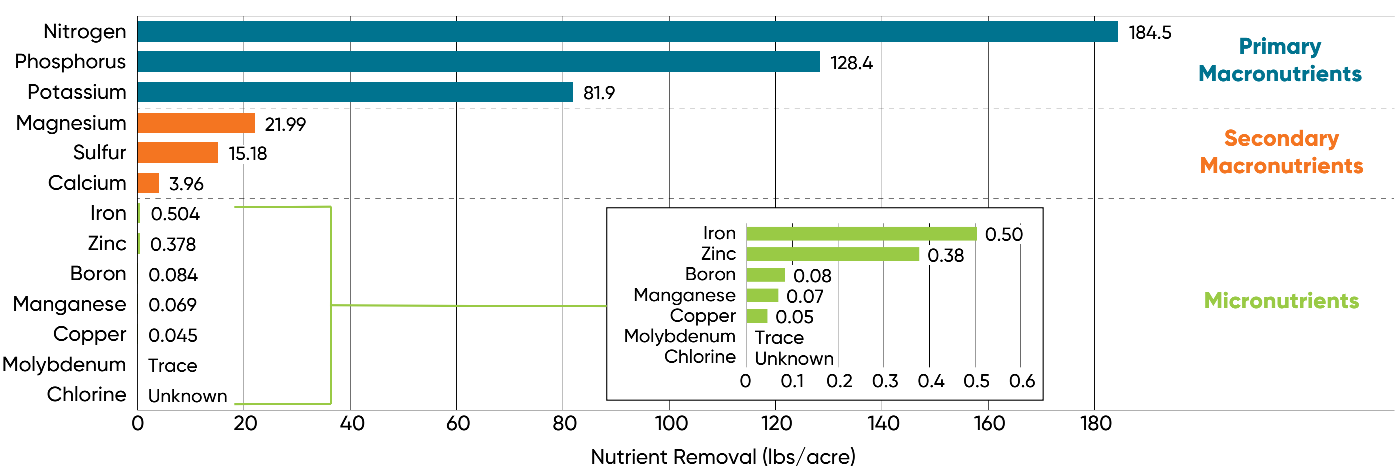


Figure 2. Nutrients removed by a 300 bu/acre crop (Heckman et al., 2003).

return to table of contents

Because of complex chemical reactions within the soil, micronutrient availability is ultimately controlled by the equilibrium between the soil solution, soil organic matter, cation exchange sites, and insoluble compounds of micro-nutrients. Soil acidity or alkalinity has a large effect on the tie-up of micronutrients or their availability to plants. Micronutrients are generally more available in acid soils and less available at high pH, with the exception of molybdenum, which is more available at higher pH (Figure 3).

Pioneer Agronomy

Micronutrients
- Mark Jeschke, Agronomy Manager

Organic Matter

Organic matter is a reservoir for essential plant nutrients, continuously supplying these nutrients to the crop as it decomposes over time. This reservoir is especially important for anions such as boron, which do not bind to soil particles and are therefore subject to losses. Soils that receive regular additions of organic residues such as manures rarely show micronutrient deficiencies. An exception is deficiencies caused by nutrient imbalances, such as a deficiency of manganese caused by an excess of phosphorus in overly manured soils. Another exception is soils with extremely high organic matter such as muck or peat soils. In these soils, strong, natural chelation (the combination of a micronutrient with an organic molecule) can make some micronutrients unavailable, particularly copper, manganese, and zinc.

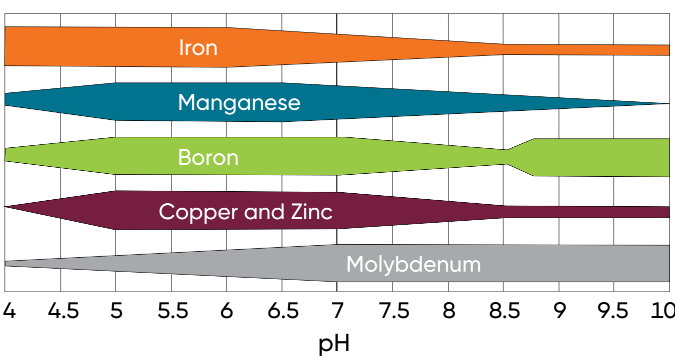


Figure 3. Relative availability of micronutrients by soil pH[9].

Micronutrient Removal by Crops

Crop yields are continually increasing due to genetic improvements in stress tolerance and disease resistance, incorporation of insect resistance traits, and use of seed treatments and other crop protection products. This means that more micronutrients are removed from the soil as yields increase. Estimates of nutrient removal for a 300 bu/acre corn crop are shown in Figure 2.

Although micronutrient removal rates are increasing, they are still very small relative to the primary and secondary macronutrients. Removal rates for a 300 bu/acre corn crop range from over 80 lbs/acre for the primary macronutrients and 4-22 lbs/acre for secondary macronutrients, compared to 0.5 lb/acre or less for micronutrients.

Symptoms of boron deficiency in alfalfa. Alfalfa is one of the few crops that can benefit from boron applications if levels become deficient.

Detecting Micronutrient Deficiencies

Micronutrient deficiencies can be detected by visual symptoms on crops and by testing soils and plant tissues. To understand visual symptoms, it is useful to know the role each micronutrient plays in plant growth and development.

Functions of Micronutrients

Micronutrients differ in the form they are absorbed by the plant, their functions and mobility in the plant, and their characteristic deficiency or toxicity symptoms (Table 2 and 3).

Table 2. Plant available forms and functions of micronutrients in plants[10].

Element and Plant-Available Form		Function in Plant
Boron	H_3BO_3 $H_2BO_3^-$	Important in sugar transport, cell division, and amino acid production
Chlorine	Cl^-	Used in turgor regulation, resisting diseases and photosynthesis reactions
Copper	Cu^{2+}	Component of enzymes, involved with photosynthesis
Iron	Fe^{2+} Fe^{3+}	Component of enzymes, essential for chlorophyll synthesis, photosynthesis
Molybdenum	MoO_4^{2-}	Involved in nitrogen metabolism, essential in nitrogen fixation by legumes
Manganese	Mn^{2+}	Chloroplast production, cofactor in many plant reactions, activates enzymes
Zinc	Zn^{2+}	Component of many enzymes, essential for plant hormone balance and auxin activity

Micronutrient Deficiency Symptoms

Except for Mo, the micronutrients are considered weakly mobile or immobile in plants. This means that deficiency symptoms appear first or most severely on newest plant tissues. For molybdenum, deficiency symptoms appear first on oldest plant tissues. Symptoms vary according to crop, but generalized symptoms are shown in Table 3.

Table 3. General micronutrient deficiency symptoms[2].

Element	General Deficiency Symptoms
Boron	Light general chlorosis, death of growing point, deformed leaves with areas of discoloration
Chlorine	Chlorosis and wilting of young leaves. Deficiency rarely seen on crop plants in field
Copper	Light overall chlorosis, leaf tips die back and tips are twisted, loss of turgor in young leaves
Iron	Chlorosis or yellowing between the veins of new leaves
Molybdenum	Similar to those of ordinary nitrogen deficiency – general chlorosis (yellowing) of young plants, chlorosis of oldest leaves
Manganese	Chlorosis or yellowing between the veins of new leaves (much like Fe deficiency)
Zinc	Stunted growth, reduced internode length, young leaves are smaller than normal

Iron deficiency chlorosis (IDC) of soybeans caused by high pH soils in the Black Belt region of central Alabama. IDC is a complex plant disorder associated with high pH soils and soils containing soluble salts where chemical conditions reduce the availability of iron.

Micronutrient deficiencies usually have a patchy distribution in fields due to variation in soil properties that affect availability (e.g., pH, drainage, and salinity) and management history such as manure applications. Learning to visually identify deficiencies is important in recognizing problem areas and planning remediation for future crops. However, it is often too late for corrective action in the current crop by the time visual symptoms appear.

Common Micronutrient Deficiencies

Micronutrient deficiencies tend to appear with much greater frequency on specific soil types and in certain crops (Table 4).

Table 4. Soil conditions which may lead to micronutrient deficiencies for various crops[11].

Element	Soil Characteristics	Crop
Boron	Sandy soils or highly weathered soils low in organic matter	Alfalfa, clover
Chlorine	Sandy soils with high rainfall, highly weathered soils low in organic matter	Wheat
Copper	Acid peats or mucks with pH < 5.3 and black sands	Wheat, corn
Iron	Soils with high soil pH, soluble salts and/or calcium carbonate levels	Corn, soybean
Molybdenum	Peats and mucks with pH > 5.8, black sands and lakebed/ low-lying soils with pH > 6.2	Soybean, wheat, sugar beets, corn
Manganese	Acid prairie soils	Soybean
Zinc	Peats, mucks and mineral soils with pH > 6.5	Corn, soybean

Soil Tests to Detect Micronutrient Deficiencies

Many plant symptoms associated with micronutrient deficiencies, including stunting and chlorosis, may have a variety of causes, including disease, insect or herbicide damage, or environmental conditions. Soil and plant analysis are both useful in determining if the cause is truly nutritional. Though adequate for this purpose, micronutrient soil tests are not as precise as soil pH, phosphorus, and potassium tests.

The most reliable micronutrient soil tests are for zinc, boron, copper, and manganese. Because interpretations are soil specific, it is best to use locally calibrated recommendations. Soil tests for iron and molybdenum are considered to be of little value in predicting the supply of these nutrients in soils. When sampling for micronutrients, sample the root zone down to 8 inches deep.

Plant Analysis to Detect Micronutrient Deficiencies

Plant tissue analysis is more reliable than soil testing for identifying many micronutrient problems and can also supplement soil test information. Tissue testing is especially valuable in cases where reliable soil tests are unavailable. However, molybdenum and chlorine levels cannot be determined by this method.

Plant analysis can be used in two ways; one is to monitor the crop's micronutrient status, and the other is to diagnose a problem situation. By quantifying the nutrient content of tissues, plant analysis can point out an existing or potential problem before visual symptoms develop.

If in-season micronutrient deficiencies are suspected, plant samples should be taken as early as practical; treatments, when needed, should be made in a timely manner. Research has shown that once a micronutrient deficiency is detected, the plant has already suffered irreversible yield loss.

Many **plant symptoms associated with micronutrient** deficiencies, including ***stunting*** and ***chlorosis***, may have a variety of causes.

Because plant nutrient composition varies depending on the crop, age of the plant, part of the plant sampled and other factors, it is important to follow the standard sampling procedures provided by your plant diagnostic laboratory. In order to obtain a representative sample, take multiple plants from areas randomly distributed throughout the affected field area. Avoid border plants and those contaminated with dust, soil or foliar sprays. Taking samples of non-symptomatic plants to compare with apparent nutrient-deficient plants can increase the usefulness of plant analysis. Be aware that interpreting results is complex and may require expert advice.

Managing Micronutrient Deficiencies

Selecting Micronutrient Sources

There are three main classes of micronutrient fertilizers: inorganic, synthetic chelates, and natural organic complexes.

Inorganic sources consist of oxides, carbonates, and metallic salts such as sulfates, chlorides, and nitrates. Sulfates are the most common metallic salts used in the fertilizer industry because of their high water-solubility and plant availability. Less soluble oxides must be finely ground or partially acidulated with sulfuric acid to form oxysulfates in order to increase their effectiveness. Metal-ammonia complexes such as ammoniated Zn sulfate decompose readily in soils and provide good agronomic effectiveness.

Chelates are fertilizers in which the micronutrient is combined with an organic molecule to increase its stability and effectiveness in the soil. Chelates such as Zn-EDTA are more stable and more effective in correcting Zn deficiency than other forms of applied Zn. Synthetic chelates are more effective and less variable than natural organic complexes such as lignosulfates, phenols, and polyflavonoids.

Method of Application

The best method of micronutrient application depends on the element and when the deficiency is being addressed.

Soil application. For deficiencies known at the start of the season, soil application is preferred to foliar application for most nutrients. Micronutrients **banded** with starter fertilizers at planting time are usually more effective over a longer period than foliar-applied micronutrients. This method also gets the nutrient to the plant at the earliest opportunity.

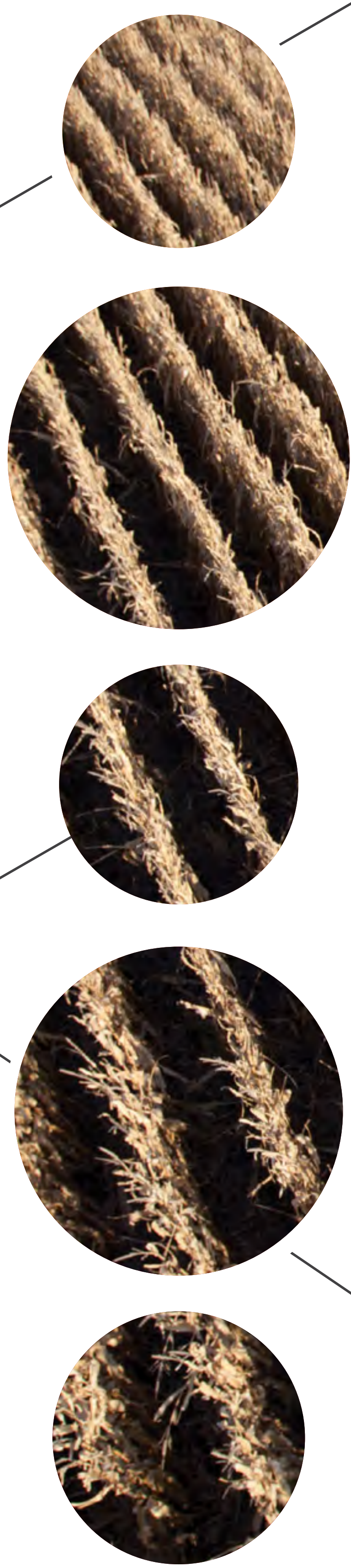
Soil-applied micronutrients may also be broadcast, but a concentrated band near the plant allows lower use rates of sometimes expensive materials. Manganese should only be banded, because of the ability of most soils to strongly "fix" this element. However, boron should not be banded, as high concentrations near the seed can be toxic.

Foliar application is especially useful for some elements that are not efficiently used when applied to the soil, such as iron. This method is also useful for quick uptake in emergency situations when deficiencies are noted or in cases where other materials are being sprayed. Like banding, foliar applications generally have lower use rates, but more than one application may be needed. However, because the crop partially develops prior to foliar application, irreversible damage may have already occurred before the needed nutrient is supplied.

Broad-spectrum micronutrient applications are not recommended to treat a single micronutrient deficiency, as this approach is expensive and potentially harmful to the crop. The harm can occur because of potential toxicities, or because the presence of additional nutrients may interfere with the uptake of the needed nutrient.

Achieving a **uniform spread pattern** is important to correct deficiencies, regardless of whether the material is liquid or solid, banded or broadcast, or preplant or foliar applied.

return to table of contents



Crop Management in a Changing Climate

Mark Jeschke, Ph.D., Agronomy Manager

Summary

- Understanding and incorporating long-term climate trends into crop management decisions can help minimize risk and increase the likelihood of success in crop production.
- Climate scientists have identified several shifts in climate associated with rising global temperatures that will affect agricultural production, many of which are already becoming apparent.
- One of the most significant climate trends for the Midwestern U.S. in recent years has been increased rainfall in the April to June timeframe and more intense rainfall events.
- Average maximum temperatures during the summer have not increased in the Midwest, but night temperatures have gotten warmer.
- The average frost-free season in the Midwest and Great Plains has expanded by 9 to 10 days and is projected to continue to increase in the future.
- The potential effects of rising global temperatures on droughts in the Midwest are unclear. Projections suggest a more frequent pattern of excess moisture in the spring followed by dry spells in the summer.
- Weed and insect pressure varies yearly but is expected to worsen overall with more diligent management necessary.
- As current climate trends continue to intensify, the need for active adaptation measures will increase, especially in regard to protecting soils and crops against a more volatile climate with a higher frequency of extreme events.

