PIONEER
HUNDRED YEARS

AGRONOMY SCIENCES

RESEARCH

SUMMARY

2026

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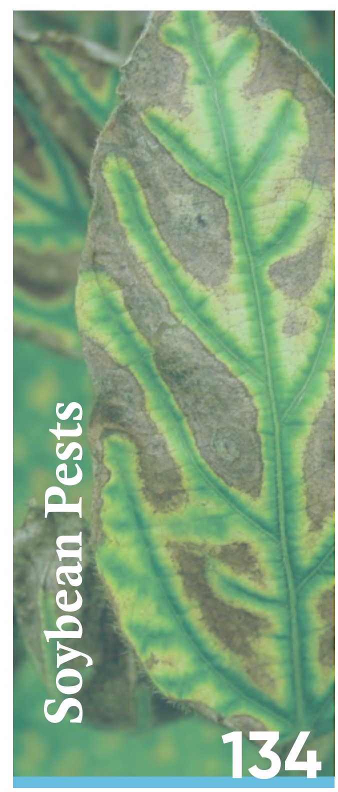
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Chad is the Global Product Director for Biofuels at Corteva Agriscience. He has served in various agronomy and technical roles at Pioneer and Corteva Agriscience for 25 years. Chad earned his B.S. and M.S. in Soil Science and Agronomy at Iowa State University.

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Lucas is a Senior Research Scientist and Research Laureate in the Farming Solutions & Digital group of Corteva Agriscience, located in Johnston Iowa. He is responsible for all the cropping systems initiatives within this department. He has been working in the company for more than three years. Lucas earned his Ph.D. at the University of Buenos Aires, Argentina.

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Kassandra Breckenridge is a Plant Pathology Technology Production Supervisor based in Johnston, IA. With over 10 years of experience, Kassandra leads the pathology production team, which consists of plant disease diagnostics and inoculum production. Her team partners closely with research and field groups, focusing on molecular detection methods for accurate pathogen identification and producing high-quality inoculum to support disease characterization.

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Matt 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 and then Territory Manager for Pioneer. Matt has served in multiple agronomy roles and is currently Agronomy Innovation Leader for the Western U.S.

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Maria Fedorova is the Global Genome Editing Technical Lead within the Regulatory and Stewardship group at Corteva Agriscience where she leads Corteva's regulatory strategies to advance genome-edited crops through the R&D pipeline and enable their regulatory clearance. Maria received a Ph.D. degree in microbiology & genetics from the Institute of Agricultural Microbiology in St. Petersburg, Russia.

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Jessica is an Environmental Data scientist, based in Johnston, IA. Originally from Brazil, she earned her B.S. and M.S. degrees in Agricultural Engineering, where her research focused on applying machine learning and remote sensing to water resource management. She continued her research as a postdoctoral fellow at the University of Nebraska–Lincoln. In her current role, Jessica supports a variety of projects focusing on environmental feature projects related to water and sustainability and crop x water interactions.

Lance Gibson, Ph.D.,

Agronomy Training Manager

Lance Gibson is Agronomy Training Manager supporting Corteva Agriscience and is based in Johnston, IA. His primary role is providing online learning content for Pioneer sales professionals and Corteva Agriscience employees. The Pioneer Agronomy Essentials program he manages has been completed by more than 3,700 participants. Lance earned a B.S. and M.S. at Iowa State University, and a Ph.D. at Kansas State University.

Rebecca Hensley, M.S.,

Senior Research Associate

Becky is a Senior Research Associate within Field Experimentation, a team within Farming Solutions & Digital, a part of Corteva's Research and Development team. Her primary area of work is leading small plot research in Indiana through the creation, implementation, preliminary analysis and execution of nitrogen and phenology trials in corn. Becky has been with Corteva for 18 years and holds a M.S. degree from Iowa State University.

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Dan Ilten is an Agronomy Innovation Manager supporting the Pioneer seed brand in the Agronomy Innovation group, based in Central Nebraska. He is primarily responsible for equipping the Pioneer team in Western Nebraska, Wyoming, Eastern Colorado, and NW Kansas with the data, technology, and resources needed to achieve their business goals. He started his career with Pioneer in 2005 after graduating from the University of Nebraska at Kearney with a Bachelor of Science in Agricultural Business.

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Mark Jeschke is Agronomy Manager supporting the Pioneer seed brand in the Agronomy Sciences group, based in Johnston, IA. His primary role is development and delivery of useful and timely agronomy information. Mark earned a B.S. and M.S. at the University of Illinois at Urbana Champaign, a Ph.D. at University of Wisconsin-Madison, and owns and operates a farm in northern Illinois.

Kevin Keller, M.S.,

Field Agronomist

Kevin is a Pioneer Field Agronomist serving south central Nebraska and co-host of the "Kick'N Dirt with Mike and The Kevins" podcast, which features discussions with growers, agronomists, and other industry professionals. Kevin earned his B.S. and M.S. degrees from the University of Nebraska.

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Technical Knowledge Solutions Scientist

Rayda Krell is part of the Technical Knowledge Solutions team, which develops educational resources to support Corteva products. She is based in Connecticut where she was formerly a biology professor. Rayda earned her B.A. in Biology and Russian from Middlebury College in Vermont and her M.S. and Ph.D. in entomology from Iowa State University.

Brent Larson, M.S.,

Field Agronomist

Brent Larson is a Pioneer Field Agronomist in SW Minnesota. His primary responsibility is supporting customers and Pioneer reps with corn and soybean product knowledge and support. Brent earned B.S. from South Dakota State University and an M.S. from Iowa State University. He also is active in the family farm operation in western Minnesota.

Bill Long,

Field Agronomist

Bill is a sales agronomist in northeastern Iowa and has been representing Pioneer for 28 years in various agronomy roles. A graduate of Iowa State University, Bill supports his field team and growers throughout northeastern Iowa providing education and agronomy advice.

Bill Mahanna, Ph.D., Dipl ACAN,

Global Nutritional Sciences Manager

Bill leads the Pioneer Global Nutritional Sciences Team and is the editor of the Pioneer Silage Zone Manual. His degrees are from Cornell (B.S.) and the University of Wisconsin (Ph.D.). He is also a collaborative professor at Iowa State University and a visiting professor at Bila Tserkva State Agrarian University in Ukraine.

Stacie McNinch, Ph.D.,

N.A. Agronomy Sciences Leader

Stacie is the Agronomy Sciences Leader, based in Johnston, IA. She leads her team's strategy to equip field teams with essential and timely agronomic data, tools, and content. The team delivers on this by deploying on-farm trials, academic partnerships, and disseminating actionable resources. She earned a Ph.D. in Plant Breeding and Genetics from the University of Wisconsin and a B.S. in Agronomy from Iowa State University.

John Mick,

Field Agronomist

John earned his B.S. in Agronomy from Kansas State University. After a short stint as an independent crop consultant, he joined Pioneer in 1993 as a Field Sales Agronomist. Since then, he has served as a Field Sales Agronomist, District Manager, and Account Manager with Pioneer in Nebraska, Kansas, and Oklahoma. He now resides in south-central Nebraska supporting a local team of Pioneer Sales Representatives delivering agronomic support to area producers.

Debora Montezano, Ph.D.,

Agronomy Research Manager

Debora is an Agronomy Research Manager in the Agronomy Sciences group, based in Johnston, IA. Originally from Brazil, she earned her B.S. and M.S. degrees while researching row crop pests, and later completed her Ph.D. at the University of Nebraska–Lincoln. Debora supports the field teams by providing the data and resources needed to be trusted agronomic advisors.

Jesse Munkvold, Ph.D.,

Program Leader, Gene Edited Breeding

Jesse serves as Program Leader for Gene Edited Breeding within the Biotechnology R&D group in Johnston, IA. He earned a B.A. in Biology from Augustana College in Sioux Falls, SD, and later completed a Ph.D. in Plant Breeding and Genetics at Cornell University. Over the past 11 years, Jesse has held various roles at Dow AgroSciences and Corteva Agriscience, focusing primarily on integrating new technologies into the seed product development process.

Brent Myers, Ph.D.,

Senior Data Science Manager

Brent is a Senior Data Science Manager and Research Laureate in the Farming Solutions & Digital group of Corteva Agriscience. Brent earned his Ph.D. from the University of Missouri-Columbia. Prior to joining Corteva, Brent worked as an Assistant Professor at the University of Missouri-Columbia and a Research Soil Scientist at USDA.

Krystel Navarro, Ph.D.,

Plant Pathology Technology Lead

Krystel Navarro is Plant Pathology Technology Lead based in Johnston, IA. She earned a B.S. in Agronomy and later pursued an M.S. and Ph.D. in Plant Pathology, focusing on soybean diseases in the Midwest. Currently, her primary role involves introducing new plant pathology technologies to support the breeding pipeline with the goal of developing new genetic resistance in our products. Additionally, Krystel supports the agronomy teams with plant pathology-related research.

Jackson Preston,

Field Experimentation Intern

Jackson Preston is a senior at Indiana University-Indianapolis majoring in biology with a minor in chemistry. As a field experimentation intern, he focused on small plot nitrogen and phenology modeling research in Indiana.