Introduction

It would be difficult to name an industry more thoroughly dependent upon weather than agriculture. Weather conditions during a growing season can have an enormous impact on the yield potential of a crop; the growth and spread of weeds, diseases, and insect species; and the ability to plant and harvest a crop in a timely manner. Looking back at years when there were severe drops in crop yields (e.g., 1983, 1988, 1993, and 2012), anyone involved in crop production during those years will immediately recall the abnormal weather conditions that caused them.

The unpredictability of weather – not knowing at the start of a growing season what it will bring – is a constant challenge to optimizing crop management practices. Understanding and incorporating long-term climate trends into crop management decisions is important for minimizing risk and increasing the likelihood of successful outcomes in any given growing season. One of the most important factors influencing climatic trends around the world right now is rising global temperatures. Climate scientists have identified several shifts in climate trends associated with rising temperatures that will affect agricultural production, many of which are already becoming apparent. Whether some of these changes can be judged as positive or negative may depend on individual circumstances and perspective. The important point for agriculture is that they will tend to produce weather patterns that are different from what we have come to expect with increasing frequency and may require adaptation in crop management in order to maintain productivity. A general trend toward increased climate volatility will require greater resilience of crop production systems against extreme weather events.

> A general trend toward ***increased climate volatility*** will require greater resilience of crop production systems against **extreme weather events.**

This article will review some of the changes in climate associated with rising global temperatures and discuss implications for agricultural production, focused primarily on the Midwestern U.S., including observed and projected changes in weather patterns and potential impacts on crop growth as well as management.

Temperature and Climate

Global average surface temperature has risen by about 1.6°F or 0.9°C since the late 19th century (Figure 1). A large body of evidence supports the conclusion that this rise in temperature is a result of human activity and primarily due to the production of greenhouse gases (Santer et al., 2019).

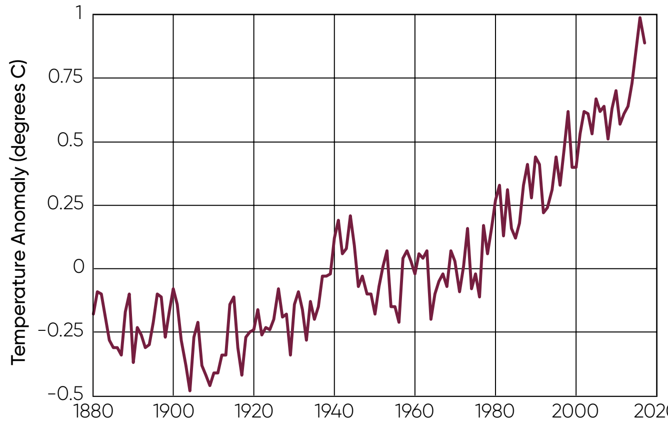


Figure 1. Annual global land and ocean temperature anomaly (deviation from 20th century average), 1880-2018 (NOAA NCEI, 2019).

Average global temperatures are increasing, but this does not mean that warmer temperatures manifest uniformly over the entire earth all of the time. Earth's climate system is complex and dynamic. The effects of altering one parameter of the system can produce different effects in different regions due to other interacting factors. Some of these associated climatological effects may have a greater direct impact on human populations and activities than the underlying rise in temperatures. For example, changes in water distribution (e.g., atmospheric humidity, sea levels, and precipitation patterns) may be a much more immediate concern for populations near bodies of water or industries dependent upon water, such as agriculture.

The following section provides an overview of some of the observed and projected climate trends relevant to agriculture summarized in the Fourth National Climate Assessment (NCA4), focusing specifically on the Midwestern U.S. (Angel et al., 2018). NCA4 provides a comprehensive overview of current climate science and potential implications for many industries and segments of society, including agriculture. The complete report, including summaries for other regions of the U.S., is available at www.globalchange.gov/nca4.

Observed and Projected Climate Trends

Temperature

One might expect the most reliable outcome of global warming to be hotter maximum temperatures during the summer, but this has not been the case in the Midwest. Annual average temperatures have increased, but this has been primarily due to higher maximum temperatures in the winter. Maximum summer temperatures have not increased in the Midwest as they have in most other regions of the country (Table 1) (Angel et al., 2018). Daily minimum temperatures have increased across all seasons, however. The 2018 growing season was the hottest on record for the continental U.S., primarily because of high nighttime temperatures.

Table 1. Observed regional changes in annual average temperature from 1901-1960 to 1986-2016. Estimates are derived from the nClimDiv dataset (Vose et al., 2017).

Region	Change in Annual Temperatures	
	Maximum	*Minimum*
Northeast	+1.16°F	+1.70°F
Southeast	+0.16°F	+0.76°F
Midwest	+0.77°F	+1.75°F
Great Plains North	+1.66°F	+1.72°F
Great Plains South	+0.56°F	+0.96°F
Southwest	+1.61°F	+1.61°F
Northwest	+1.52°F	+1.56°F

Research indicates that one of the reasons maximum temperatures during the summer have not increased in the Midwest is because of greater precipitation in the spring and early summer as well as subsequent high levels of evapotranspiration of water from agricultural crops (Alter et al., 2017). As agricultural productivity in the region has increased, so has the amount of water transpired from growing crops into the atmosphere. This causes humidity to rise, which tends to reduce daytime maximum temperatures, increase nighttime temperatures, and increase precipitation. This same phenomenon has been observed in other areas of the world where intensive agricultural production has been associated with a suppression of extreme temperatures in the region (Mueller et al., 2017).

Although the Midwest has thus far not experienced higher maximum temperatures during the summer months, higher night temperatures have the potential to be detrimental. Research has shown that above-average night temperatures during reproductive growth can reduce corn yield both through reduced kernel number and kernel weight due to accelerated phenological development as well as increased rates of cellular respiration (Lutt et al., 2016).

Precipitation

One of the most significant climate trends that has been observed for the Midwestern U.S. over the past few decades has been increased rainfall, particularly in the April to June timeframe (Figure 2) (Angel et al., 2018; Feng et al., 2016).

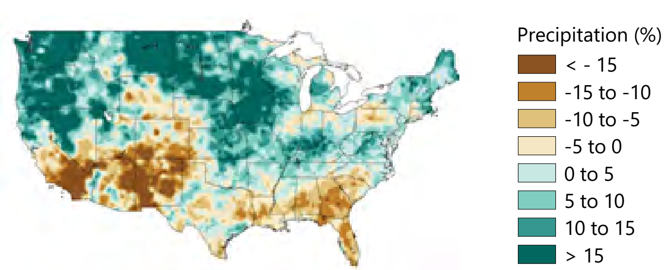


Figure 2. Change in spring precipitation from 1986-2015 compared to 1901-1960 (Easterling et al., 2017).

In general, warmer air is able to hold more moisture, increasing the amount of water available to fall as precipitation. In Des Moines, IA, for example, total rainfall between April and June has increased nearly 50% from an average of around 10 inches in 1950 to 15 inches in 2018 (Figure 3).

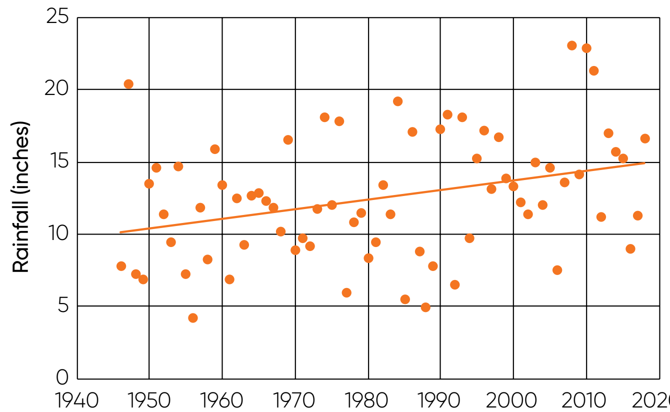


Figure 3. Annual cumulative rainfall in April, May, and June at the Des Moines International Airport, Des Moines, IA (NOAA NCEI, 2019).

Rainfall overall has also tended to be concentrated into more intense rainfall events with the frequency of heavy rainfall events doubling in the Midwest over the past century (Hayhoe et al., 2009). A shift toward a greater percentage of total precipitation falling in very heavy rainfall events has occurred in many parts of the Continental U.S. with the greatest change occurring in the Northeast. These trends are larger than natural variations for the Northeast, Midwest, Southeast, and Great Plains (Walsh et al., 2014) (Figure 4).

A shift toward a ***greater percentage of total precipitation*** falling in **very heavy rainfall events** has occurred in many parts of the continental U.S.

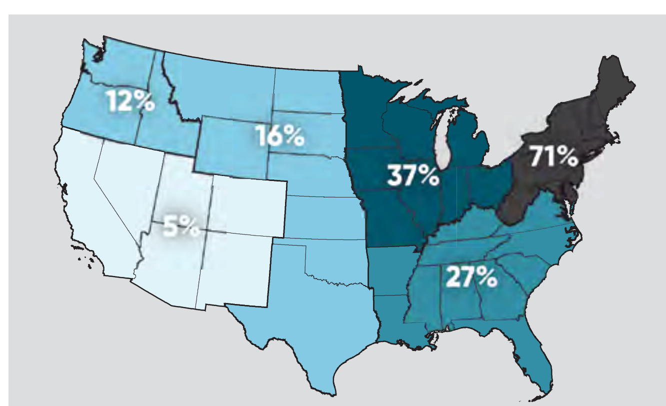


Figure 4. Percent increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958-2012 for each region of the Continental U.S. (Walsh et al., 2014, updated from Karl et al., 2009).

One of the reasons for the shift toward more intense rainfall events in the Midwest is the effect that warmer temperatures have on storm systems called ***mesoscale convective systems*** (MCSs). Mesoscale convective systems are complexes of thunderstorms that can spread over an entire state and last more than 12 hours. They are typically most active at night and extend into the morning hours. These types of systems have historically accounted for 30 to 70% of the total warm-season precipitation in the Central U.S. (Fritsch et al., 1986). Research shows that warmer spring temperatures are causing these storms to be more frequent, more intense, and longer-lasting in the Central U.S. (Feng et al., 2016).

Nearly all of the Midwestern U.S. has experienced a significant increase in rainfall from mesoscale convective systems over the past 40 years (Feng et al., 2016). In the Midwest, these systems are produced by a low-level jet stream, called the ***Great Plains low-level jet***, that transports heat and moisture from over the Gulf of Mexico north and east. Higher temperatures over the Southern Great Plains tend to strengthen this jet stream and increase the amount of moisture evaporated from the Gulf of Mexico that is transported inland, which leads to stronger and more frequent storms (Figure 5).

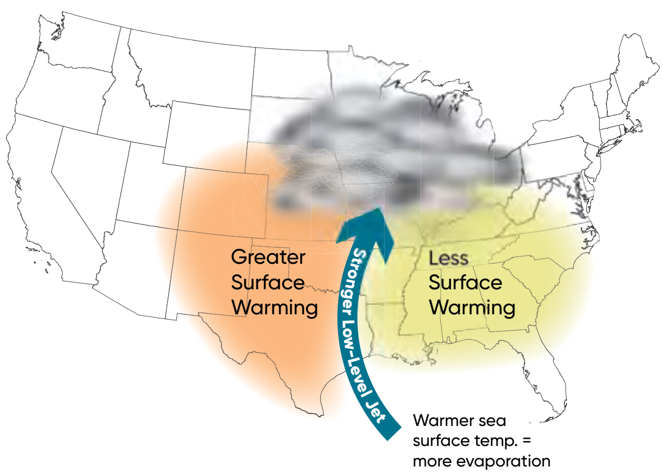


Figure 5. Warmer sea surface temperatures in the Gulf of Mexico increase water evaporation into the atmosphere. Surface warming over the Southern Great Plains increases the pressure gradient across the Central U.S., which strengthens the Great Plains low-level jet, increasing the amount of moisture carried up to the Midwest that falls as precipitation.

Rainfall during the April to June timeframe provides the benefit of charging the soil profile early in the season, which can help mitigate the effect of dry spells later in the summer on growing crops. However, excessive rainfall during this time can also cause delays in field work due to saturated or flooded soils. Intense rainfall events can also erode soils that may have little or no protection at this time of the season.

Projected changes in precipitation over the next century vary greatly across different regions of the U.S. Significant increases in winter and spring precipitation are projected for the Midwest and Northern Great Plains. Changes in summer and fall precipitation are not expected to exceed the range of natural variability. Studies project that the trend toward more frequent and intense heavy precipitation events will continue in the future (Easterling et al., 2017).

Drought

Projections suggest a ***more frequent pattern of excess moisture*** in the spring followed by a **lack of moisture** in the summer.

The frequency of widespread droughts in the Midwest has decreased in the latter half of the 20th century (Mishra and Cherkauer, 2010). Climate scientists are uncertain how the severity, frequency, and duration of droughts will change in the future. Season-long droughts, such as those experienced in 1988 and 2012, are not necessarily expected to increase in frequency. Rather, projections suggest a more frequent pattern of excess moisture in the spring given the changes in precipitation trends, followed by a lack of moisture in the summer due to higher temperatures and evapotranspiration (Angel et al., 2018).

Frost-Free Season

The length of the frost-free season (the length of time between the last spring frost and the first fall frost) has gradually increased throughout the entire continental U.S. since the 1980s. Compared to the 1901 to 1960 time period, the frost free season was 9 to 10 days longer on average in the Midwest and Great Plains during 1991 to 2012 (Walsh et al., 2014) (Figure 6). The length of the frost-free season is projected to continue to increase in the Midwest by up to 20 days by mid-century and possibly a month by late-century (Angel et al., 2018).

A longer frost-free season means a longer period for plant growth and productivity each year, which, by itself, can generally be considered positive for agricultural production, particularly in northern areas where productivity is greatly constrained by the length of the growing season. Adaptation to this trend is already apparent with the expansion of corn production in the Northern Great Plains and western Canada. It is important to remember, though, that it is not just crops experiencing a longer growing season but weeds, insects, and diseases. The Southern areas of the Midwest will experience fewer frosts as the freeze zone moves north, which has implications for pests and pathogens.

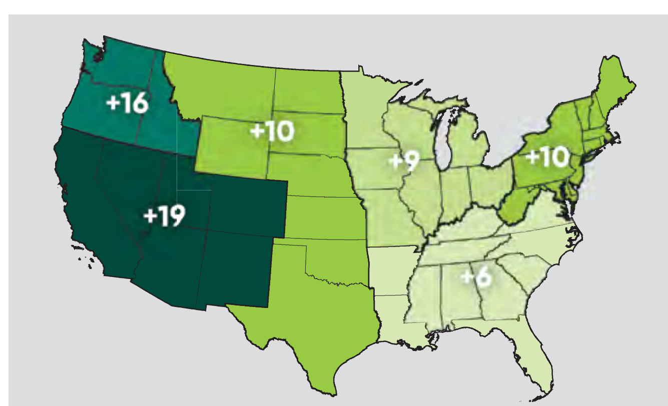


Figure 6. The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960 (NOAA NCDC / CICS-NC, 2019).