José Rotundo, Ph.D.,

Research Scientist

José Rotundo is a Research Scientist in Farming Solutions & Digital, located in Seville, Spain. He is responsible for many cropping systems initiatives. He earned his M.S. at University of Buenos Aires, Argentina, and his Ph.D. at Iowa State University, and has been in the company more than 7 years. He is currently a Technical Editor of Crop Science Journal.

Alejo Ruiz, Ph.D.,

Research Scientist

Alejo Ruiz is a Research Scientist in Farming Solutions & Digital, located in Johnston, Iowa. He is responsible for analyzing the data of various projects related to sustainability, focusing on carbon intensity and water use efficiency. Alejo recently joined the company after completing his Ph.D. at Iowa State University.

Jeffry Sander, Ph.D.,

Program Manager for Genome Editing Technologies

Jeffry leads strategic initiatives spanning internal research and external collaborations. He holds a B.S. in Computer Science and a Ph.D. in Bioinformatics and Computational Biology from Iowa State University. Jeff was appointed as a postdoctoral fellow and later served as an instructor at both Harvard Medical School and Massachusetts General Hospital and over the last 12 years has held a variety of technology and production roles at Corteva.

Jonathan Siebert, Ph.D.,

Area Agronomy Leader

Jonathan Siebert is the agronomy leader supporting the Pioneer and PhytoGen seed brands in the midsouth (LA and AR) and PhytoGen and Brevant brands in the southwest (TX, OK, KS and NM); based in Greenville, MS. His primary role is leading field agronomists to create demand for Corteva seed products through data generation, product characterization, education and customer support. Jonathan earned a B.S., M.S., and Ph.D. at Louisiana State University.

Darren Vanness,

Agronomy Project Leader

Darren is Agronomy Project Leader for Corteva Agriscience based in Nebraska. His primary role is testing early agronomic solutions designed to help customers make confident decisions to maximize performance of the products they purchase from Corteva.

Daniel Wiersma, M.S.,

Global Product Manager, Wheat

Dan earned his B.S. and M.S. in Agronomy from the University of Wisconsin-Madison. After working as a Research Scientist at the UW Marshfield Agricultural Research Station for 16 years, he joined Pioneer in 2001 as a Field Agronomist. Dan served in multiple field sales roles before becoming the Alfalfa Business Manager in 2015. Most recently, Dan was named the Global Wheat Product Manager for Corteva Agriscience and currently resides in Wisconsin.

Jay Zielske,

Field Agronomist

Jay is a Pioneer Field Agronomist serving south central Minnesota. He has been with Pioneer for 33 years and is co-host of the “Your Field is Our Office” podcast.

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.

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

STRESS LESS, YIELD MORE – DRIVING CONSISTENT ROI WITH CORTEVA BIOLOGICALS

Every grower has experienced seemingly similar parts of a field yielding differently. When yields are inconsistent, farmers try anything they can to even it out and increase ROI.

Dr. Mario Carrillo, North America Biologicals Commercial Agronomy Leader, explains how farmers can use biologicals in their fields to stress less and yield more, by driving more consistent returns.

COMBAT RED CROWN ROT IN SOYBEAN

Red crown rot is a concerning disease more and more farmers are finding in their fields. Often misdiagnosed, this disease causes deterioration of the stem and roots and premature senescence, which can result in significant reductions in yield.

Dr. Carl Bradley, a renowned plant pathologist at the University of Kentucky, provides valuable insights into the nature of Red Crown Rot, its symptoms, its spread, and how it can be managed.

CARBON CURIOSITY: UNLOCKING CARBON MARKET OPPORTUNITIES

Carbon markets offer farmers, ranchers, and forest landowners the opportunity to diversify their income through the adoption of sustainable practices and sequestering carbon on their land.

Matt Kilworth, Carbon & Ecosystems Manager at Corteva Agriscience, delves into the latest insights and updates on topics ranging from carbon offsets to biofuels, as well as the Corteva Carbon Program.

ADDRESSING SOUTHERN RUST IN CORN: OUTBREAK TRENDS AND FUTURE SOLUTIONS

Southern rust, a destructive fungal disease, took over an unprecedented number of corn fields in 2025. What factors contributed to the outbreak? How can growers combat this disease in future growing seasons?

Dr. Krystel Navarro, Plant Pathology Lead at Corteva Agriscience, and **Dr. Brandon Wardyn,** Corn Evaluation Zone Lead at Corteva Agriscience, get to the root of this fungal issue.

Agriscience Explained™

PODCAST

Agriscience Explained: From Science to Solutions is a Corteva Research and Development podcast that launched in January 2025. The podcast is hosted by Tim Hammerich, a leader in agricultural communications with a background in crop science. Each 30-minute episode features a scientist helping to develop agricultural innovations and a farmer who describes the impact on the farm. New episodes are posted every other week on any topic related to transformation in pest management and agriculture.

AGRISCIENCE EXPLAINED WITH SAM EATHINGTON

In this first episode, learn about what you can expect to hear from the podcast. Why did Corteva start a podcast? What makes this agricultural podcast different?

Sam Eathington, Chief Technology and Digital Officer at Corteva Agriscience

HISTORY OF AGRISCIENCE INNOVATION

Hear about the history of agricultural innovation and how it informs the future. How have genetics propelled the current agriculture industry and how will it solve future problems?

Dean Podlich, Corteva Agriscience Distinguished Laureate and Digital Seeds Platform Leader

Heather Hampton-Knodle, a fourth-generation crop and livestock farmer in Illinois

David Hula, farmer in Virginia and 2024 National Corn Yield contest winner

JOURNEY OF A SEED

What does it take to build a world record hybrid? And why does it take so long to develop new hybrids? Follow the journey of the seed from inbreds to hybrids to traits to becoming a commercial product.

Dean Podlich, Corteva Agriscience Distinguished Laureate and Digital Seeds Platform Leader

David Hula, Virginia farmer and 2024 National Corn Yield contest winner

INVISIBLE PEST MANAGEMENT

Nematodes are microscopic worms that are the most abundant multicellular organism on the planet. Often, they go completely unnoticed until we see their impact on crops.

Tim Thoden, Global Biology Program Leader at Corteva Agriscience

Michael Logoluso, California raisin grape farmer and farm manager for Lion Farms

TODAY IS YESTERDAY'S FUTURE

There are tremendous opportunities that are emerging because of gene editing. This ability is distinctly different from transgenic or GMO approaches, and its impact could be even greater on the future of food and agriculture.

Dave Bubeck, Global Breeding Alliances Lead for Seed Product Development

Heather Hampton-Knodle, a fourth-generation crop and livestock farmer in Illinois

GENE EDITING: PATHWAY TO PROGRESS

What will the path forward for gene editing look like for farmers and consumers? How is gene editing different from transgenic approaches to developing new seed offerings? What will it take to make this new technology more widely available?

Reza Rasoulpour, Vice President of Global Regulatory and Stewardship at Corteva Agriscience

Heather Hampton-Knodle, a fourth-generation crop and livestock farmer in Illinois

MEET CARL: YOUR DIGITAL AGRONOMIST

Digital agriculture, decision science and generative artificial intelligence (AI) all converge into a new tool for agronomists and seed sales reps. How will this enhance the way trusted advisors make recommendations to farmers?

Matt Smalley, Data Science Leader at Corteva Agriscience

Mike Anderegg, Agronomy Innovation Manager for Corteva Agriscience

PERMANENT COVER CROPS TAKE ROOT

Why do fewer than 10% of U.S. row crop acres incorporate cover crops? What might it look like to create a better cover crop system?

Sara Lira, North America Cropping Systems Lead at Corteva Agriscience

Chris Gaesser, a southwest Iowa farmer

SCIENCE MAKES ACTIVE INGREDIENTS MORE ACTIVE

A crop protection product is more than just an active ingredient. How a particular product is formulated really makes a big difference.

John Atkinson, Application Technology Group Leader at Corteva Agriscience

Lance Lillibridge, a crop and livestock farmer in eastern Iowa

TOO TALL? A LOOK AT REDUCED STATURE CORN

Does corn really need to be so tall? With increases in severe wind events and interest in planting at higher densities, reduced stature corn could provide a solution.

Sara Lira, North America Cropping Systems Lead at Corteva Agriscience

Blake Johnson, a fifth-generation corn farmer in Nebraska

REDUCED STATURE CORN: HEIGHT EXPLAINED

What goes on inside a corn plant to make it shorter without sacrificing yield? Learn about the science that goes into making reduced stature corn a reality.

Jeff Habben, Senior Research Manager and plant physiologist at Corteva Agriscience

John Becker, a southwest Iowa farmer

FUNGICIDE TIMING SOLUTION: CONFIDENT APPLICATION TO MAXIMIZE ROI

Learn about a tool that uses the power of artificial intelligence to signal the optimal timing for a fungicide application per label directions.

Layton Peddicord, Research Scientist for Farming Solutions and Digital at Corteva Agriscience

Makenna Green, a sixth-generation farmer in east central Illinois

FUELING GROWTH IN WINTER CANOLA

What would a truly renewable biofuel look like? The feedstock would have to come from a crop that is productive, profitable, and resilient to grow. Could winter canola be that crop?