Polar Vortex Disruption

Winter temperatures in the Midwest and Great Plains have generally increased and are projected to continue to do so. However, one of the more counterintuitive manifestations of increasing global temperatures may be the potential to produce extreme cold snaps, such as the one experienced in the Midwest and Northern Great Plains in late January of 2019. The cold air over the Arctic is generally separated from the warmer mid-latitude air by the jet stream – a river of wind that flows from west to east over North America. Over the past century, the Arctic has warmed at a much faster rate than the rest of the earth, which has decreased the temperature differential between the Arctic and North America. As the difference in temperature decreases, so does the difference in atmospheric pressure, which causes the jet stream winds to weaken. As the jet stream weakens, extremely cold high-altitude Arctic air has the potential to plunge south into the U.S. (Figure 7). The potential for cold snaps like this to increase in frequency in the future is undetermined and currently an active area of research.

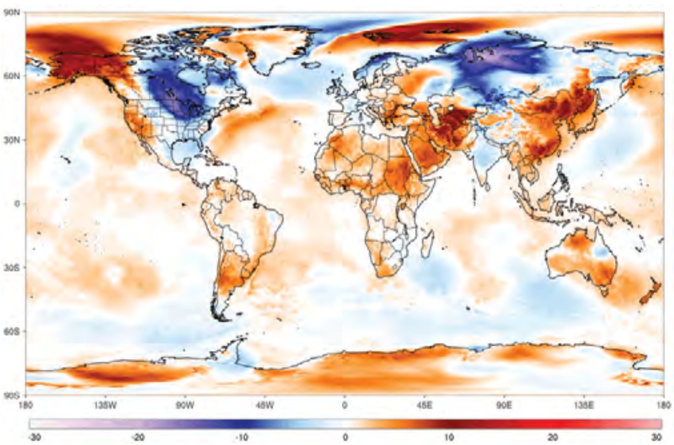


Figure 7. Average near-surface temperature anomaly for January 28-30, 2019, showing an area of extreme cold over North America (Climate Reanalyzer, Climate Change Institute, University of Maine. Data from NOAA Global Forecast System model).

Crop Management Implications

Crop Yield

When considering the possible implications of climate change for agricultural productivity in the U.S., one must first consider two indisputable facts: 1) significant shifts in climate are already occurring, and 2) U.S. average corn and soybean yields have continued to go up. This would suggest one of three possibilities: 1) climate change experienced thus far has required little, if any, adaptation to maintain yield trends; 2) adaptation is being implemented and has been successful; or 3) yields have been reduced by climate change, but these losses have been more than offset by gains from better genetics and management.

In the near-term, the **greatest need for active adaptation** will likely not be associated with rising temperatures and longer growing seasons, so much as with ***more abundant and intense rainfall.***

Forward-Thinking Farming Webinar

Climate Change and Crop Management

Dr. Mark Jeschke, and Dan Berning, Agronomy Managers

Pioneer Agronomy managers discuss climate change implications for agriculture, including observed and projected changes in weather patterns, potential impants on crop growth, and management ideas to consider.

Unrelenting rainfall caused widespread delays in spring tillage and planting in 2019. The continuing trend toward more spring rainfall will be a major challenge for crop production in the Midwestern U.S.

To some extent, adaptation by crop producers to changing climatic conditions has been and will continue to be automatic – by continually optimizing crop selection, hybrid/variety selection, and agronomic management for maximum yields, adaptation happens without anyone necessarily thinking about it. As current climate trends continue to intensify in the future, however, adaptation may become more important to specifically plan towards. It will be very important to protect soils and crops against a more volatile climate with a higher frequency of extreme events. In the near-term, the greatest need for active adaptation will likely not be associated with rising temperatures and longer growing seasons so much as with more abundant and intense rainfall. Specific adaptive practices will vary by geography, crop, and operation.

Field Work Suitability

One of the greatest risks to crop yield associated with climate change will likely be the inability to conduct field operations, particularly planting, in a timely manner. The continuing trend toward more precipitation in the spring with a greater proportion concentrated into intense rainfall events will result in fewer days suitable for field work. Adequate field drainage will be increasingly important to help move water out of fields as well as shorten the time between heavy rains and suitability of soils for fieldwork. Machinery and labor resources may also need to be increased to allow more fieldwork to be done within smaller windows of time in which conditions are favorable.

Soil Conservation and Health

The trend toward greater precipitation and more intense rainfall events will place a greater importance on good soil conservation practices to protect against erosion. Protecting the soil will be especially important during the fallow periods of late winter and spring when precipitation is forecast to increase the most. Shorter and warmer winters mean a greater proportion of total precipitation will fall as rain rather than snow, which will increase the risk of erosion and flooding from heavy rains in late winter and early spring.

Increased soil conservation measures will be necessary to protect against more frequent and intense precipitation in the late winter and spring.

Managing soil compaction will be important as farmers may be increasingly compelled to conduct field operations when soil conditions are wetter than optimal in part or all of the field. The dramatic increase in the weight of many farm machines over the past few decades coupled with wetter soils means the risk of deep and persistent soil compaction will be greater than ever before (Jeschke, 2018). Management practices that help build soil organic matter and structure will help make the soil more resilient to compaction, increase water-holding capacity, and allow excess water to drain more quickly, all of which will be increasingly important with the greater frequency of growing seasons that are too wet early and too dry late.

Disease, Insect, and Weed Management

Some of the most noticeable impacts of climate change on crop production may not be to the crop itself but to associated weeds, diseases, and insects. The geographic distribution of pest species is heavily influenced by climate, so as climate changes, pest distribution and activity will also change. In general, the Midwestern states are likely to face more challenges from pests traditionally associated with southern states due to rising temperatures and shorter winters. Two examples that fit this expected pattern for which changes have already been observed are southern rust of corn (*Puccinia polysora*) and Palmer amaranth (*Amaranthus palmeri* (S.) Wats.), both of which have become a greater problem in the Midwest in the past decade (Jeschke et al., 2017; Kistner and Hatfield, 2018). Pests, such as corn earworm (*Heliothis zea*), that do not currently overwinter in the Midwest are expected to increase in prevalence as the southern boundary of the seasonal freeze zone moves north.

Weed management will likely become more challenging with rising temperatures and atmospheric CO_2. Research has shown that weed species tend to respond more to elevated CO_2 than crop species, making them more competitive with growing crops (Ziska, 2004). Higher temperatures give a competitive advantage to weed species with the C4 photosynthetic pathway, such as waterhemp (*Amaranthus tuberculatus*), Palmer amaranth, and Johnsongrass (*Sorghum halepense).* Weed management programs that include multiple modes of action and sequential treatments will be critical for effective weed control.

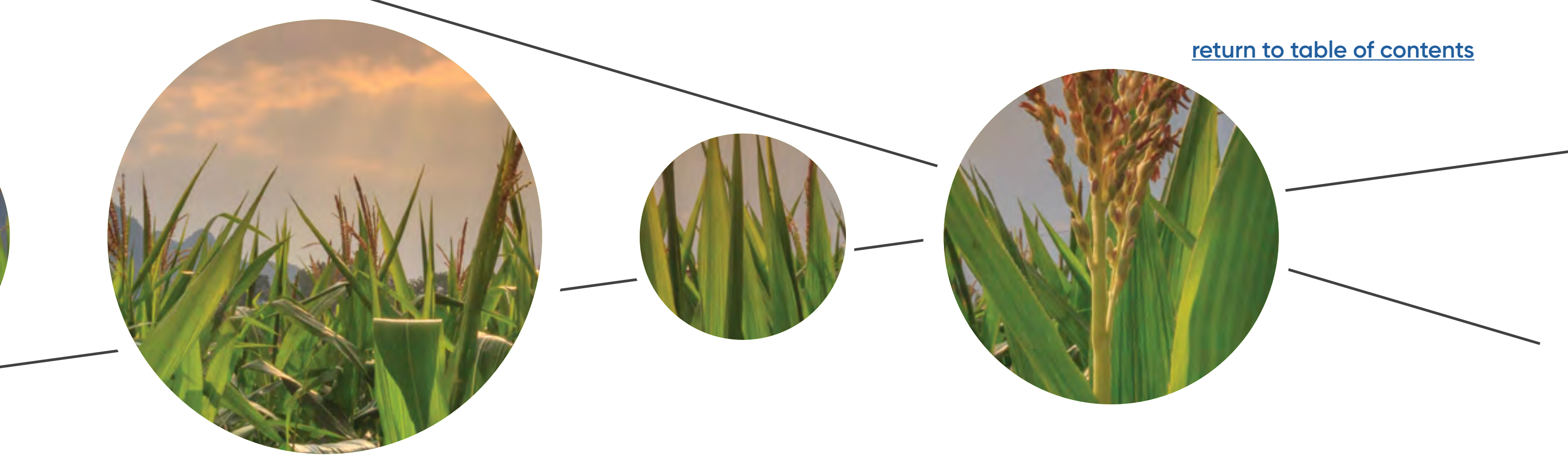
Climate change effects on corn disease severity is projected to be mixed with differing effects on individual pathogens (Juroszek and von Tiedemann, 2013). Plant pathogens are highly responsive to humidity, precipitation, and temperature. Pathogens will generally be favored by increased humidity and frequency of rainfall, but a greater frequency of dry conditions during pollination and grain fill could limit the spread of foliar disease in the crop canopy during the most critical period for yield. Wetter conditions during the fall, such as those experienced in 2018, may increase the severity of diseases that affect grain quality and harvestability.

Insect pests of crops are likely to increase in the Midwest. Research has shown that temperature is the single most important factor driving insect ecology, epidemiology, generations per growing season, and distribution (Coakley et al., 1999), so warmer temperatures and longer frost-free periods will generally be favorable to insects. Greater insect pressure could put increased stress on the effectiveness of insect protection technologies and treatments, making the use of integrated management strategies with multiple tactics and modes of action more important.

Fertility Management

Increased frequency and intensity of rainfall early in the growing season may impact nitrogen management in corn by increasing the risk of nitrogen loss. In such situations, nitrate may be lost from the soil either by leaching or denitrification, depending primarily on soil characteristics. Coarse-textured soils allow water and nitrates to move readily downward

return to table of contents



through the soil profile. When this leaching places nitrate below the root zone, it is of no use to the plant and essentially lost. Fine-textured soils, on the other hand, have capillary pores that hold water tightly, restricting its downward movement. In this situation, saturated soils and anaerobic conditions may result in nitrate being lost to the atmosphere through denitrification.

The use of nitrification inhibitors can help reduce the risk of nitrogen loss from the soil by slowing the conversion of ammonium to nitrate, thus prolonging the period of time that nitrogen is in the immobile ammonium form. Applying nitrogen in-season can help protect against nitrogen loss by timing application more closely to plant uptake. However, uptake of late-season nitrogen can be limited if conditions turn dry during the summer.

In addition to nitrogen, the availability of other nutrients that are mobile in soil water can be affected by frequent early season rains. Sulfur and boron are both highly mobile in their plant-available forms and subject to loss through leaching. Sulfur deficiencies are most common on sandy or other low organic soils because of their reduced ability to supply sulfur and losses due to leaching. In recent years, however, deficiencies have become more prevalent across a variety of soil types, likely due to increased crop removal and reduced atmospheric deposition. Boron can also become deficient in areas where the nutrient is readily leached and is not replenished through organic matter decomposition.

Conclusions

Midwest farmers will need to adapt and protect their farms from increased precipitation in the winter and spring and more intense storms, which will lead to a greater frequency of saturated soils and flooding. This will have implications for field operations, soil conservation practices, and fertility management. Warmer temperatures and longer frost-free seasons may alter the crop rotations used or hybrid/variety maturities selected. Weed and insect pressure varies yearly and is expected to worsen overall, making more diligent management necessary.

Corteva Agriscience offers a range of tools and tactics to help growers adapt their crop production systems to changing conditions and new challenges:

- Crop breeding efforts in key geographies coupled with extensive local testing ensures that new hybrids and varieties have the characteristics necessary to thrive in the environments in which they are grown.
- Extensive research on pest management tools, seed treatments, and crop management helps farmers protect yield potential in the face of environmental stresses and shifting pest spectrums.
- Crop management research and insights provided by Pioneer agronomists helps farmers optimize management practices and stay ahead of emerging issues.
- Granular tools and analytics allow farmers to monitor crop conditions, proactively identify issues, and efficiently allocate inputs.
- And finally, Corteva Agriscience support for numerous university research studies helps develop solutions tailored to address unique challenges in specific geographies.

return to table of contents

Factors Contributing to Rising Global Temperatures

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Multiple independent datasets show that global average surface temperature has risen by about 1.8°F or 1.0°C since the late 19th Century.
- Many different factors can influence global temperature; however, the overwhelming scientific consensus is that recent warming is predominantly due to human activity.
- Adaptation of crop production systems will be necessary to ensure resiliency and sustained productivity under changing climatic conditions driven by higher temperatures.

Introduction

One of the most important factors influencing climatic trends around the world right now is rising global temperatures. Climate scientists have identified several shifts in climate trends associated with rising temperatures that will affect agricultural production, many of which are already having an impact.

This article will discuss how global temperature is measured, how scientists know that the rise in global temperature is being driven by human activity, and what that means for crop production going forward.

Climate scientists have identified **several shifts in climate trends** associated with rising temperatures that **will affect agricultural production**, many of which are ***already having an impact.***

How do Scientists Measure Global Temperature?

Global average temperature is easy to conceptualize, but much more difficult to measure due to the variation of temperature over space and time. To get a comprehensive picture of global temperature, scientists combine thousands of individual measurements taken over land and ocean all around the world. Each individual measurement is compared to the long-term average temperature for its place and time to determine the temperature anomaly, or deviation from normal (Pidcock, 2015). The entire planet's surface is then divided out into a grid and the average temperature anomaly for each grid square is determined (Figure 1). All daily temperature anomalies across all grid squares over the course of a year are then used to determine the annual global temperature anomaly.

Further complicating the process is the fact that temperature instrumentation and observation practices are continually changing. Historical temperature records must account for changes in measurement practices, changes in measurement locations, and changes in land use around weather stations. Temperature records must also account for spatial gaps in temperature measurements.

There are four major global surface temperature datasets scientists use. These datasets differ in the data they use, the timescales they cover and the statistical methods they employ; consequently, they do not match each other exactly. However, all four datasets show a very similar trend, which is an increase in global average surface temperature of about 1.8°F or 1.0°C since the late 19th Century (Figure 2).

The question of whether the planet is warming is not the subject of any serious scientific dispute. Multiple independent datasets from scientific agencies around the world all show a similar trend of rising global temperatures since the late 19th Century. The next step is to understand why it is warming.

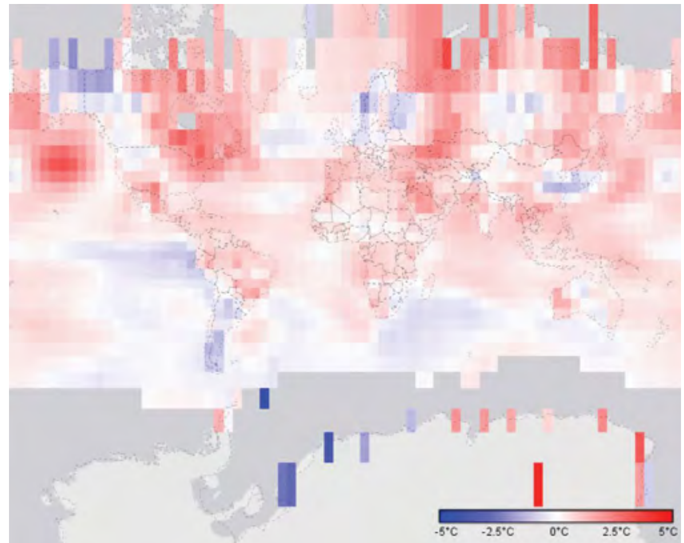


Figure 1. Global surface temperature anomalies on a 5 x 5 grid for July 2020 (NOAA NCEI 2021).

Global Surface Temperature Datasets

- **MLOST:** Produced by the U.S. National Oceanic and Atmospheric Administration (NOAA)
- **GISTEMP:** Produced by the U.S. NASA Goddard Institute for Space Sciences (GISS)
- **HadCRUT:** Produced jointly by the UK Met Office Hadley Centre and the University of East Anglia's Climatic Research Unit
- **JMA:** Produced by the Japan Meteorological Agency

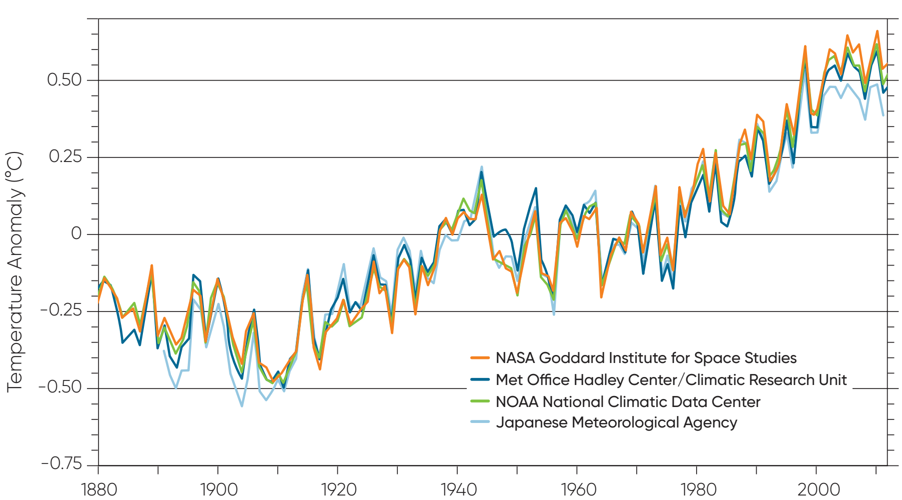


Figure 2. Global average temperature anomaly from 1880 to 2012, compared to the 1951-1980 long term average. Source: NASA Earth Observatory.

What is Causing the Rise in Global Temperature?

The overwhelming scientific consensus is that warming over the past century is predominantly due to human activity (Santer et al., 2019); however, there are a number of factors – both natural and human-caused – that can and do influence Earth's temperature.

Natural Factors

Among the natural factors are **long-term cycles in Earth's orbital patterns**, known as Milankovitch cycles. These are slight variations in Earth's orbit and tilt that cause the planet to cycle between ice ages and interglacial periods (Buis, 2020).

These cycles have a large effect on Earth's climate, but only over long periods of time. The most recent glacial period reached its maximum around 20,000 years ago with a global average temperature that was about 11°F (6°C) cooler than today (Tierney et al., 2020). The subsequent warming period peaked 6000-8000 years ago (Renssen et al., 2012). Since then, the effect of Earth's orbital patterns has been a very slow, steady rate of cooling.

The **overwhelming scientific consensus** is that warming over the past century is ***predominantly due to human activity.***

Variations in solar activity can also affect temperature. Solar output doesn't stay completely constant over time, with total solar irradiance varying over roughly 11-year cycles (Figure 3). However, solar output only varies by 0.15% or less over the course of these cycles so the impact on Earth temperature is minimal, only around +/-0.1°C.

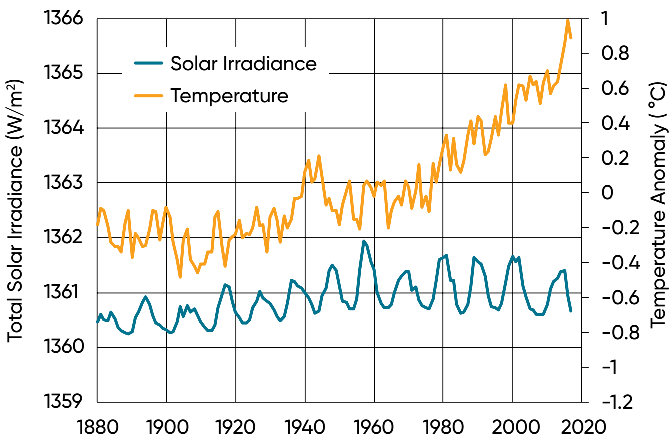


Figure 3. Annual global land and ocean temperature anomaly (GISTEMP 3.1) and total solar irradiance (SATIRE-T2 + PMOD), 1880-2017 (NASA, 2019).

Ocean temperature cycles can cause short-term variations in climate due to changes in the balance of heat energy between the oceans and the atmosphere. The El Niño Southern Oscillation (ENSO) is an example familiar to most farmers in North America due to its potential to affect growing conditions.

Volcanic eruptions can cause a short-term cooling effect. When a volcano erupts, it can eject large quantities of sulfur dioxide, which combines with water in the stratosphere to form sulfate aerosols. These particles reflect incoming solar radiation back out into space, reducing solar transmission through the atmosphere. If the eruption is large enough, this can have a temporary global cooling effect. A relatively recent example of an eruption causing such an effect was the eruption of Mt. Pinatubo in the early 1990s. Volcanic activity can also release carbon dioxide and methane, which are both greenhouse gases, potentially leading to a warming effect.

And finally, we know that **changes in atmospheric composition** influence temperature. Ice core samples and other paleoclimatology records show that the concentration of greenhouse gases – carbon dioxide, specifically – has varied greatly over the history of the planet, which has been associated with large variations in global temperature.

Human Activity

Human activity can also influence temperature in ways that are analogous to some natural factors.

Industrial pollution that releases sulfur dioxide into the atmosphere contributes to stratospheric sulfate aerosols much like a volcanic eruption, reflecting solar radiation and creating a cooling effect. Global sulfur dioxide emissions have declined since the 1970s, largely due to sharp reductions in North America and Europe resulting from clean air regulations.

Greenhouse gases produced through human activities include carbon dioxide, methane, nitrous oxide and fluorinated gases. Carbon dioxide is by far the most important of these gases due to the massive quantities of it injected into the atmosphere through the burning of coal, gas, and oil. Unlike sulfur dioxide emissions, output of carbon dioxide has continued to increase. Consequently, atmospheric carbon dioxide levels have increased from around 280 ppm prior to the industrial era, to over 400 ppm today.

Modeling the Effects on Global Temperature

Computer models of Earth's climate system allow scientists to explore the impact of each of these factors and compare their predicted effects to observed changes in temperature.

Figure 4a shows the predicted effects of natural factors, including solar output, orbital cycles, and volcanic activity. The combined predicted effect of all natural factors on temperature is relatively flat over this time period, with intermittent downward spikes associated with major volcanic events. The combined trend line does not match observed temperatures well, particularly from 1960 to present, indicating that rising temperatures are not due to natural factors.

Figure 4b shows the predicted effects of human factors, including greenhouse gases, aerosol particles, changes in land use, and changes in ozone levels. Predicted effects of changes in land use and ozone levels on temperature are relatively small. A cooling effect is associated with aerosols produced by human activity and a strong warming effect is associated with greenhouse gas emissions. The combined trend line for human factors matches observed temperatures much more closely than natural factors.

Figure 4c shows the combined effects of all natural and human factors. The combined trend line matches observed temperatures very well, suggesting that the climate model is doing a good job of accounting for the effects of the different factors.

Out of all of the factors modeled in Figure 4, greenhouse gas emissions is the only factor predicted to cause a strong warming effect and is the predominant factor to which the increase in global average temperature over the past century can be attributed.

What Does This Mean for Crop Production?

Understanding the reason for rising global temperatures is a critical prerequisite for considering its implications for crop production. Shifts in weather patterns that we have experienced in recent years cannot be dismissed as the result of a random oscillation of the planet's climate system that will inevitably revert back to normal. We know that these changes are not random or unpredictable, but rather they are being driven by a persistent imbalance that has been introduced into Earth's climate system through human activity. Furthermore, we know that – absent an immediate global effort to dramatically reduce greenhouse gas emissions – this imbalance will continue to grow, and its associated climatological effects will continue to intensify.

Year-to-year variation in weather will continue to exist, and some years will be hotter or wetter than others. However, we know that certain changes in climate associated with rising global temperatures that impact agriculture, such as higher night temperatures during the growing season and more intense rainfall events, will occur with greater frequency in the coming years. Because we know these changes are coming, we have the ability to start planning and implementing adaptation measures to build more resilient crop production systems.

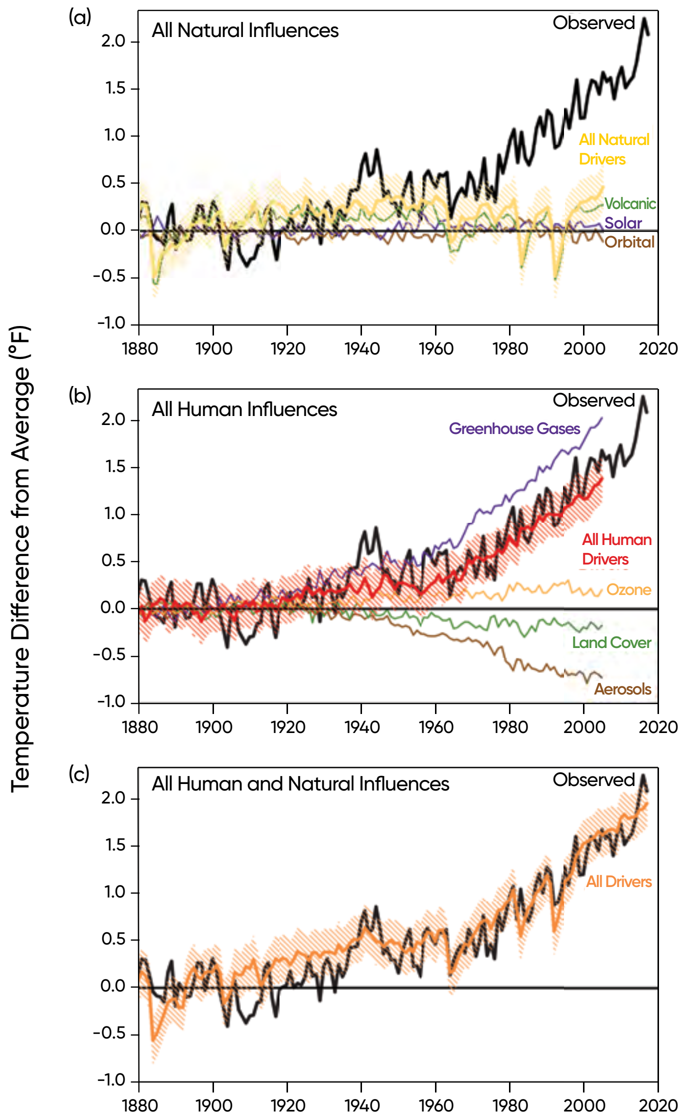


Figure 4. Human and natural influences on global temperature, 1880-2018 (Hayhoe, et al., 2018).

Shifts in weather patterns that we have experienced in recent years ***cannot be dismissed*** as the result of a random oscillation of the planet's climate system that will inevitably revert back to normal.

return to table of contents

The Greenhouse Effect and Greenhouse Gases

Mark Jeschke, Ph.D., Agronomy Manager

Key Points

- Human activities have increased the concentration of several greenhouse gases in the atmosphere, which has amplified Earth's greenhouse effect and elevated global mean temperature by around 1.8°F.
- Carbon dioxide is the most important anthropogenic greenhouse gas – it comprises the largest proportion of emissions from human activity and is the largest contributor to global warming.
- Methane and nitrous oxide are more powerful greenhouse gases but are emitted in smaller quantities than carbon dioxide.
- Carbon dioxide, methane, and nitrous oxide all cycle in and out of the atmosphere through natural processes but human emissions have altered the balance of these cycles, leading to buildup in the atmosphere.
- Transportation and electricity generation are the largest sources of greenhouse gases, accounting for over half of total emissions, with agriculture accounting for around 10%.

What are Greenhouse Gases?

A greenhouse gas is a gas with a molecular structure that causes it to absorb and emit infrared radiation. When incoming radiant energy from the sun is absorbed by the Earth's surface and re-emitted as infrared energy, greenhouse gases in the atmosphere prevent some of this heat from escaping into space, instead reflecting the energy back to further warm the surface creating an insulating effect from the cold of space (Figure 1).

Industrial activities carried out on a **global scale** have increased the concentration of ***several greenhouse gases*** in the atmosphere.

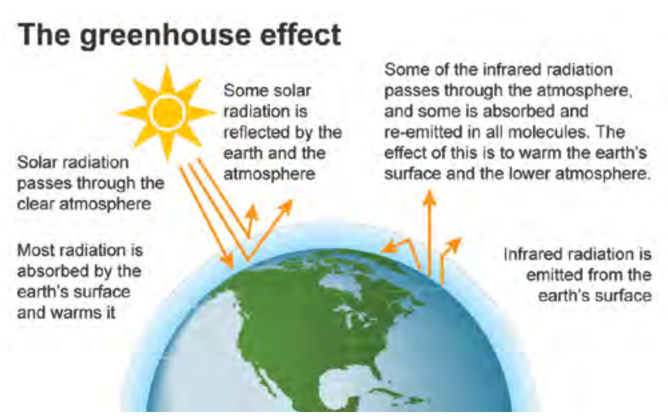


Figure 1. Illustration of Earth's greenhouse effect. *Source: U.S. Energy Information Administration.*

The Greenhouse Effect

This heat-trapping phenomenon is known as the greenhouse effect and it is essential for life on Earth. Without any greenhouse effect at all, Earth would be uninhabitable – global mean surface temperature would be around 5°F (-15°C) rather than the current average of 59°F (15°C). The strength of the greenhouse effect is determined by the concentration of greenhouse gases in the atmosphere. Consequently, any process that significantly changes the concentration of these gases – be it natural or human-caused – will alter the energy balance between incoming solar radiation and the heat released back into space, resulting in a change to Earth's temperature.

Paleoclimatology records show that, over the vast timescales of Earth's history, greenhouse gas concentrations have varied considerably and, along with several other important factors, have caused dramatic changes in Earth's temperature and climate. However, the beginning of the industrial era marked the first time in human history in which population growth and technological innovation made it possible for humans to significantly alter the composition of the atmosphere. Industrial activities carried out on a global scale have increased, and continue to increase, the concentration of several greenhouse gases in the atmosphere; the result of which has been an amplification of the greenhouse effect that has raised global mean temperature by around 1.8°F since the late 19th Century.

return to table of contents

Greenhouse Gases Differ in Strength

Greenhouse gases produced through human activities include carbon dioxide, methane, nitrous oxide and fluorinated gases. Carbon dioxide, methane, and nitrous oxide all have natural sources as well, while fluorinated gases come exclusively from human activity. The overall contribution of each of these gases to climate forcing depends on their inherent heat-trapping efficiency (referred to as *global warming potential*), abundance, and residence time in the atmosphere (Table 1).

Table 1. Greenhouse gas emissions from human activity: global warming potential and percent of total (U.S. EPA, 2019).

Greenhouse Gas	Global Warming Potential*	Percent of U.S. GHG Emissions
Carbon dioxide (CO_2)	1	81%
Methane (CH_4)	25	10%
Nitrous Oxide (N_2O)	298	6%
Fluorinated gases	7,390-22,800	3%

*A measure of how much energy the emissions of 1 ton of a gas will absorb over 100 years, relative to the emissions of 1 ton of carbon dioxide (CO_2).