Chad Berghoefer, Global Product Director for biofuels at Corteva Agriscience

Jamison Turner, a farmer in western Tennessee

CRUCIAL CONVERSATIONS ABOUT BIOLOGICALS IN AGRICULTURE

Are biological products ready for prime time on the farm, or still struggling to prove their return on investment? Where are biologicals finding traction and what are the barriers and opportunities for this category going forward?

Josh Armstrong, Integrated Discovery and Bioprocess Leader

Joe Coelho, a fourth-generation specialty crop farmer in California

REVOLUTIONARY PLANT BREEDING: BREAKTHROUGH UNLOCKS HYBRID WHEAT

Wheat is an important crop around the world; but why haven't hybrids been commercialized? This episode examines the science that is making hybrid wheat a reality.

Jessie Alt, Global Wheat Lead for Corteva Agriscience

Brad Erker, CEO of Colorado Wheat

SCIENCE, SUSTAINABILITY AND THE ART OF FARMING

The ability to farm productively and profitably can also be sustainable. Learn about the priorities that drive crop protection development to minimize off-target effects and conserve biodiversity, especially related to protecting bees.

Jonathan Nixon, Insect Management Biology Scientist at Corteva Agriscience and beekeeper

Trey Hill, Maryland farmer and owner of Harborview Farms

UNLOCKING AGRISCIENCE INNOVATION

Learn about the challenges and opportunities to unlock agriscience innovation, both at the farm and corporate level.

Sam Eathington, Chief Technology and Digital Officer at Corteva Agriscience

Corey Hillebo, Iowa farmer and podcaster

DISCOVERING TOMORROW'S BIOTECH TRAITS

What goes into the traits farmers can purchase with their seed? How are these traits found, developed, and ultimately packaged into crop genetics?

Julian Chaky, Trait Characterization and Development Team Lead at Corteva Agriscience

Mark Knupp, a sixth-generation farmer in Iowa

THE RECIPE FOR PROTECTING SEED POTENTIAL

Seed treatments are incredible tools that help protect the seed and seedling plants in the first 10-30 days of development. Because these treatments are delivered on the seed without having to spray this area of agriscience is sometimes overlooked.

Mark Howieson, Global Technical Services Team Leader for Seed Applied Technologies at Corteva Agriscience

Scott Van Veldhuizen, an Iowa corn and soybean farmer

Don't miss an episode!
Follow Agriscience Explained on your favorite podcast platform.

USING BIOLOGY TO PROTECT YOUR MOST VALUABLE ASSET

Termites cost U.S. homeowners at least $5 billion per year. But, by starting with an understanding of termite biology, a game-changing management approach was developed that is celebrating 30 years of innovation.

Garima Kakkar, Global Biology Lead for Urban Pests at Corteva Agriscience

Neil Spomer, Technical Manager and Field Trial Modernization Lead at Corteva Agriscience

Stephen Gates, Vice President of Technical Services at Cook's Pest Control

FROM RUM TO REVOLUTION: HOW SPINOSYNS CHANGED PEST CONTROL

The incredible of how a soil sample collected on a vacation brought an effective biological insecticide to farmers in need of new solutions for pest management.

Jesse Richardson, Corteva Agriscience Crop Health Field Scientist

Bill Fox, Pest Control Advisor in Yuma, Arizona

2025 Growing Season in Review

The 2025 growing season was one likely to be remembered for exemplifying the unpredictable nature of crop production. Despite well-laid plans and best efforts to control the controllables, nature always has the final word on crop growth and yield. Every growing season is unique, and impacts of environmental conditions on crops can sometimes play out in unexpected ways.

General soil moisture trends in 2025 followed a pattern somewhat similar to those of 2024, with widespread drought conditions from the previous season lingering into the spring, abundant rainfall largely breaking the drought during the growing season, and a return to dry conditions in the fall. The 2025 season began with much of the East Coast, Midwest, and Great Plains under some degree of drought (Figure 1). Dry conditions eased somewhat during the spring and then dramatically during the summer with above average rainfall during June and July.

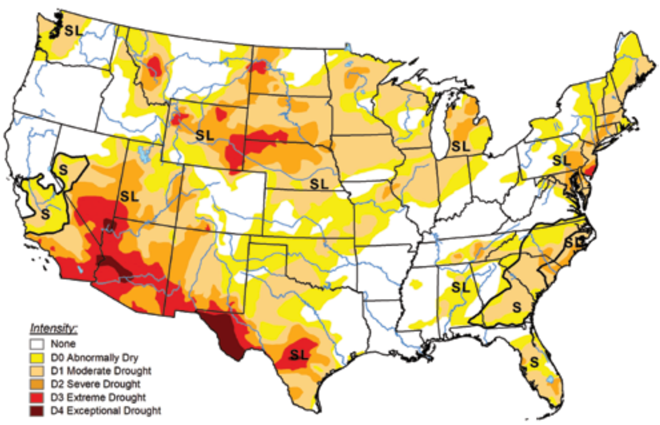

Figure 1. U.S. Drought Monitor map, March 4, 2025 (National Drought Mitigation Center, University of Nebraska-Lincoln).

Corn planting got off to a good start in April, with U.S. planting progress running about a week ahead of 2024. Weather conditions did not give the crop the best start though – GDU accumulation during the month of May was below average through most of the Central U.S. (Figure 2). This stress was compounded in some areas by soil crusting issues. As a result, 2025 wound up being a season in which early planting did not necessarily pay off.

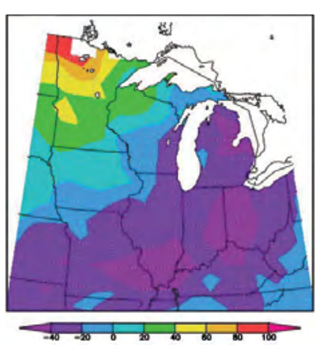

Figure 2. GDU accumulation deviation from normal for the period of May 1 to 27, 2025.

Growing conditions quickly turned more favorable during June and July, with warmer temperatures and ample rainfall across many areas. In some areas rainfall became excessive, resulting in flooding damage and nitrogen loss. Iowa experienced its second wettest July on record, with average total rainfall only slightly less than that of 1993 (Figure 3).

Summer temperatures were above average, not due to extreme daytime highs as much as exceptionally warm nights (Figure 4). July minimum temperatures approached or exceeded all-time records for most of the eastern half of the U.S.

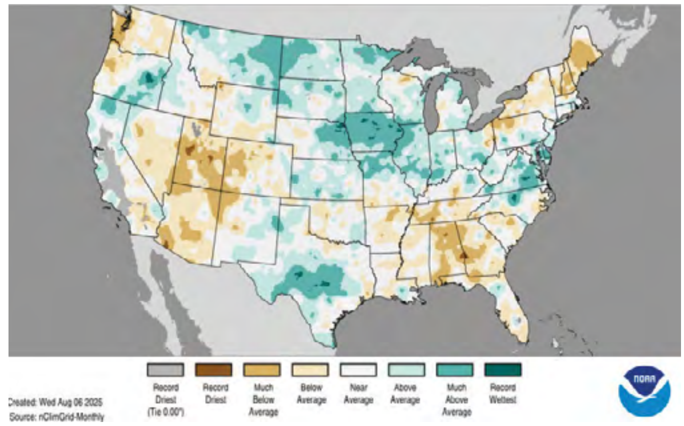

Figure 3. Total precipitation percentiles for July 2025 (NOAA).

The most unusual occurrence of the 2025 season began to show up in fields in early July – a developmental abnormality that would come to be known as tassel wrap, in which the uppermost leaves remain wrapped around the emerging tassel instead of unfurling normally. This issue appeared to be a later than normal manifestation of rapid growth syndrome – a phenomenon that normally occurs earlier in the vegetative stages in which an abrupt acceleration in plant growth causes the plant leaves to become tightly wrapped as new leaves emerge faster than existing leaves can unfurl. Locations with tassel wrap generally experienced cooler temperatures earlier in the season, followed by a surge in temperatures prior to tasseling with exceptionally low vapor pressure deficit – indicating a near complete absence of water stress.

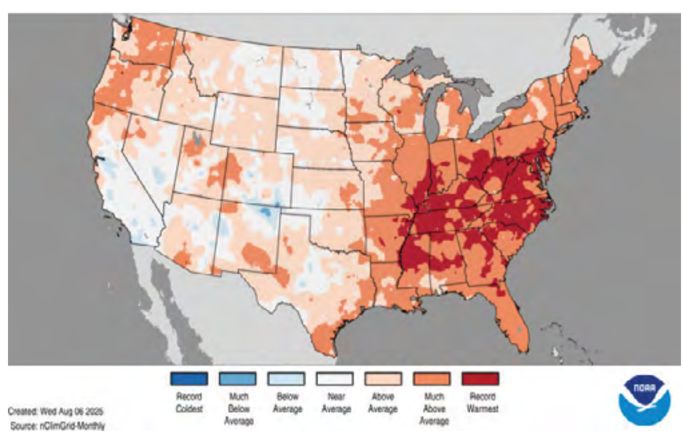

Figure 4. Minimum temperature percentiles for July 2025 (NOAA).

During the latter portion of the summer, focus shifted to crop diseases. The warm and wet conditions of July lead to proliferation of foliar diseases during August, with southern rust and tar spot being the two most impactful diseases in corn. For a second year

THE PIONEER LONG LOOK

1. We strive to produce the best products on the market.

2. We deal honestly and fairly with our customers, seed growers, employees, sales force, business associates, and shareholders.