Global warming potential of greenhouse gases is expressed as an index relative to CO_2. For example, the global warming potential of methane is 25, meaning it has 25 times the heat trapping efficiency as CO_2. Nitrous oxide is an even more power greenhouse gas with a global warming potential of 298 and fluorinated gases are extremely powerful. When discussing emissions of greenhouse gases other than CO_2, quantities are often expressed in terms of their equivalency to CO_2 (CO_2e).

Much of the concern around greenhouse gas emissions has focused on CO_2. It has a relatively low global warming potential relative to other greenhouse gases but comprises by far the largest proportion of emissions from human activity and is the largest contributor to overall climate forcing (Figure 1). In contrast, the fluorinated gases are far more powerful greenhouse gases but comprise a relatively small proportion of emissions and consequently have a smaller contributing effect to climate forcing (Figure 2).

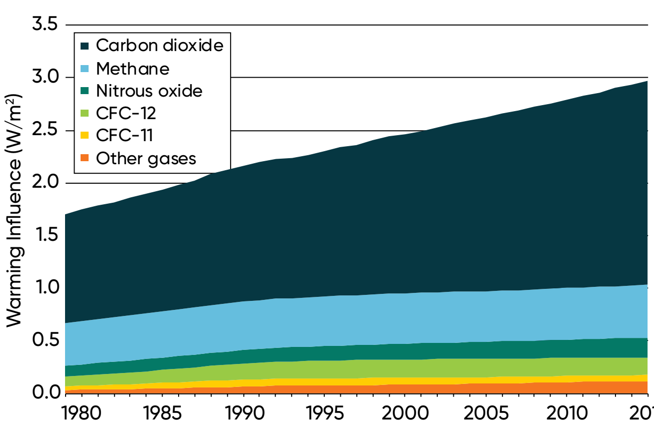


Figure 2. Radiative forcing caused by major long-lived greenhouse gases produced by human activity, 1979-2015 (NOAA, 2021).

Carbon Dioxide Emissions

Human CO_2 emissions are primarily a product of the burning of fossil fuels for electricity generation, transportation, and industry but are also produced by deforestation and land use change. Carbon dioxide is naturally present in the atmosphere as a part of the Earth's carbon cycle and is essential for plant life. In fact, carbon flux from human activity is relatively small compared to the carbon flux associated with natural processes such as photosynthesis and respiration (Figure 3). However, carbon dioxide emissions constitute a persistent shift in the balance of the Earth's carbon cycle, pulling billions of tons of carbon stored in the Earth's crust and putting it into the atmosphere on an ongoing basis and causing atmospheric CO_2 concentrations to rise.

> Global carbon dioxide emissions currently ***exceed 35 billion metric tons per year*** and are primarily the result of **fossil fuel burning, cement production, and gas flaring.**

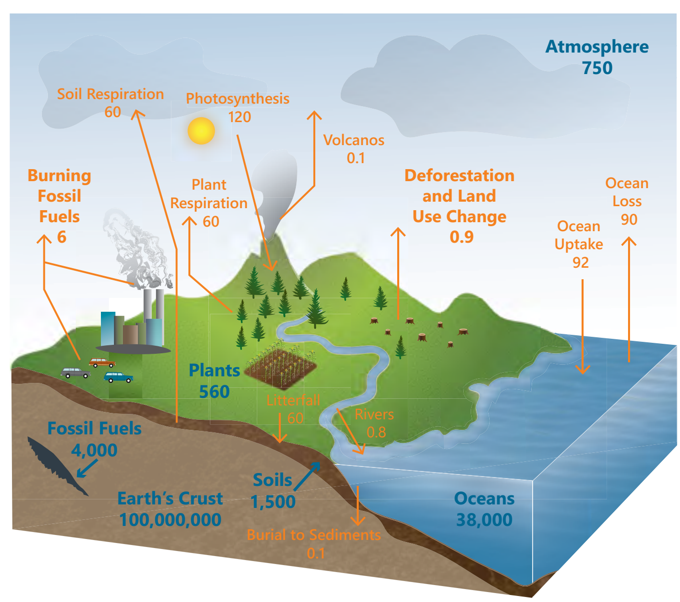


Figure 3. Global carbon cycle diagram showing carbon pools (blue text) and annual carbon fluxes (orange text) measured in petagrams. *Source: Univ. of New Hampshire GLOBE Carbon Cycle, globecarboncycle.unh.edu*

return to table of contents

Global carbon dioxide emissions currently exceed 35 billion metric tons per year and are primarily the result of fossil fuel burning (coal, oil, and natural gas), cement production, and gas flaring (Figure 4).

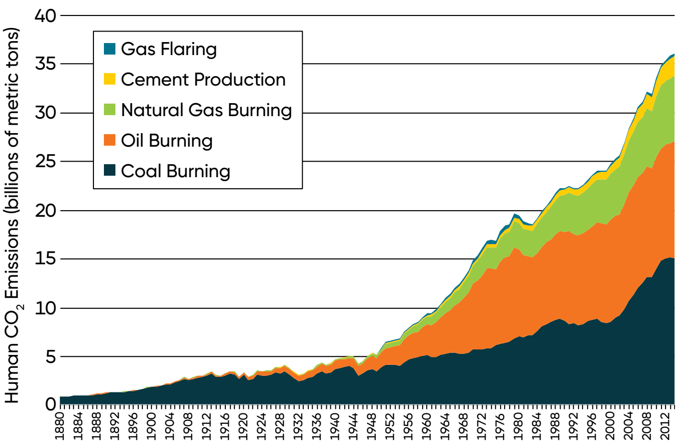


Figure 4. Global CO_2 emissions from fossil fuel burning, cement production and gas flaring, 1880-2014. (Source: Carbon Dioxide Information Analysis Center).

The concentration of carbon dioxide in the atmosphere naturally cycles over extremely long time scales as the Earth cycles between ice ages and interglacial periods; however, emissions from fossil fuel burning over the past 150 years or so have dramatically increased the amount of CO_2 in the atmosphere in an extremely short period of time relative to changes driven by natural factors (Figure 5).

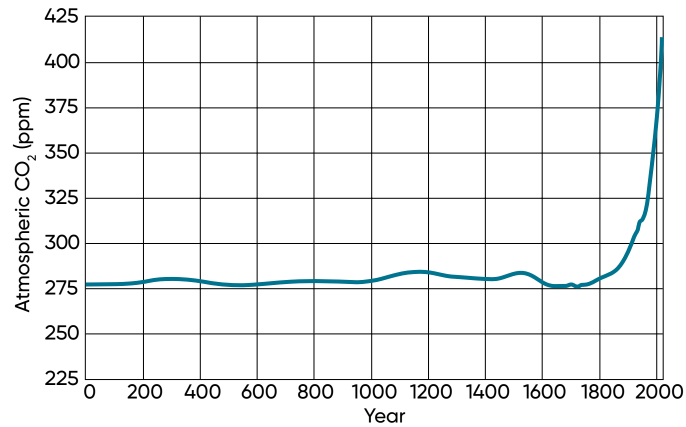


Figure 5. Atmospheric CO_2 concentration over the past 2000 years based on ice core data (before 1958), and direct measurements taken at Mauna Loa and the South Pole (1958-present) (Keeling et al., 2001; MacFarling Meure et al., 2006).

A combination of direct measurements and ice core data allow us to track the concentration of CO_2 in the atmosphere over a long period of time. For most of the past 2000 years, CO_2 levels were relatively stable, fluctuating in a range between 275 and 285 ppm until the mid-1800s when emissions from human activity began driving atmospheric CO2 upward. Atmospheric CO_2 reached 300 ppm in 1912, 350 ppm in 1988, and 400 ppm in 2015. In fact, over the course of the past 800,000 years for which we have a reliable ice core record, atmospheric CO_2 never exceeded 300 ppm until the 20th Century, making our current state unprecedented in human history (Lüthi et al., 2008).

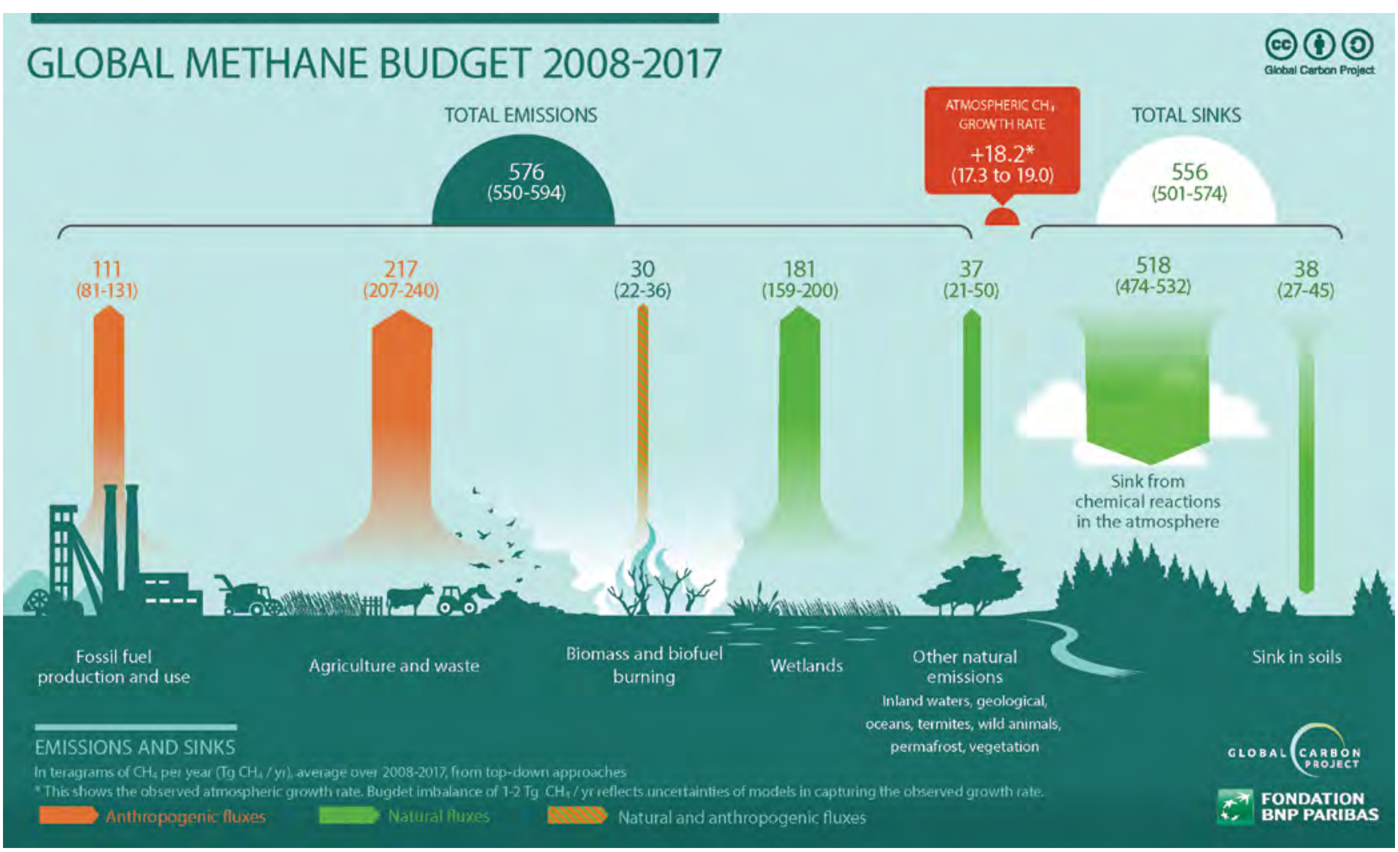


Figure 6. Diagram of the global methane budget showing anthropogenic and natural fluxes of methane into and out of the atmosphere. *Source: Global Carbon Project.*

Methane Emissions

The largest anthropogenic source of **methane emissions is livestock production,** with methane emitted via enteric fermentation and manure ***comprising two of the top four sources overall.***

Methane (CH_4) is a considerably more powerful greenhouse gas than CO_2, with a 25x greater heat-trapping capacity. Like CO_2, methane is a naturally occurring gas and cycles in to and out of the atmosphere via a number of different natural processes. The largest natural source of methane is wetlands, where certain types of microorganisms produce methane as a byproduct of metabolic reactions carried out in anaerobic environments.

As with CO_2, human activity has altered the balance of the global methane cycle, with total inputs of methane into the atmosphere exceeding removal by approximately 18.2 Tg per year (Figure 6). This has resulted in an increase in atmospheric methane levels. The concentration of methane in the atmosphere has more than doubled from a pre-industrial level of 722 ppb to 1,892 ppb in 2020 (Dlugokencky, 2021).

The largest anthropogenic source of methane emissions is livestock production, with methane emitted via enteric fermentation (primarily from cattle) and manure comprising two of the top four sources overall (Figure 7). Other major sources include natural gas systems, landfills, coal mining, and petroleum systems.

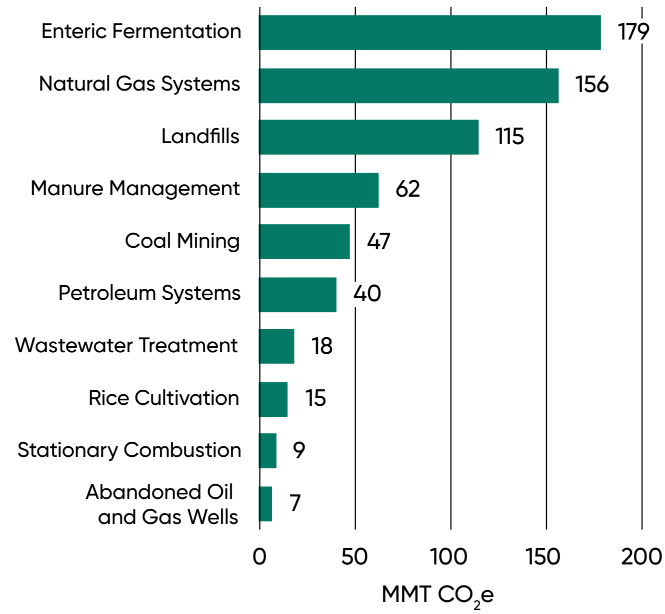


Figure 7. Major sources of methane emissions in the U.S., 2019. (Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Figure ES-9).