3. We advertise and sell our products vigorously, but without misrepresentation.

4. We give helpful management suggestions to our customers to assist them in making the greatest possible profit from our products.

in a row, southern rust made a strong surge into the central and northern Corn Belt, brought up from the South by prevailing winds during June (Figure 5). Midwestern weather conditions proved more hospitable for southern rust than they were in 2024, causing it to spread rapidly. A return to moderate temperatures later in the summer allowed tar spot to take off as well, particularly in the eastern part of the Corn Belt.

Figure 5. Southern rust of corn and sudden death syndrome of soybean were widespread in 2025.

Soybeans were impacted by disease as well. Sudden death syndrome showed up widely during August – an occurrence that was surprising to no one given the perfect set-up of weather conditions for SDS in 2025. Cool conditions during May allowed infection to take hold in the roots and heavy rainfall in July promoted translocation of the SDS phytotoxin to the leaves, causing the characteristic foliar symptoms.

A record-shattering corn crop was forecast throughout much of the growing season, but expectations began to wane a bit during harvest, with many growers reporting good but not exceptional yields. The lack of drought stress during much of the growing season kept expectations high, but foliar diseases, excessive rainfall, and high night temperatures all took a toll.

Spring of 2026 marks the start of a new growing season, as well as the start of a new century for Pioneer. Pioneer was founded as the Hi-Bred Corn Company on April 20, 2026, at a time when corn yielded around 20-30 bu/acre and was mostly harvested by hand. The ensuing century has seen massive change – both in how crops are produced and in the Pioneer business itself. One thing that hasn't changed though, is the essential role of agronomy in the Pioneer business.

The importance of agronomy to Pioneer was codified in *The Long Look*, written by Executive Vice President James W. Wallace and Director of Sales Nelson Urban in 1952. *The Long Look* consists of four foundational principles that embody the values and priorities that define the Pioneer way of doing business. Point number four of *The Long Look* states "We give helpful management suggestions to our customers to assist them in making the greatest possible profit from our products."

Pioneer leaders recognized the importance of supporting our products with an extensive program of agronomy research, training, and service, to ensure customers realize the greatest potential from those products and – in doing so – continue to be customers for years to come. This Agronomy Research Summary represents a continuation of that legacy, and that commitment to Pioneer customers, that began one hundred years ago.

Mark Jeschke, Ph.D.
Agronomy Manager

Pioneer at 100 - A Look Back at a Century of Growth

LANCE GIBSON, PH.D., AGRONOMY TRAINING MANAGER
MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- The selection techniques used by farmer-breeders to create open pollinated varieties had little impact on improving corn yield, which remained between 20 and 30 bu/acre on average from 1860 until the 1930s.
- Henry A. Wallace was one of the first people to understand the significance of the methods for hybridizing corn that were first published by George Shull in 1909.
- Wallace organized a group of Des Moines businessmen to form the Hi-Bred Corn Company, which was incorporated in Iowa on April 20, 1926. Pioneer was added to the company name in 1935.
- As the first company devoted solely to marketing hybrid corn seed, Pioneer was instrumental in establishing many industry norms that are still in practice today.
- Raymond Baker led corn breeding at Pioneer for over 40 years and built the foundation for Pioneer's rapid growth in the U.S. and around the world.
- The breadth and depth of its germplasm has remained a key differentiator for Pioneer for a century.

A CENTURY OF PROGRESS

As Pioneer celebrates its 100th anniversary in 2026, this milestone offers a moment to reflect on a century of innovation, leadership, and impact in the seed industry. Founded by Henry A. Wallace in 1926, Pioneer began as a bold experiment in corn breeding and quickly grew into a driving force for agricultural progress. Wallace's vision and scientific curiosity laid the foundation for a company that would revolutionize crop genetics, empower farmers, and set enduring standards for quality and agronomic support. This article traces Pioneer's journey from its origins in Iowa to its global leadership, honoring the legacy of its founder and the generations who have shaped its story.

A REVOLUTION IN CORN BREEDING

Prior to the development of hybrid corn, all corn produced by farmers consisted of open pollinated varieties, which were the result of selection of ears and seeds by farmers from fields where corn pollen was allowed to freely flow among plants. The most widely grown open-pollinated varieties were Corn Belt dents created by farmer breeders in the late 1800s and early 1900s. 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. Selection criteria for open pollinated corn included maturity before frost; well-matured, solid ears; free of disease; a stiff upright stalk at harvest, and an ear height convenient for hand picking. The techniques used by farmer-breeders had little impact on improving yield though, which remained between 20 and 30 bu/acre on average from 1860 until the 1930s.

Figure 1. Bags of Pioneer seed corn in the 1940s.

Henry A. Wallace began questioning these seed selection tactics as a method for improving yield when he was just sixteen years old. Experiments Wallace conducted in 1904 as a teenager on three acres in his family's garden on the west side of Des Moines began an interest in methods for improving corn yield that would lead to the founding of the Hi-Bred Corn Company two decades later. After graduating from Iowa State College in 1910, Henry A. Wallace worked as a writer and editor for his family's weekly farm publication, Wallaces' Farmer, but actively maintained his interest in improving corn genetics.

Wallace was one of the first people to understand the significance of the methods for hybridizing corn that were first published by George Shull in 1909 and further developed by Edward East at the Connecticut Agricultural Experiment Station. Wallace began corn-breeding experiments in 1913 near his home on the west side of Des Moines. Many land-grant colleges were also establishing hybrid corn breeding programs at this time and Wallace established working relationships with several of them. Wallace was an early proponent of the need for scientific yield testing to determine the best performing corn varieties. He, along with Professor H.D. Hughes of Iowa State College, was largely responsible for starting the Iowa Corn Yield Test in 1920.

Figure 2. Henry A. Wallace organized a group of Des Moines businessmen to form the Hi-Bred Corn Company, which was incorporated in Iowa on April 20, 1926.

FORMATION OF THE HI-BRED CORN COMPANY

Five hybrids from crosses containing inbreds created by Henry A. Wallace, including Copper Cross, were entered in the 1924 Iowa Corn Yield Test. These were some of the first hybrids entered in the test and all five finished near the top against the best open-pollinated varieties of the day. Based on the success of his hybrids in the Iowa tests, Henry A. Wallace confidently and prophetically concluded the lead article in the March 25, 1925, issue of Wallaces' Farmer with the following, "A revolution in corn breeding is coming which will affect directly or indirectly every man, woman and child in the Corn Belt within twenty years." Convinced that hybrids would revolutionize corn production and farmers, Henry A. Wallace organized a group of Des Moines businessmen to form the Hi-Bred Corn Company, which was incorporated in Iowa on April 20, 1926.

"A revolution in corn breeding is coming which will affect directly or indirectly every man, woman and child in the Corn Belt within twenty years."

FARMER ADOPTION OF HYBRID CORN

In early 1933, Henry A. Wallace left Iowa for Washington D.C. to join Franklin D. Roosevelt's cabinet as Secretary of Agriculture. He turned the supervision of the Hi-Bred Corn Company over to associates who were already running most of the daily operations. Pioneer was added to the company name in 1935 to differentiate it from other companies and reinforce its place as an innovator in the breeding and sale of hybrid corn seed.

In 1935, only around 6% of Iowa corn acreage was being planted to hybrids, as most farmers continued to save seed from their own fields. 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 drought stress. Once farmers had solid evidence of the benefits of hybrid corn, the transition away from open-pollinated varieties was rapid. In 1938, hybrid corn occupied 50% of Iowa corn acres and adoption was nearly 100% by 1942.

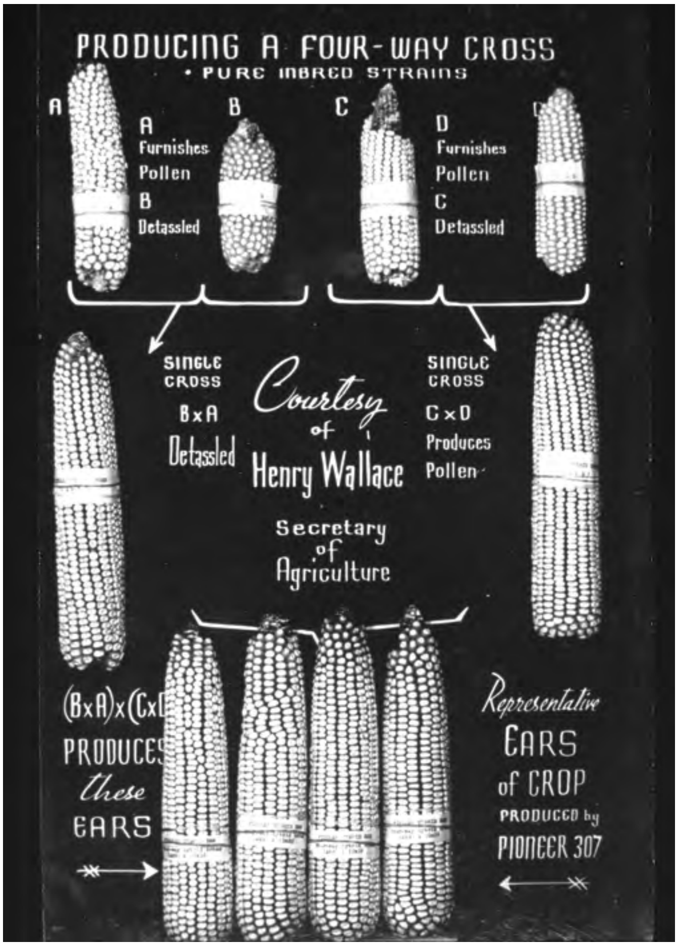

Figure 3. The earlist commerical hybrids were double-crosses, with two pairs of inbred parent lines. Plants of a double-cross are not as uniform and high-yielding as those for a single-cross, but the seed can be grown at lower cost, and they exhibited greater vigor and performance than the open-pollinated corn varieties.

Figure 4. Henry A. Wallace served as the U.S. Secretary of Agriculture from 1933-1940, the 33rd Vice President of the United States from 1941-1945, and the U.S. Secretary of Commerce from 1945-1946.

U.S. EXPANSION OF THE PIONEER HI-BRED CORN COMPANY

Pioneer expanded rapidly along with the adoption of hybrid corn. By 1945, Pioneer had 10 corn breeders, and Pioneer hybrids were being processed in 12 production plants spread across Iowa, Illinois, and Indiana. Pioneer's annual participation in the Iowa Corn Yield Test, official performance tests in other states, and publishing of the results in Wallaces' Farmer were major drivers for the acceptance of hybrid corn and growth of Pioneer. By 1940, Pioneer hybrids had begun to dominate official yield tests in Illinois, Michigan, Minnesota, Missouri, Nebraska, and South Dakota. Even as competition from other companies began to build, Pioneer hybrids almost made a clean sweep of first place honors in the 1949 Iowa test.

PIONEER LEADERSHIP IN THE SEED CORN INDUSTRY

As the first company devoted solely to marketing hybrid corn seed, Pioneer was instrumental in establishing many industry norms that are still in practice today. These including advertising in farm periodicals, local seed representatives, plants exclusively for processing corn seed, artificial drying, more precise grading of kernel sizes and shapes, germination and vigor testing standards, standardized maturity recommendations, seed treatment, planter setting recommendations for each seed lot, two or more product test plots per county, product field days, grain quality testing, and free seed for replanting.

Figure 5. J. J. Newlin, 1925.

Many of these efforts were initiated by J. J. Newlin, a founder and first general manager of the Hi-Bred Corn Company. In addition to being responsible for sales and promotion, Newlin was responsible for seed production in Johnston, Iowa from the founding of the company until retiring from Pioneer in 1968. Nelson Urban, the company's first business and sales manager, helped establish the farmer-dealer Pioneer sales representative system, which utilized respected farmers to promote and sell seed to their neighbors.

James W. Wallace, brother of Henry A., was influential to the success of Pioneer for more than four decades starting as Secretary when the company was formed and concluding as Chairman of the Board in 1969. James and sales director Nelson Urban codified four principles that continue to guide Pioneer today. Originally jotted on the back of an envelope in preparation for the 1951 Pioneer sales Christmas party, they were published in a small booklet titled, *The Long Look*, in 1952. These guiding principles were written as simple statements describing how Pioneer offers quality products, honest product information, aggressive marketing without misrepresentation, and management advice for getting optimum profits from Pioneer products.

First: We try to produce the best seed corn and baby chicks on the market.

Second: We try to deal honestly and fairly with our employees, salesmen, business associates, customers and stockholders.

Third: We try to advertise and sell our products vigorously, but without misrepresentation.

Fourth: We try to give helpful management suggestions to our customers to assist them in making the greatest possible profit from their corn fields and laying houses.

Figure 6. The four points of *The Long Look*, as originally written by James Wallace and Nelson Urban in 1952. The original wording is reflective the fact that Pioneer was also in the chicken breeding business at the time. Later revisions dropped the references to chickens after the Hy-Line poultry business was spun off in 1978.

PIONEER HYBRID NUMBERING SYSTEM

The earliest hybrids sold by the Hi-Bred Corn Company were assigned three digit numbers in which the first two digits indicated the year of delivery (28 = 1928) and the thrid digit was either 1, indicating flat seed, or 2, indicating round seed.

Beginning in 1930, all new hybrids began with a 3. This numbering convention of three-digit numbers starting with 3 was maintained beyond the 1930s, up until 1960 when a fourth digit was added. Many hybrid numbers in the 300 series were used multiple times over the years. Hybrid numbers continued to start with 3 until the numbering system was completely reworked in 2009.

Pioneer Hybrid Numbering Convention Examples:

307	1930-1961	P1151HR	2009-2022
3780	1960-1996	P05737PCE	2023-present
33W84	1997-2008		

INTERNATIONAL EXPANSION

Pioneer expanded operations into Ontario through the formation of the Pioneer Hi-Bred Corn Company of Canada in 1946. By the 1960s, the North American hybrid seed corn market became saturated with little unit growth, forcing a higher level of competition. This led to Pioneer concentrating on development of overseas operations, establishing joint ventures outside the U.S. and Canada. Pioneer breeding efforts during this era focused on delivering ever higher yields, faster dry down, easier shelling by combine harvesters, and increasing the number of generations of inbreeding per year using winter nurseries in Hawaii. Beginning in 1960, hybrid naming was expanded to a four-digit number but continued to use 3 as the first digit. Seed bags were switched from cloth with blue, red, and yellow printing to the now familiar gold and white paper bag with the Pioneer trapezoid symbol and name in green in 1965.

History of Agriscience Innovation

- Agriscience Explained Podcast

Figure 7. A Pioneer hybrid show plot. The presence of both three and four-digit numbered hybrids places this scene in the early 1960s.

PIONEER TAKES THE LEAD IN AGRONOMY SUPPORT

Pioneer began to differentiate itself from other corn seed companies in the 1950s and 1960s through their crop management service and support. One of the first formal Pioneer crop management publications was *Keys to Corn Profits*, which was first produced in the 1950s and continued through the 1970s. A Pioneer Technical Services Department was formed in 1962 followed by the addition of full-time field agronomists in 1965. The principal activities of the early Pioneer Agronomists were to train the Pioneer salesmen, lead customer meetings over the winter, and make follow-up customer contacts during the spring. These efforts rapidly built a reputation for Pioneer for providing customers the highest level of agronomy support in the industry.

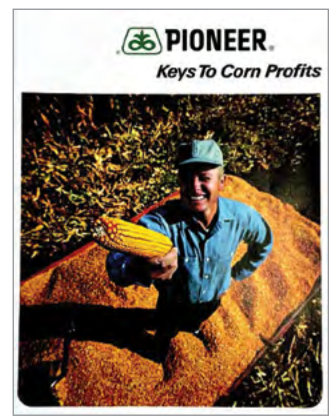

Figure 8. Keys to Corn Profits booklet from 1968.

PIONEER DIFFERENTIATION IN THE MARKETPLACE

During the first five decades of the hybrid corn industry, inbreds were developed by Land Grant Universities and private entities, like Pioneer. 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.

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 attributed 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 College. Through many selection cycles, Pioneer plant breeders optimized the performance of Iodent inbred lines. The Iodent germplasm is now recognized as a third heterotic group of inbreds for creating corn hybrids in addition to the stiff-stalk germplasm originating from Iowa State University and non-stiff-stalk inbreds. These lines, as well as other Pioneer-developed inbreds, produced industry-leading corn hybrids that outperformed other popular products. This performance was rapidly recognized by farmers and Pioneer corn sales in North America increased by 2.5 million units between 1972 and 1977. The unique and proprietary germplasm developed by Pioneer was a clear differentiator in the marketplace and by the early 1980s, the era of university-derived corn inbreds had passed.

Figure 9. Henry A. Wallace (left) and Raymond Baker (right). Baker's focus on rigorous scientific methods in the development and testing of hybrids built the foundation for Pioneer's rapid growth in the U.S. and around the world.

EXPANSION OF PIONEER RESEARCH AND DEVELOPMENT

Pioneer positioned itself as the leader in improving corn genetics through its large network of breeding stations, utilizing higher planting density stress for selecting inbreds and hybrids, extensive use of wide-area testing across the various conditions encountered throughout the U.S. and Canada, performing a vast number of on-farm hybrid comparisons, and computer-based information management. Establishment of a research station at York, NE in the early 1950s and screening of crosses at locations throughout the dryland areas of the U.S. High Plains were critical to improving the resistance of corn to drought.

A four-row cone research plot planter was developed by Pioneer in 1968, allowing a small crew to plant many more plots in less time than previous methods. This was soon followed by modification of combines to rapidly weigh and sample corn as it was harvested. Research plots were placed in customer fields beginning in 1973, allowing expansion of the number of trial locations.

Figure 10. Harvesting research plots in the 1960s.

PIONEER BUSINESS GROWS AND EVOLVES

Prior to 1970, Pioneer was a federation of geographically based companies across multiple U.S. states, Canada, and outside North America. Each of these companies purchased its parent seed from Pioneer's centralized research division but was responsible for its own operations. In 1970, Pioneer operations were reorganized into a single entity for the U.S. with a separate division overseas and renamed Pioneer Hi-Bred International. These changes brought greater uniformity to company policies, pricing, and promotion.