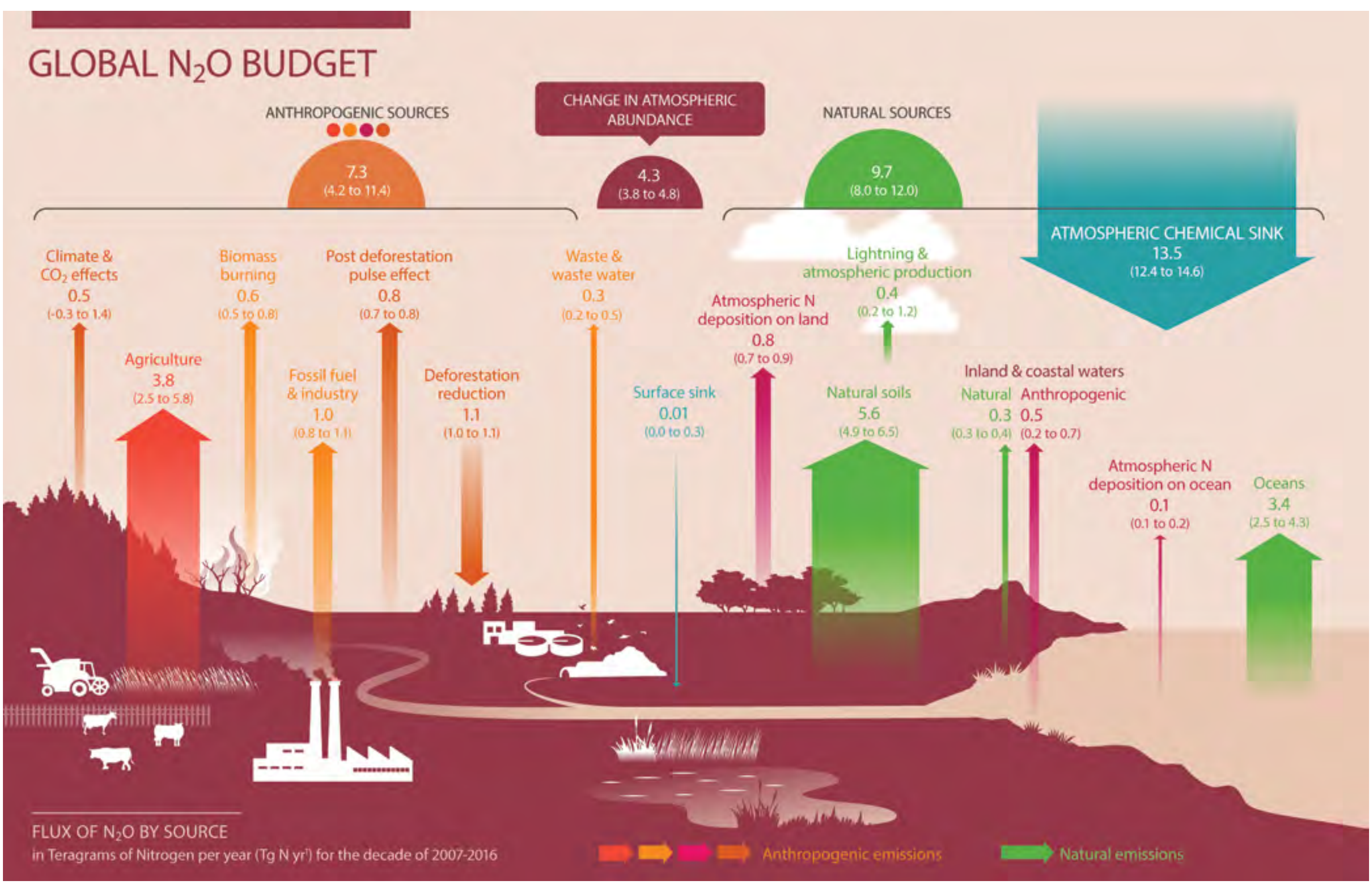


Figure 8. Diagram of the global nitrous oxide budget showing anthropogenic and natural fluxes of methane into and out of the atmosphere. *Source: Global Carbon Project.*

What About Water Vapor?

The gas that contributes the most to Earth's greenhouse effect is water vapor, accounting for about 60% of the total warming effect – so why is it never mentioned when discussing global warming? It's because water vapor in the atmosphere is not a driver of higher temperatures. Rather it reacts to higher temperatures.

The temperature of the atmosphere dictates the maximum amount of water vapor the atmosphere can contain. If air contains its maximum amount of water vapor and the temperature decreases, some of the water vapor will condense to form liquid water and precipitate out of the atmosphere.

As temperatures rise due to the increasing concentrations of other greenhouse gases, the amount of water vapor can increase as well, creating a positive feedback effect and further amplifying the greenhouse effect.

Nitrous Oxide Emissions

Nitrous oxide is a much more powerful greenhouse gas than either CO_2 or methane, with a heat-trapping capacity 298 times that of CO_2. Like the other two major greenhouse gases, nitrous oxide is naturally occurring and cycles into and out of the atmosphere through natural process. Nitrous oxide is produced by biological processes that occur in soil and water (Figure 8).

By far, the largest anthropogenic source of nitrous oxide emissions is nitrogen losses from agriculturally managed soils, accounting for over 75% of total nitrous oxide emissions and around 5% of greenhouse gas emissions overall. Wastewater treatment, fossil fuel combustion, livestock manure, and various industrial processes are also major sources (Figure 9). Atmospheric nitrous oxide levels have increased by around 20% during the industrial era, from 270 ppb in 1850 to 335 ppb today (MacFarling Meure et al., 2006; Elkins et al., 2021).

The largest anthropogenic source of **nitrous oxide emissions** is nitrogen losses from ***agriculturally managed soils.***

Greenhouse Gases in Agriculture

The economic sectors responsible for the majority of greenhouse gases are transportation, electricity generation, and industry, accounting for a combined total of 77% of emissions in the U.S. (Figure 10). Agriculture accounts for around 10% of greenhouse gas emissions, making it a significant contributor, but not nearly as large as the top three sectors. The percent of greenhouse gas emissions attributable to agriculture is somewhat lower in the U.S. than it is globally due to the greater efficiency of agriculture in the U.S. compared to much of the world.

Greenhouse gas estimates for agriculture typically do not include emissions associated with production of agricultural inputs or the transportation, processing, and packaging of agricultural products, so estimates of greenhouse gas emissions attributable to the global food system as a whole often run much higher – as much as 34% (Crippa et al. 2021).

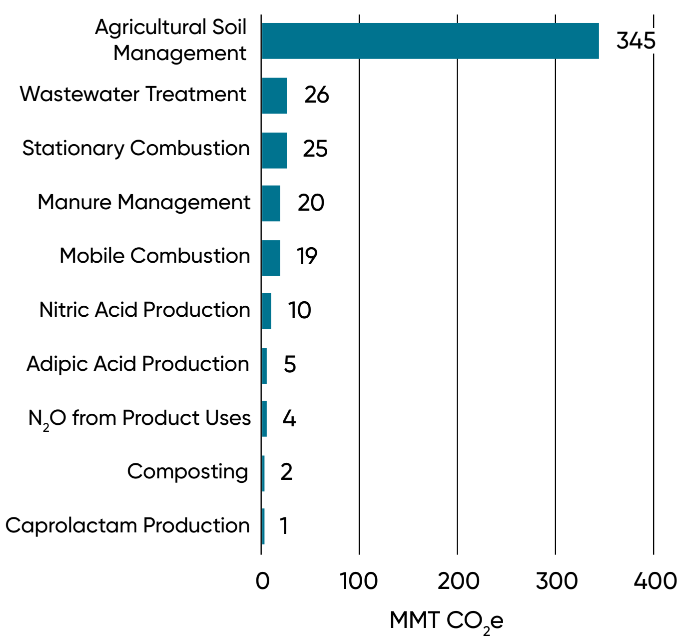


Figure 9. Major sources of nitrous oxide emissions in the U.S., 2019. *Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Figure ES-10.*

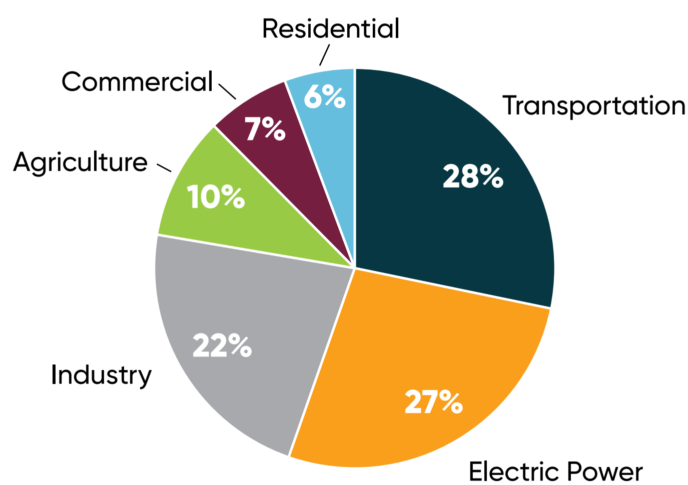


Figure 10. U.S. greenhouse gas emissions by economic sector, 2018. *Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Table ES-6.*

return to table of contents

Greenhouse Gas Emissions in Agriculture

Mark Jeschke, Ph.D., Agronomy Manager

Summary

- Agriculture is a significant source of greenhouse gas emissions, contributing around 10% of total U.S. emissions and 17% of global emissions.
- Agriculture is unique among economic sectors in that its greenhouse gas emissions are mostly nitrous oxide and methane rather than carbon dioxide.
- The largest contributors to agricultural greenhouse gas emissions are nitrous oxide emitted from agricultural soils, methane from livestock production, and methane from rice production.
- Agricultural emissions largely come from natural biological processes carried out by microbes in animals and soil, but the scale of those processes has been greatly amplified by the expansion of agricultural production.
- Several management practices and technologies available now or currently in development offer the potential to reduce agricultural emissions.
- A major contributor to agriculture's carbon footprint globally is the conversion of new land to agricultural production, making it critical to continue to drive greater productivity on existing agricultural land.

With the ***rapid expansion of carbon credit programs*** and other initiatives aimed at **reducing agriculture's climate impact**, it is important to understand how agriculture contributes to greenhouse gas emissions.

Greenhouse Gas Emissions in Agriculture

Efforts to reduce greenhouse gas emissions have brought increased attention to the role of agriculture, both as a source of greenhouse gas emissions and for potential strategies within the industry for sequestering emissions. With the rapid expansion of carbon credit programs and other initiatives aimed at reducing agriculture's climate impact, it is important to understand how agriculture contributes to greenhouse gas emissions, where the greatest opportunities lie for reducing those emissions, and how agriculture fits into the wider effort to drawdown greenhouse gas emissions.

Agricultural production is both a source and sink for greenhouse gases. Numerous processes involved in crop and livestock production release carbon dioxide and other greenhouse gases into the atmosphere. Crop production also captures carbon dioxide from the atmosphere through photosynthesis. Management practices such as conservation tillage and cover crops can help increase the amount of that captured carbon that is stored in the soil.

On balance though, agriculture is a net emitter of greenhouse gases, with the quantity emitted through various processes far exceeding the quantity stored (Figure 1).

Emissions Compared to Other Sectors

Agriculture accounts for around 10% of U.S. greenhouse gas emissions according to the U.S. Environmental Protection Agency (EPA), making it a significant contributor, but not nearly as large as the top three sectors: transportation (28%), electricity generation (27%), and industry (22%) (Table 1).

Estimates of greenhouse gas emissions attributable to agriculture vary widely though, and figures produced by other organizations are often higher than the EPA estimate of 10%. For example, the U.N. Food and Agriculture Organization (FAO) estimates that 17% of anthropogenic greenhouse gas emissions are attributable to agriculture (FAO, 2020). The World Resources Institute estimates that agriculture and land use change, which is primarily driven by agriculture, collectively account for nearly 24% of greenhouse gas emissions (Arcipowska et al., 2019). Discrepancies in these es-

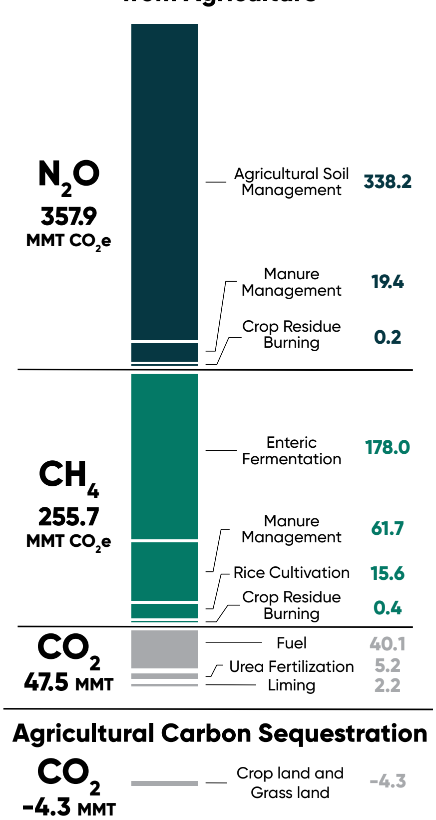


Figure 1. Greenhouse gas emissions from agriculture and sequestration in crop and grass land in the U.S., 2018. *Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.*

Table 1. U.S. greenhouse gas emissions by economic sector, 2018. *Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Table ES-6.*

Economic Sector	Greenhouse Gas Emissions	
	MMT CO_2e	% of total
Transportation	1,883.1	28.2
Electric Power	1,807.5	27.1
Industry	1,488.9	22.3
Agriculture	661.6	9.9
Commercial	448.5	6.7
Residential	378.2	5.7

timates can sometimes become contentious when evaluating where attention, resources, and regulations for reducing greenhouse gas emissions should be prioritized.

There are a few reasons why estimates of agriculture's contribution to greenhouse gas emissions vary so widely:

- The proportion of emissions attributable to agriculture differs dramatically by country. In highly industrialized countries with relatively efficient agricultural systems, such as the U.S., agricultural emissions are a much smaller proportion of the total compared to less-industrialized nations, so estimates for the U.S. (EPA) are generally lower than global estimates (FAO, WRI).
- Agricultural emissions are inherently more difficult to measure than fossil fuel emissions because they involve complex biological systems.
- How emissions are categorized can make a big difference. Greenhouse gas estimates for agriculture typically do not include emissions associated with production of agricultural inputs or the transportation, processing, and packaging of agricultural products, so estimates of greenhouse gas emissions attributable to the global food system as a whole often run much higher than those attributed specifically to agricultural production (Crippa et al., 2021).
- Land use change associated with agriculture is also a major contributor to greenhouse gas emissions globally. Native vegetation and soil contain large amounts of carbon that are released into the atmosphere when the land is cleared and brought into agricultural production. The World Resources Institute estimates that agricultural production accounts for around 14% of greenhouse gas emissions globally – a figure that rises to 24% when land use change is factored in.

The ***urgent need to reduce greenhouse gas emissions*** while continuing to increase production to feed a growing global population is one of the **most important challenges** facing agriculture today.

Reducing Emissions from Food Systems

Efforts to reduce greenhouse gas emissions associated with the global food production system have prioritized a few key areas spanning across food production, supply chains, and consumption that offer the greatest opportunity for emissions reduction (Ritchie, 2021):

1. **Higher yields:** Increasing agricultural output is necessary to feed a growing global population but it needs to be done without converting more land area to agricultural production. This means that closing yield gaps and continuing to drive higher yield potential through better genetics and management are crucial.
2. **Better management practices:** Greenhouse gas emissions associated with crops and livestock can vary greatly depending on where and how they are produced. Improved management practices can help reduce emissions associated with agricultural production.
3. **Reduce food waste:** Around one quarter of the total food calories the world produces are wasted. This includes food wasted by consumers as well as supply chain losses due to spoilage during transit and processing.
4. **Optimize calorie intake:** Many people currently consume more calories than necessary to maintain a healthy weight. A scenario in which calorie consumption was optimized to maintain body mass index in a healthy range, including increases for those currently undernourished, would reduce overall emissions associated with food systems.
5. **Plant-rich diet:** Calories derived from meat are generally more greenhouse gas intensive to produce than those from plants. A shift toward diets with a higher proportion of plant-based calories could reduce emissions.

Two of these five areas, higher yields and better management practices relate directly to how food is produced and are key areas of focus for improving agricultural production systems.

Composition of Agricultural Emissions

The urgent need to reduce greenhouse gas emissions while continuing to increase production to feed a growing global population is one of the most important challenges facing agriculture today. The first step in meeting that challenge is understanding how and where greenhouse gases are being emitted from agricultural systems.

Efforts to reduce greenhouse gas emissions have most commonly focused on carbon dioxide. Across all economic sectors, carbon dioxide is the predominant anthropogenic greenhouse gas, accounting for 79% of emissions, followed by methane (11%), nitrous oxide (7%), and fluorinated gases (3%). In the agriculture sector, however; carbon dioxide comprises only 7% of emissions, with 54% coming from nitrous oxide and 39% from methane.