In 1973, the company became incorporated as Pioneer Hi-Bred International, Inc. with its first public offering of company stock. At the time, Pioneer had 79 scientists and technicians employed in research. There were 21 research stations for seed corn located in 13 states and five countries. Seed was produced under arrangements with 640 independent farmer growers and processed in 15 seed corn production plants located in Illinois, Indiana, Iowa, North Carolina, and Texas. Sixty-five corn hybrids were being marketed primarily through 2,500 independent dealers, and to a much lesser extent through 2,000 agricultural retailers. Annual worldwide sales of Pioneer corn seed surpassed 10 million units in 1980.

GROWTH IN PIONEER AGRONOMY SUPPORT

Two company restructurings during the 1980s expanded on-farm agronomy research and service to farmers. The first of these occurred in 1986 and involved a significant expansion in the number of commercial Pioneer Agronomists. Delivery of agronomy information underwent a substantial leap forward in quality, sophistication, and coordination during this time as well. Walking Your Fields, an agronomy newsletter delivered to customers by mail, was established in 1982. This newsletter rapidly became the go-to source of agronomic information for farmers across North America and continues to be a valued source of timely agronomy information to this day as an email. Several other newsletters and publications used by Pioneer Agronomy up through the present day also have their origins in this era.


CROP INSIGHTS
PIONEER
NO-TILL FARMERS PLAN MORE DRILLED SOYBEANS

Figure 11. Pioneer Crop Insights from 1992.

INDUSTRY CHANGES

The seed industry went through extensive changes in the 1990s as the commercialization of the first biotechnology traits reshaped the business landscape. Monsanto had positioned itself as a major competitor to Pioneer by developing and marketing insect protection and herbicide tolerance biotech traits. They also acquired Asgrow, Holden Foundation Seeds, and DeKalb Genetics Corporation. Pioneer began searching for a partner that would allow them to spend the research and development dollars to compete under the new reality biotech crops presented and found it in DuPont Co.

In 1997, DuPont acquired a 20% stake in Pioneer and the companies formed a joint venture called Optimum Quality Grains LLC. In 1999, DuPont acquired the remaining 80 percent of Pioneer bringing together DuPont's desire to increase its presence in the life sciences and Pioneer's expertise in seed development, production, and distribution. Pioneer continued to operate under the Pioneer name as Pioneer, A DuPont Company and remained headquartered in Des Moines, Iowa.

RAPID ADOPTION OF BIOTECHNOLOGY

Pioneer began developing its own proprietary trait technologies in the 1980s by organizing a genetic transformation team and creating its first laboratory transformation in 1990. This early research got a boost when Pioneer entered a research partnership with Mycogen Corporation in 1991. Through a series of acquisitions and buyouts, Mycogen was absorbed into Dow Agrosciences LLC in the late-1990s. The collaboration on insect protection technologies allowed Pioneer and Dow AgroSciences to pool their talents to research, develop, and seek regulatory approval for the Herculex® family of insect protection traits. Pioneer introduced the Herculex® I corn protection trait in 2003. It controlled above-ground insects by expressing the Cry1F Bt protein, which had a different molecular structure than other Bt traits being sold at the time. In 2006, Pioneer released the first hybrids containing the Herculex RW gene for transgenic corn rootworm control.

Pioneer first offered herbicide tolerant corn hybrids with the introduction of imidazolinone-resistant (IR) corn in 1992. These hybrids were first marketed as IMI corn and rebranded as Clearfield® corn in the late 1990s. Pioneer developed an IR inbred line using plant tissue culture techniques. Because transformation from another species was not required, the IR trait was considered non-GMO. Pioneer® brand corn hybrids with the LibertyLink herbicide tolerance trait were introduced in the late 1990s. For the 2003 planting season, Pioneer introduced corn seed products containing the RoundUp Ready herbicide tolerance trait.

Farmers around the world recognized the value of biotechnology and adopted products resulting from their use at an amazing pace. Major benefits to planting corn hybrids containing plant-incorporated insect protectants and herbicide tolerance included increased yield, improved harvestability, and reduced risk. By 2005, biotech seeds had been planted on more than one billion acres. By 2010, 86% of U.S. farmers were planting corn hybrids containing traits developed with genetic engineering. A major development occurred with the introduction of the Optimum® AcreMax® (OAM) family of insect protection traits in 2011. These products from Pioneer offered growers additional choices to help reduce refuge, maximize yields and preserve valuable Bt technology. OAM products were the industry's first corn products with a single-bag integrated refuge.

R&D EXPANSION IN THE BIOTECHNOLOGY ERA

The development and introduction of biotech crops required new ways of breeding, producing seed, and doing business. This included expansion of winter production, trait integration capabilities, breeding stations, and the number of employees; addition of advanced genotyping facilities, phenotyping capabilities, and field-testing methods; expansion of the regulatory group; improvements to seed handling and quality assessment; and providing farmers with information and digital tools for improving their operations.

The need to rapidly introduce biotech traits to farmers required a significant investment in winter seed production in both research and development and seed production, with major expansions and new locations in Hawaii, Puerto Rico, and Chile. To enhance the development of base genetics, new breeding stations were opened in Champaign, Illinois; LaSalle, Colorado; and Brookings, South Dakota. The site at LaSalle was equipped with highly controlled and sophisticated irrigation capabilities, including drip technology that allowed researchers to better focus on drought evaluation efforts. In 2006, Pioneer announced an expansion of R&D efforts at 67 of its 92 research centers worldwide. This was followed by the addition of more than 400 employees in 2007.

A three-year investment beginning in 2004 allowed Pioneer to speed up the development and dramatically grow the supply of products with triple stacks of corn rootworm protection, corn borer protection, and herbicide tolerance. The Accelerated Trait Integration process developed by Pioneer researchers facilitated the combination of base genetics with key traits one to two years sooner than previous methods. The heart of the Accelerated Trait Integration process was making the inbred conversions earlier in the development pipeline to allow advanced research testing to be conducted on the desired stacked combinations for all pre-commercial hybrids in the pipeline. This required aggressively integrating technology traits early in the development process, increasing the number of growing cycles per year by using numerous tropical and temperate locations throughout the world, and use of molecular markers to ensure optimal conversions were obtained.

LEADERSHIP IN PRECISION AGRICULTURE

The initial commercialization of biotech seed occurred simultaneously with the advent of precision farming technologies. Differential GPS systems from the U.S. Coast Guard and Federal Aviation Administration, as well as similar agencies in other countries began to broadcast local GPS corrections in the 1990s, which provided farmers and agricultural retailers with geospatial information they could use to more precisely apply and track crop management products and crop yields. Pioneer was an early leader in helping farmers get the most value out of these new technologies. A Precision Farming group was established in the late 1990s and began work on combine yield monitor accuracy and how to best use variable rate planting systems. The group also worked directly with Pioneer sales representatives who offered their customers precision farming services.

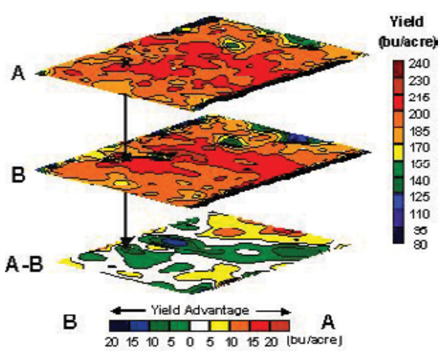

Figure 12. Diagram of GIS layers used to create a yield difference map for a Pioneer split-planter trial, 1996.

Beginning in 1996, Pioneer leveraged precision farming technologies to develop and introduce the split-planter method of evaluating farming inputs and practices. It was a simple, low-cost technique that simply required placing a different product in each half of the planter. The split-planter method has been used to compare hybrids, tillage treatments, pesticide selections, nutrient applications, or any pair of agronomic treatments. Combine yield monitors and geographical information systems were used to create a yield difference map from the two treatments.

INTRODUCTION OF THE PROBOX SEED HANDLING SYSTEM

Pioneer continued as an industry leader in seed handling, production, and quality assurance throughout the biotech era. The PROBOX bulk seed handling system was introduced exclusively to Pioneer customers in 1998 and made available to the rest of the seed industry in 1999. Made of rigid, injection-molded plastic, these rectangular containers hold 2,500 pounds or 50 "traditional bag" equivalents of seed and could be moved and unloaded using a heavy-duty forklift or a forklift attachment for a tractor. They stacked easily and unloading seed was made simple with a center drain hopper.

Figure 13. Pioneer introduced the PROBOX bulk seed handling system in 1998.

CONTINUED FOCUS ON SEED QUALITY

For many decades, Pioneer has tested its seed for germination, vigor, genetic purity, trait purity, size and plantability to ensure its customers have high-quality seed. These efforts were enhanced with the introduction of new technologies and expansion of the Beal Seed Quality Lab in Johnston, Iowa in 1997 and the seed quality lab in Tipton, Indiana in 2007. Both expansions allowed more than 125,000 tests to be conducted annually, making them among the world's largest seed labs.

The Pioneer Stress Test (PST), a proprietary vigor test used on all Pioneer brand corn products, was developed in the early 2000s to ensure growers get the highest quality seed for planting. This test imposes extreme imbibitional chilling and anaerobic stresses, beyond that of the industry-standard saturated cold test. Over many years of use, it has proven to be more predictive of hybrid performance under extreme cold stress and to provide better differentiation among genetics and seed lots. The Pioneer Stress Test allows for optimal separation between high and low quality. It can detect small differences in vigor that may indicate a seed lot that needs to be discarded. Its use has provided customers with confidence that every batch of seed the plant meets Pioneer's industry leading seed quality standards.

MOLECULAR TECHNOLOGIES REVOLUTIONIZE PLANT BREEDING

While much of the public focus on biotech has been on transgenic crops, other molecular technologies have resulted in substantial advances in plant breeding and seed product development in recent decades. Foremost among them are the use of molecular markers, doubled haploid techniques, and managed environments. DNA markers, also known as molecular markers, have been used by Pioneer since the 1980s for improving disease resistance, genotype identification, purity assessment, and to protect intellectual property within its proprietary germplasm. A genomics program using molecular markers was started in 1996. Pioneer began using genomic selection in the early 2000s to breed for quantitative traits affected by many genes, such as yield and drought tolerance.

Before the use of genomic selection, breeders were limited to using visual observations and yield data to evaluate varieties and make selections. With genomic selection, genetic markers spread across the genome, pedigree information, and phenotypic data have been integrated to predict performance of experimental lines before they are field tested. With genomic selection, Pioneer scientists have been able to understand the genetic basis for what they are seeing and use this knowledge to design and select better inbreds and combine them to produce superior hybrids. Pioneer Optimum® AQUAmax® corn hybrids were the first seed product concept delivered using DNA markers covering the entire corn genome to improve quantitative traits, in this case increased drought tolerance.

BREEDING INNOVATIONS LEVERAGED A BROAD AND DEEP GERMPLASM LIBRARY

The innovations introduced through genomic selection were built upon the most diverse and well-characterized germplasm library in the industry. The breadth and depth of its germplasm has remained a key differentiator for Pioneer for a century. Pioneer can trace each of its corn products to its first inbred development program that began in 1920. Over the years its germplasm library has grown to be one of the industry's largest and most robust, giving our breeders a considerable advantage to create new hybrids that meet local needs. All hybrids sold in Pioneer brand bags continue to be genetically different from those of other corn seed brands. With the expansion of experimental lines created by Pioneer corn researchers and high standards of performance, less than 0.01% of hybrids tested now make it into a Pioneer bag.

The breadth and depth of its germplasm has remained a key differentiator for Pioneer for a century.

In 2017, an analysis of 30 years of Pioneer trials showed that not only had breeding and technology traits increased corn yield but had also significantly improved yield stability. For the first 80 years of hybrid corn, yield gains came mainly from increased stress tolerance that allowed more plants to be grown per acre. Ear size and kernel size remained relatively unchanged. More recently, studies have indicated that the yield per plant is now increasing. With modern hybrids, planting more plants per acre continues to propel yield, but there is also stability that old hybrids did not possess. Over the duration of the study, average corn yield over all locations at the agronomic optimum plant density increased from 135 bu/acre in 1987 to 188 bu/acre in 2015, representing an overall yield gain of 53 bu/acre. With new genetic technologies, breeders found a level and class of genetic response that was previously hidden.

OWNERSHIP CHANGES

The early 2010s brought another round of sweeping changes to the agricultural industry. In December 2015, it was announced that DuPont and Dow would merge. This merger was driven in part by conditions within the agriculture economy. Low corn and soybean prices, and high costs for land, equipment, fertilizer and other chemicals had driven down farming income for consecutive years. Commodity prices during this period had been putting immense pressure on the revenues and earnings for the major publicly traded agriculture input providers. Within a couple years of the announced merger of DuPont and Dow, Syngenta was purchased by ChemChina and Monsanto was acquired by Bayer.

The DowDuPont merger closed in 2017. In February 2018, the intended agriculture company was announced as Corteva Agriscience, which became a standalone publicly traded company in June 2019. Pioneer became the flagship seed brand of Corteva Agriscience, providing high-quality seeds to farmers in more than 90 countries. Further changes came in October of 2025, when it was announced that the seed and crop protection businesses of Corteva Agriscience would split into separate companies, with the crop protection business retaining the Corteva name and seed business to operate under a new name.

LOOKING TO THE FUTURE

The future of plant breeding promises advancements through genetic tools, precision breeding techniques, and climate-resilient crops to address global food security. Key genomic resources include genetic markers, reference genomes, databases, transcriptomes, and gene expression profiles. These tools are crucial for identifying genes linked to desirable traits, understanding genetic diversity, and accelerating breeding programs. Molecular markers and advanced analytics will continue to enhance traditional breeding by enabling the selection of disease-resistant, drought-tolerant, and high-yield plants, leading to faster and more precise crop development.

Recently developed genome editing processes have enabled precise alteration of crop traits, accelerating breeding processes. CRISPR, a method of gene editing based on natural defense mechanisms bacteria use to protect themselves from virus invasion, stands out for its affordability, simplicity, efficiency, and versatility. Pioneer was an early adopter of CRISPR technology, signing licensing and research collaboration agreements in 2015 with the key academic organizations that discovered that CRISPR could be used to precisely edit targeted sections of an organism's DNA to achieve a specific outcome. CRISPR is now being used to make changes within a plant's own genome that otherwise requires time-consuming and costly field breeding approaches. It has immense potential for creating crops with reduced susceptibility to diseases and pests, increased environmental resilience, and improved nutritional content and other end-use properties.

THE SECOND CENTURY OF PIONEER

Pioneer has a storied history as the seed industry leader for agronomy research, knowledge, and expertise. This reputation was built over decades through talented and dedicated people, sound crop management research, and timely and accurate crop management information. These investments will allow Pioneer to continue offering growers better products year after year, decade after decade. Pioneer brand products, coupled with industry-leading agronomic support and local sales experts, will continue to deliver strong performance to farmers for years to come.

A Century of Progress in Corn Production

LANCE GIBSON, PH.D., AGRONOMY TRAINING MANAGER
MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- In the early 20th Century, the two-row riding corn planter pulled behind a horse was the most common method for planting corn.
- Harvesting corn was mostly done by hand up through the 1930s. Mechanical corn pickers did not become common on farms until after WWII.
- The reduction in horses as farms switched to tractor power after WWII started a shift to soybean as the primary crop grown in rotation with corn and away from oats and clovers.
- Equipment for applying anhydrous ammonia as a nitrogen fertilizer was introduced in the 1930s and became widely used for corn production in the late 1950s.
- Growing awareness of the soil erosion caused by intensive tillage led to the adoption of conservation tillage methods beginning in the 1970s and accelerating in the 1980s and 1990s.
- The adoption of genetically engineered corn expressing insecticidal proteins from *Bacillus thuringiensis* (Bt) revolutionized pest management in the 1990s and 2000s.

MILESTONES IN CORN PRODUCTION HISTORY

The commercialization of hybrid corn a century ago kicked off a revolution in corn production that has driven continuously increasing yields up to the present day (Figure 1). During that time, corn production technology evolved alongside corn genetics, from a mix of hand labor and horse-drawn equipment in the 1920s to the large, efficient, GPS-guided machines of today. Many innovations in corn production technology have helped drive higher yields. Others have come about *because* of higher yields, and the need to efficiently handle an ever-increasing amount of corn produced on each acre of land. Challenges to corn production – such as diseases and insect pests – have evolved as well, necessitating continual innovations in crop protection. This article provides an overview of some of the major milestones in corn production technology over the century-long history of the hybrid corn era.

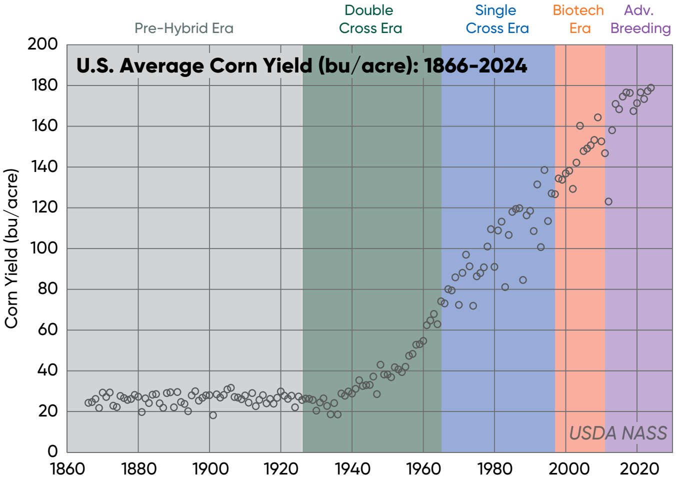

Figure 1. U.S. average corn yields across different eras of corn breeding technology: Pre-Hybrid Era: before 1926, Double-Cross Hybrid Era: 1926-1965, Single-Cross Hybrid Era: 1966-1995, Biotechnology Era: 1996-2010, and Advanced Breeding Technologies Era: 2011-present.