Total greenhouse gases emissions are often expressed as CO_2 equivalent units (CO_2e or CO_2-eq) which allows different greenhouse gases to be combined into a single metric while accounting for the differing global warming potential of the different gases. For example, the global warming potential of methane is 25, meaning it has 25 times the heat trapping efficiency as CO_2. Nitrous oxide is an even more powerful greenhouse gas with a global warming potential of 298.

Major Sources and Sinks

The largest sources of agricultural greenhouse gas emissions in the U.S. are nitrous oxide emissions from agricultural soils and methane emissions from livestock production (enteric fermentation and manure). Methane from rice production is also a major contributor to agricultural greenhouse gas emissions globally, but not as much in the U.S. since rice is not a major U.S. crop. Contributions of agricultural emission sources compared to other major sources of methane and nitrous oxide are shown in Figure 2.

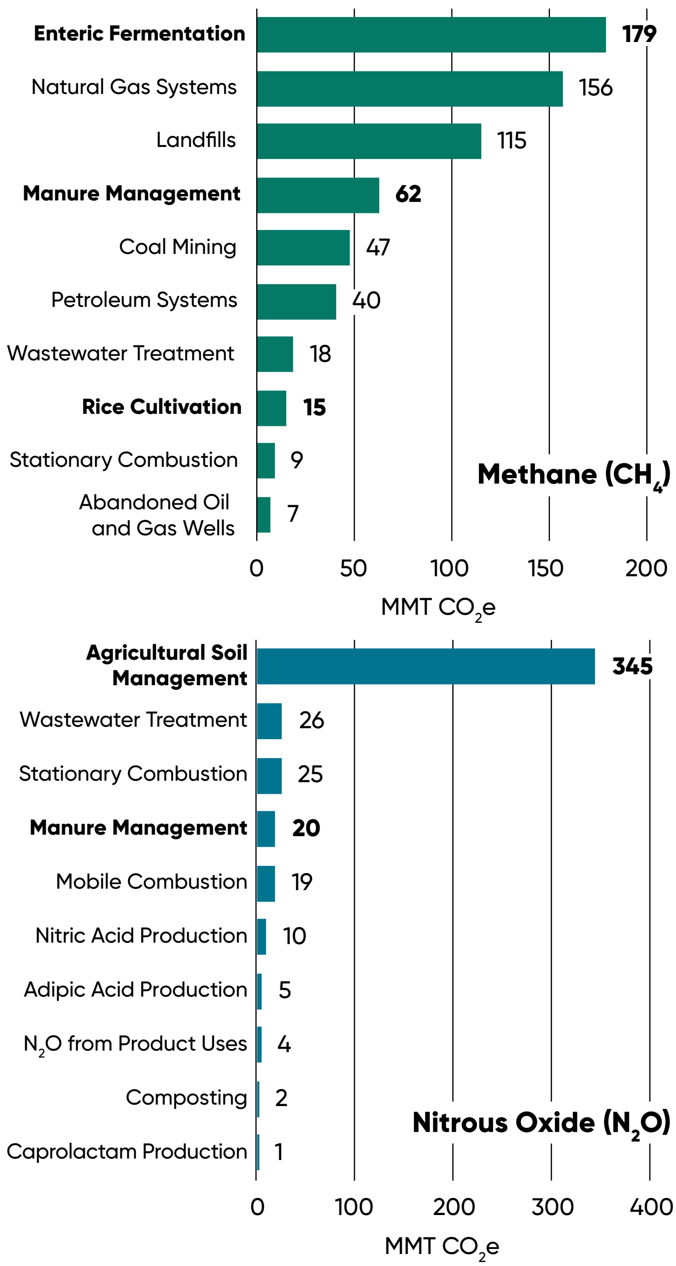


Figure 2. Major sources of methane (top) and nitrous oxide (above) emissions in the U.S. *Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.*

Agricultural production is a source of greenhouse gas emissions, but it can also serve as a greenhouse gas sink by removing carbon dioxide from the air. Plants take in carbon dioxide and incorporate it into plant tissues via photosynthesis. A portion of this carbon can remain in the soil as soil organic carbon. Management practices that favor the buildup of soil organic carbon over time can sequester carbon in the soil and offset a portion of greenhouse gas emissions. However, the quantity of carbon dioxide sequestered in agricultural soils currently is relatively small. Net carbon dioxide sequestered in agricultural crop and grass land offsets less than 1% of the total greenhouse gases emitted by agriculture (U.S. EPA, 2021).

Trends in Greenhouse Gas Emissions

Overall greenhouse gas emissions in the U.S. have declined over the past 15 years. Total greenhouse gas emissions in the U.S. peaked in 2007 at 7,464 MMT CO_2e and have fallen by about 13% since then. This downward trend has largely been due to emissions reductions in industry and electricity generation. Agricultural emissions, on the other hand, have continued to increase, rising by about 4% over the same period. Emissions from the agriculture sector have increased steadily over the past 30 years by around 1.9 MMT CO_2e per year (Figure 3).

Emissions from the agriculture sector have ***increased steadily*** over the past 30 years.

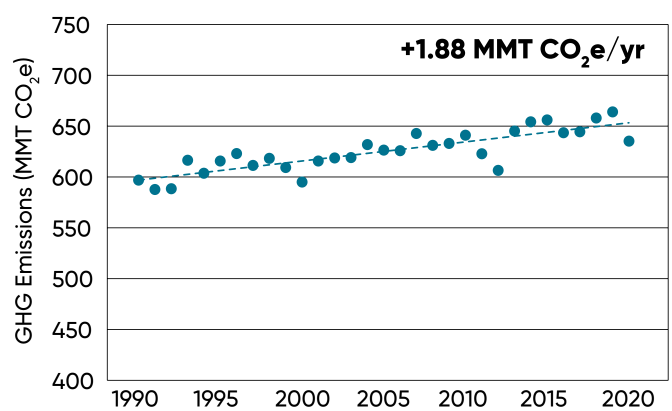


Figure 3. Recent trend in greenhouse gas emissions from the U.S. agriculture sector, 1990-2020. *Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.*

While greenhouse gas emissions from agriculture have continued to increase, agricultural productivity has increased at an even faster rate, meaning that emissions per unit of production have gone down for most major commodities in the U.S. This is a noteworthy accomplishment – U.S. agriculture has been able to greatly increase output without concomitant increases in inputs or land use. However, meeting the emissions targets necessary to avoid the most severe climate impacts means that emissions across all economic sectors, including agriculture, need to be reduced.

Perspectives on Agricultural Emissions

The majority of anthropogenic greenhouse gas emissions come from the burning of fossil fuels (coal, oil, and gas) for energy. Consequently, this is where the most urgency for reducing emissions has been focused and it tends to be dominant lens through which the issue is viewed. However, emissions associated with agricultural processes differ in some important ways that are relevant in developing emission reduction strategies.

Natural vs. Artificial Processes

The burning of fossil fuels involves extracting deposits of hydrocarbons locked deep in the Earth's crust and, through combustion, releasing the carbon back into active circulation in Earth's carbon cycle. This process is entirely the product of human intervention – there are many natural processes that continually cycle carbon in and out of the atmosphere; however, fossil fuel burning is an artificial process that has been added to the system. Consequently, when setting targets for greenhouse gas reductions, the goal for fossil fuel emissions ultimately needs to be zero – the complete elimination of oil, gas, and coal as sources of energy.

Many of the greenhouse gas emissions associated with agriculture, on the other hand, come from natural processes. Methane and nitrous oxide are naturally produced by animals and soil bacteria, and production of these gases would still be going on without any human intervention. What is "unnatural" is the scale at which these processes are now occurring. The massive expansion of agricultural activity around the world that has accompanied population growth over the past century has amplified these processes to a degree that it has created persistent imbalances in the global nitrogen and methane cycles, resulting in rising atmospheric concentrations of both (Duglokencky, 2022; Elkins et al., 2022). Completely eliminating these emissions sources is not possible or even desirable, so efforts need to be focused on finding areas in agricultural systems where emissions can be reduced to a degree that will help bring these natural cycles back into balance.

Residence Time of Gases in the Atmosphere

Agricultural greenhouse gas emissions are primarily in the form of nitrous oxide and methane, which both have a much greater warming effect than carbon dioxide, but also do not persist as long in the atmosphere.

The urgency surrounding elimination of fossil fuel emissions is partly due to the vast quantities of carbon dioxide being emitted, but also due to the persistence of carbon dioxide in the atmosphere. A significant fraction of the carbon dioxide being emitted today will remain in the atmosphere for a thousand years or more (Archer and Brovkin, 2008). This means that, even if net zero carbon dioxide emissions could be achieved immediately, the warming impact of carbon dioxide that has already been emitted will continue to be felt for centuries. This is why the elimination of fossil fuel emissions is such a critical goal.

Nitrous oxide, and especially methane, have shorter residence times in the atmosphere; 121 years in the case of nitrous oxide and 12.4 years for methane (U.S. EPA, 2022). Since they do not accumulate in the atmosphere in the same way as carbon dioxide, there is greater potential for achieving an equilibrium concentration where ongoing emissions can be offset by natural atmospheric removals. And if emissions can be eliminated, their climate impact will be gradually reversed rather than persisting for centuries or millennia like that of carbon dioxide (Lynch et al., 2021). Atmospheric concentrations of both gases continue to rise due to anthropogenic emissions and reductions in both are critical for meeting climate goals, but their long-term impact is not the same as that of carbon dioxide.

Major Sources of Agricultural Emissions

The two largest sources of greenhouse gas emissions in U.S. agriculture are nitrous oxide emissions from agricultural soils and methane emissions from livestock production. Consequently, these two areas offer the greatest opportunity for reducing total agricultural emissions.

Agricultural Soil Management

Nitrous oxide emissions categorized under agricultural soil management include emissions from land in crop production as well as managed grass lands (Figure 4). Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification. These processes are driven by the availability of mineral nitrogen (NH_4^+ and NO_3^-) in the soil. Mineral nitrogen is made available via natural processes such as decomposition of soil organic matter and plant material, and by asymbiotic nitrogen-fixing bacteria.

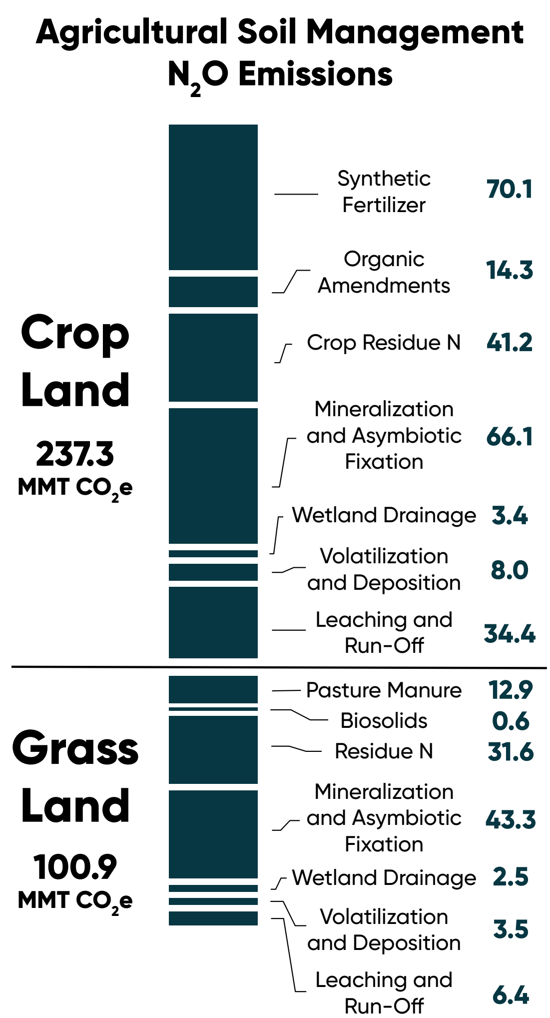
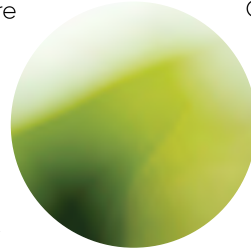


Figure 4. Direct and indirect nitrous oxide emissions from agricultural soils by land type. *Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.*

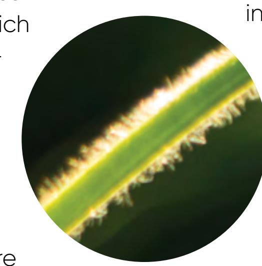
The majority of nitrous oxide emissions from soils are produced during denitrification, in which nitrate (NO_3^-) is converted to N_2 gas. When nitrate is not completely converted to N_2 gas, the resulting byproduct is nitrous oxide (N_2O). Denitrification occurs when oxygen availability is limited in the soil due to water saturation. Nitrous oxide emissions from denitrification are triggered by rainfall events of sufficient volume to saturate at least 60% of soil pore space. Lesser amounts of nitrous oxide are produced during nitrification, which is the conversion of ammonium to nitrate.



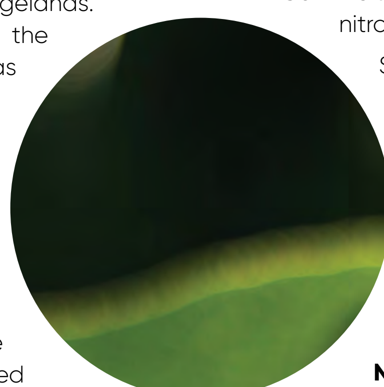
Several agricultural activities increase nitrous oxide emissions beyond what would occur naturally by increasing the amount mineral nitrogen in the soil. The most significant of these activities is adding mineral nitrogen to the soil via synthetic fertilizers. Additionally, agricultural soil management activities such as irrigation, drainage, and tillage can increase the rate of nitrogen mineralization and asymbiotic nitrogen fixation occurring in the soil, which can also increase nitrous oxide emissions.

Climate change driven by greenhouse gas emissions is ***not a future problem*** – its impacts are **already being felt around the world** and affecting agricultural production.

Nitrous oxide emissions attributed to agricultural soil management also include indirect emissions, which occur when nitrogen that moves off of agricultural land is subsequently converted to nitrous oxide. This includes volatilization and subsequent deposition of applied or mineralized nitrogen, as well as surface runoff and leaching of nitrogen into groundwater and surface water.



Agricultural soil management emissions are subdivided by crop land and grass land, the latter of which includes both pastures and native rangelands. Crop land accounts for around 2.3 times the total amount of nitrous oxide emissions as grass land; however, the land area in the U.S. categorized as grass land is far larger. On a per acre basis, emissions from crop land are closer to 5 times those of grass land.



Reducing Nitrous Oxide Emissions

The most important step in reducing nitrous oxide emissions from crop production is increasing nitrogen use efficiency, which is the fraction of applied nitrogen that is harvested as product. Globally, less than half of nitrogen applied to crop land is taken up by the crop (Zhang et al., 2015) with most of the rest lost to the environment. Not only is this economically wasteful, the loss of reactive nitrogen from agricultural soils is associated with several adverse environmental consequences, including contamination of ground and surface water, algal blooms in lakes and rivers, hypoxic dead zones in coastal waters, and nitrous oxide emissions into the atmosphere.

Opportunities and strategies for improving nitrogen use efficiency vary widely around the world due to differences in crops and agronomic management. The greatest need for improvement is in China and India, both of which use large amounts of nitrogen fertilizer and have very low nitrogen use efficiency, at around 30%. This low efficiency is partly due to overapplication of fertilizer but also due to lower nitrogen use efficiency of crops commonly grown there.

Nitrogen use efficiency in the U.S. is relatively high, at around 70%, and has improved in recent decades from around 60% in 1990 (Lassaletta et al., 2014). Increased efficiency in the U.S. is largely attributable to improvements in genetics and management that have resulted in greater yield stability and, consequently, a greater likelihood that applied nitrogen will be taken up by the crop (Ciampitti and Vyn, 2014; DeBruin et al., 2017). However, despite higher nitrogen use efficiency in the U.S., nitrous oxide emissions from agricultural soils have continued to go up, increasing by around 6% since 1990. The reductions in nitrogen loss from greater efficiency have been more than offset by an increase in total nitrogen applied.

Reducing nitrous oxide emissions will require further improvements in nitrogen use efficiency. Nitrous oxide emissions can effectively be reduced by reducing or minimizing the concentration of inorganic nitrogen in soils, especially during periods when denitrification or nitrification are most likely to occur. The trend toward increased volume and intensity of rainfall events during the spring in the U.S. Corn Belt will make it increasingly important to manage nitrogen to avoid losses during this time.

Several management practices and technologies may help reduce nitrous oxide emissions from soils (Millar et al. 2014, adapted from Cavagelli et al., 2012).

Nitrogen Application Rate: Optimizing application rates may reduce nitrous oxide emissions substantially where nitrogen fertilizer is applied at rates greater than the economic optimum rate.

Nitrogen Fertilizer Source: Nitrogen sources include urea, anhydrous ammonia, urea ammonium nitrate, ammonium nitrate and manure. Slow-release fertilizers, such as polycoated urea, are not widely used because of increased costs. Urea, urea ammonium nitrate, and polycoated ureas can decrease nitrous oxide emissions by 50% or more compared with anhydrous ammonia in some locations, but research has shown no impact in other locations.

Nitrogen Fertilizer Placement: Nitrogen fertilizer may be broadcast or applied in bands, applied on the surface or below the surface (such as manure). Incorporating bands of nitrogen in soil can improve nutrient use efficiency and can reduce nitrous oxide emissions by about 50% compared with broadcast application in some locations.

Nitrogen Application Timing: Nitrogen fertilizer should be applied as close as possible to when the crop needs it. Applying nitrogen at planting or at times of peak crop nitrogen demand can increase nutrient use efficiency and would be expected to decrease nitrous oxide emissions; however, results from field studies are mixed.

Nitrification and Urease Inhibitors: Nitrification and urease inhibitors can decrease nitrous oxide emissions by 50% in dry climates, but results have been mixed for humid climates.

Cover Crops: Winter cover crops can reduce nitrogen losses due to leaching and runoff but may not affect direct nitrous oxide emissions.

Improved Irrigation Management: Reducing application rates to minimize soil wetness can reduce nitrous oxide emissions. Subsurface drip irrigation can reduce nitrous oxide emissions compared with overhead sprinkler irrigation because soil moisture is better regulated, but data are limited.

Reduced Tillage: A long-term no-till strategy has been shown to reduce nitrous oxide emissions by up to 50% but data are limited. Short-term no-till results are more mixed.

Methane Emissions from Livestock

Methane from livestock production comes primarily from enteric fermentation (74%) and manure (26%) (Figure 5). Enteric fermentation is the process by which microbes in an animal's digestive system ferment food consumed by the animal during digestion. Methane is produced as a byproduct and is either exhaled or belched out of the animal. The amount of methane produced and emitted depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals, such as cattle, goats, and sheep, emit methane at a much higher rate because of their unique digestive systems. Ruminants have a large fore-stomach (rumen) in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest complex carbohydrates from plants, such as cellulose and hemicellulose, that non-ruminant animals cannot digest. Non-ruminant animals also produce methane emissions through enteric fermentation; however, microbial fermentation in non-ruminants occurs in the large intestine and at a much lower rate. Methane emissions are also affected by feed intake and quality. Larger animals such as cattle produce more methane because of their higher feed intake.

Methane can also be emitted by livestock manure. Methane is produced when manure is stored or treated in systems that create anaerobic conditions, such as lagoons or pits. Bacteria convert organic wastes into volatile acids, which are then converted into methane by a type of archaea known as methanogens. Since this process only occurs under anaerobic conditions, how manure is stored and handled can greatly affect how much methane is produced. When manure is handled as a solid or deposited in a pasture by grazing animals, it tends to decompose aerobically and produce little or no methane. The shift toward larger confinement livestock operations in which manure is handled as a liquid and stored for longer periods of time has resulted in increased methane emissions compared to traditional, smaller livestock farms where manure was often hauled and spread daily.

The majority of methane emissions from livestock come from beef and dairy cattle due to the high amount of methane produced through enteric fermentation (Figure 5). Methane emissions via enteric fermentation from non-ruminant animals are relatively low. Methane emissions from manure are largely associated with dairy and swine production, due to the prevalence of liquid manure storage and handling systems on these types of operations.

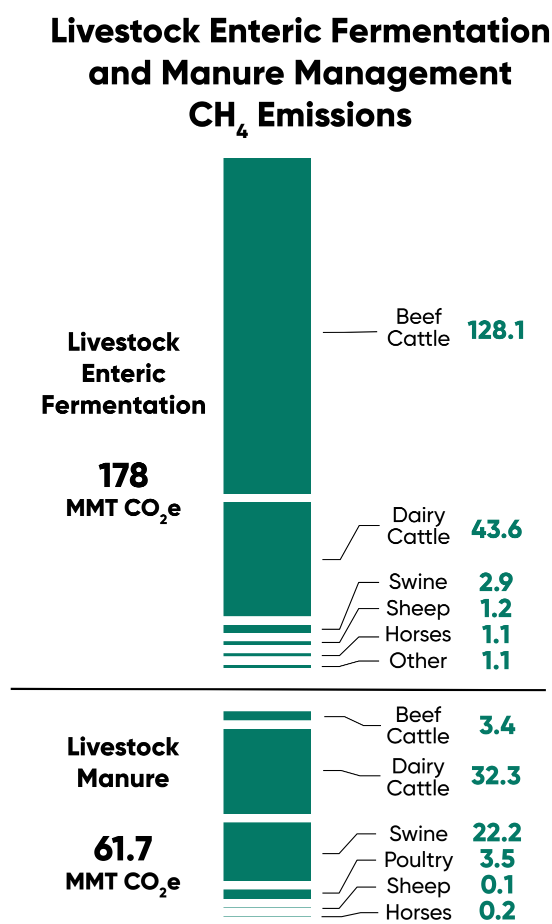


Figure 5. Methane emissions from livestock enteric fermentation and manure management by livestock type. *Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.*

Management to Reduce Methane Emissions

Advances in manure handling systems that can reduce methane emissions are already being deployed and offer the opportunity for greater reductions in emissions as they become more prevalent.

Solid-Liquid Separation: Separating the solid and liquid components of manure is a relatively simple tactic that reduces methane emissions. The solid portions of manure are drier after separation, eliminating the anaerobic conditions that favor methane production. The liquid fraction will also produce fewer emissions because methane-producing microorganisms have less organic matter to feed on.

Methane Digesters: Methane digesters are systems that capture methane released from liquid manure and burn it to produce heat or electricity. By replacing fossil fuels that would otherwise be used to produce the same amount of heat or electricity, the digesters result in a net greenhouse gas benefit. Digester systems can also help reduce odor and disease-causing pathogens.

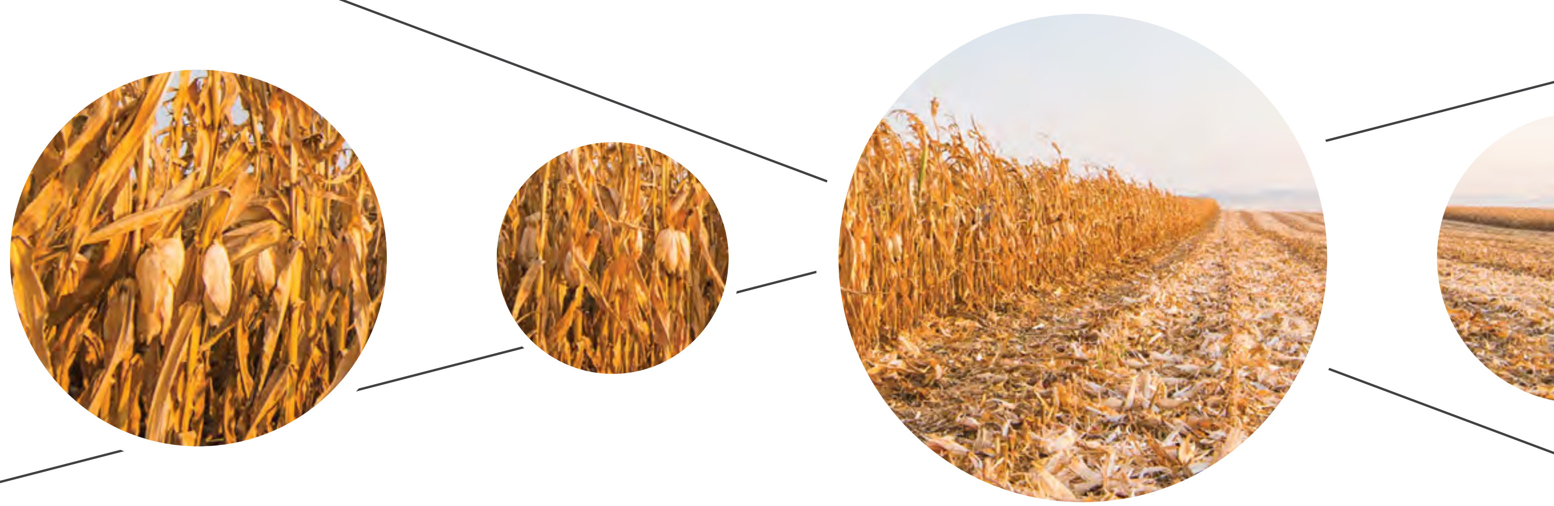
Reducing methane emissions from enteric fermentation has proven more difficult. Approaches at reducing emissions have included animal breeding, vaccines, drugs, and feed additives. The majority of results have had limited success though, due to the ability of the digestive microorganism populations to adapt over time to tactics aimed at suppressing them.

Recent research into feed additives has been much more promising, however. Research has shown that supplementation with a type of red seaweed *(Asparagopsis taxiformis)* can reduce enteric methane production in beef cattle by over 80%, while allowing the cattle to use a greater proportion of the energy in their feed (Roque et al., 2021).

Conclusions

Climate change driven by greenhouse gas emissions is not a future problem – its impacts are already being felt around the world and affecting agricultural production. Changes in climate have shifted weed, insect, and disease pressures, increased extreme weather events, and amplified stress on crops in many regions. These effects will intensify as atmospheric concentrations of greenhouse gases continue to rise; consequently, the urgency of reducing greenhouse gas emissions as rapidly as possible across all economic sectors cannot be overstated. The challenge facing agriculture is to achieve significant reductions in emissions while simultaneously ensuring the stability and resiliency of global food production, resiliency that will increasingly be tested by a more volatile climate.

There are two primary ways in which agriculture can meet this challenge: 1) Continuing to drive higher yields and efficiency to allow greater production using less land, and 2) Implementing management practices that reduce emissions. Tremendous improvements in yield have already been achieved through improvements in crop genetics and management. Future efforts need to continue to raise the bar on yield potential, improve efficiency, and close yield gaps in agricultural systems around the world. Several management practices and technologies available now or currently in development offer the potential to reduce emissions from the few key processes responsible for the majority of agricultural greenhouse gases. Increased efforts to develop and implement these technologies at scale could make significant strides toward improving the sustainability of agriculture going forward.



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return to table of contents

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footnotes

return to table of contents

[1] All Pioneer products are hybrids unless designated with AM1, AM, AMRW, AML, AMT, AMX, AMXT and Q, in which case they are brands.

[2]Adapted from Purdue Univ. Ext. 2009. Two-spotted spider mite. Purdue Univ. Ext. Field Crops IPM. https://extension.entm.purdue.edu/fieldcropsipm/insects/corn-spidermite.php

[3]Adapted from Perring, T.M., T.L. Archer, D.L. Krieg, and J.W. Johnson. 1983. Relationships between the Banks grass mite (Acariformes: Tetranychidae) and physiological changes of maturing grain sorghum. Environ. Entomol. 12:1094-1098.

[4]Adapted from Peairs, F.B. 2014. Spider mites in corn. Fact Sheet No. 5.555. Colorado State Univ. Ext., Fort Collins, CO. https://extension.colostate.edu/docs/pubs/insect/05555.pdf. and Holzer and Kalisch, Univ. of Nebraska.

[5]Images courtesy of Wright, R.J., R.C. Seymour, L.G. Higley, and J.B. Campbell. 1993. Spider mite management in corn and soybeans. NebGuide #G1167. Univ. of Nebraska-Lincoln, Lincoln, NE. https://entomology.unl.edu/NEBGuides/G93-1167%20Spider%20Mite%20Management%20in%20Corn%20and%20Soybeans.pdf

[6]Table 3 from Archer, T.L., and E.D. Bynum, Jr. 1993. Yield loss to corn from feeding by the Banks grass mite and two-spotted spider mite (Acari: Tertranychidae). Exp. & Appl. Acarology. 17:895-903.

[7]Adapted from Zukoff, S., R.J. Whitworth, J.P. Michaud, H.N. Davis, and B. McCornack. 2019. Corn insect management. MF810. Kansas State Univ. Ext., Manhattan, KS. https://bookstore.ksre.ksu.edu/pubs/Mf810.pdf

[8] Average yield response based on 30 on-farm trial locations in 2015 with high SCN pressure (>450 eggs/100 cc of soil). Multi-year and multi-location is a better predictor of future performance. Do not use these or any other data from a limited number of trials as a significant factor in product selection.

[9] Adapted from E. Truog. 1946. Soil reaction influence on availability of plant nutrients. Soil Science Society of America Proceedings 11, 305-308.

[10] Adapted from W.F. Bennett (editor), 1993. Nutrient deficiencies and toxicities in Crop Plants, APS Press, St. Paul, MN.

[11] Adapted from Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa, Ohio State University. Online at: https://agcrops.osu.edu/FertilityResources/tri-state_info

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Photo on page 112 provided courtesy of CNH.

return to table of contents

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.

AML - Optimum® AcreMax® Leptra® products with AVBL, YGCB, HX1, LL, RR2. Contains a single-bag integrated refuge solution for above-ground insects. In EPA-designated cotton growing countries, a 20% separate corn borer refuge must be planted with Optimum AcreMax Leptra products.

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, a Bt trait, 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.

YGCB, HX1, LL, RR2 (Optimum® Intrasect®) - Contains a Bt trait and Herculex® I gene for resistance to corn borer.

AVBL,YGCB,HX1,LL,RR2 (Optimum® Leptra®) - Contains the Agrisure Viptera® trait, the Bt trait, the Herculex® I gene, the LibertyLink® gene, and the Roundup Ready® Corn 2 trait.

Q (Qrome®) - Contains a single-bag integrated refuge solution for above- and below-ground insects. The major component contains the Agrisure® RW trait, the Bt trait, and the Herculex® XTRA genes. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Qrome products. Qrome® products are approved for cultivation in the U.S. and Canada. They have also received approval in a number of importing countries, most recently China. For additional information about the status of regulatory authorizations, visit http://www.biotradestatus.com/.

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

The Optimum® GLY herbicide tolerance trait will not be offered for sale or distribution until completion of field testing and applicable regulatory reviews.

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