PRE-HYBRID ERA 1900–1920s

In the early 20th Century, the two-row riding corn planter pulled behind a horse was the most common method for planting corn (Figure 2). These planters placed three to four corn seeds together in the soil with the assistance of a check wire. The check wire had regularly placed knots that tripped a mechanism on the planter box to drop the seed. The typical distance between hills and each row was forty-two inches. Being just wider than a horse's body, this spacing, done in a checkerboard fashion, allowed for inter-row cultivation in any direction to control weeds without damaging the corn plants.

Figure 2. A horse-drawn planter typical of what was used for planting corn at the dawn of the hybrid era.

Soil preparation in the 1910s was done with steel plows and harrows pulled by horses with a driver sitting in the middle of the implement. Crop fertility was provided by what was available from nutrient mineralization in the soil and animal manure. The mechanical, horse-drawn, wheel-powered manure spreader became a standard farm tool in the early 1900s.

In the 1920s, corn planting in the Central Corn Belt started in the middle of May and was completed by mid-June. Waiting to plant until the soil temperature was 60°F was required to minimize losses from seed and seedling decay and to help the crop compete with weeds. Harvest in the Corn Belt began in the last half of October with the goal of completing by Thanksgiving. Average U.S. corn yields remained relatively unchanged from 1866 to 1916 at around 26 bu/acre.

Most corn was hand harvested using the hook method of corn husking. One person with a team of horses and a wagon harvested two rows at a time. The picker would "husk" the ear off each plant using a hook attached to his hand with a leather strap. The opposite side of the wagon was equipped with a "bang board" against which the picker threw the husked ear (Figure 3).

Figure 3. Hand-harvesting corn; 1939.

Although invented in 1909, corn picking machines were used only on the largest farms for many years. Use of the combustion-engine tractor was in its infancy with less than 15% of farms having them in 1926 (Figure 4).

The Haber-Bosch process for industrial production of ammonia developed in Germany was rapidly ramping up in the U.S., but its use in the production of crop fertilizers was still limited. Superphosphate, containing 16 to 20 percent P_2O_5, was the most important fertilizer material, but was used on a relatively small scale.

The most economically important diseases during this era were ear and seedling rots. The European corn borer had recently destroyed the corn crop in southern Ontario and was rapidly moving into northwest Ohio and northeast Indiana. This caused panic within the Corn Belt leading to the appropriation of significant funds from the U.S. Congress for the undertaking of a comprehensive control campaign in cooperation with state and county organizations.

Figure 4. A group of farmers taking delivery of new tractors. Lena, Illinois; 1925.

DOUBLE-CROSS HYBRID ERA (1930s–1950s)

The double cross hybrid era was a period of rapid change in corn productivity and production methods, driven in large part by the rapid switch from open pollinated varieties to hybrid corn during the 1930s. After being stagnant for more than six decades, U.S. average corn yield began a steady increase with the adoption of hybrid corn.

After being stagnant for more than six decades, U.S. average corn yield began a steady increase with the adoption of hybrid corn.

The switch to planting and cultivating corn with tractors began in the 1920s with the introduction of the Farmall tractor manufactured by International Harvester. Due to its narrow front wheel arrangement, the Farmall was the first tractor that could make the tight turns required to efficiently plant and cultivate with the two-row equipment of the day (Figure 5). However, most farmers still pulled their planters with horses into the 1940s because it was much easier to get on and off the planter at the end of each row to reset the check-row wire than to get on and off a tractor. It would be 1945 before tractor power surpassed horsepower on U.S. farms and 1954 before farms had more tractors than horses and mules.

Figure 5. Cultivating corn with a tractor; late 1930s.

As tractors became more widely used for planting, farmers switched from planting in hills using a check wire to "drilling" in rows. Spacing between rows was reduced from the 42 inches required to accommodate cultivating with horses to 36 or 38 inches. The switch from using horses to tractors for planting was accompanied by a switch to using interrow cultivators mounted on tractors for weed control. Four-row planters became more widely used in the 1950s and six-row equipment became available in 1957.

Anhydrous ammonia came into wide use as a nitrogen fertilizer in corn production in the late 1950s.

Equipment for applying anhydrous ammonia as a nitrogen fertilizer was introduced in the 1930s and became widely used for corn production in the late 1950s. Increasing use of nitrogen, phosphorus, and potassium fertilizers allowed farmers to capitalize on the higher yielding corn hybrids resulting from advancements in corn genetics through breeding.

A loss of domestic sources of fats, oils, and protein meals during World War II stimulated the creation of a soybean production and processing industry in the U.S. These developments, along with the reduction in horse numbers, started a shift to growing corn in rotation with soybean and away from rotation with oats and clovers. Soybean acreage in the United States increased significantly between 1940 and 1965, growing from approximately 6 million to 34 million acres (Figure 6). Total harvested oat acres were approximately 38.6 million in 1940 and had decreased below 18 million acres in 1965.

The use of herbicides for weed control began at the conclusion of World War II with the introduction of 2,4-D in 1945. Advances in herbicides for corn production occurred with the launch of atrazine in 1958 and dicamba in 1965. While these herbicide active ingredients improved weed management by farmers, inter-row cultivation continued to be used to complement them.

While corn rootworm damage was first noted in 1909, it began to rapidly expand as a major corn pest in the 1950s with more widespread planting of continuous corn. By 1959, control failures were reported as the insect developed resistance to the organochlorine insecticides that were commonly used at the time. Diplodia stalk and ear rot was a prevalent issue in the early 20th century. Burying crop residue through fall moldboard plowing, which became a common practice starting in the 1930s, significantly reduced its occurrence.

A major advancement in American agriculture occurred in 1940 with the invention of the center pivot irrigation system.

The use of irrigation in U.S. corn production remained relatively low up to the early 1960s at less than 2 million acres. A major advancement in American agriculture occurred in 1940 with the invention of the center pivot irrigation system.

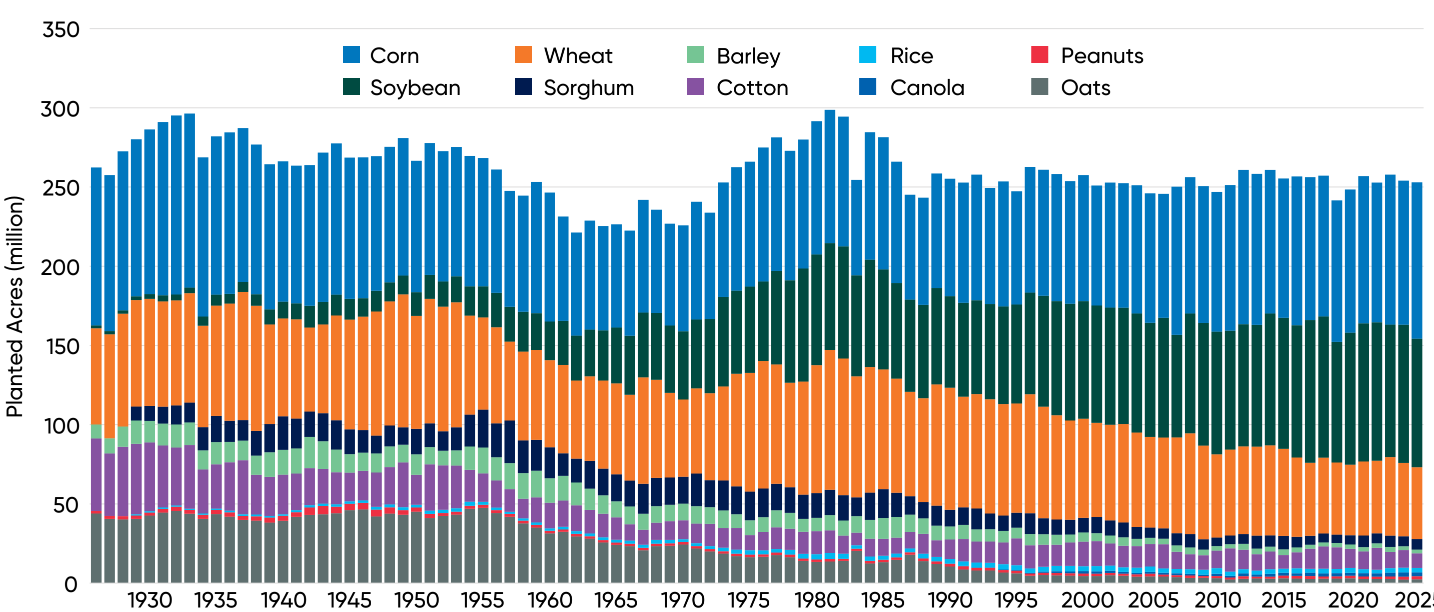

Figure 6. Total planted area of major crops in the United States; 1926-2025 (USDA-NASS).

This groundbreaking technique allowed water to be efficiently distributed across large fields through pipes on wheels that slowly move across fields in a circular pattern. Adoption of center pivot irrigation by famers was slowed significantly by problems with early designs. Design modifications through the 1940s and 1950s and new technology for drilling and pumping water from deep wells stimulated an increase of irrigated corn acres in the Plains states beginning in the mid-1960s.

The harvesting process in the 1930s still heavily relied on manual labor. The first mechanical corn picker for removing ears from corn plants was invented in 1909, but it wasn't until 1928 that the first widely successful corn picker was introduced. This mechanization of harvest greatly increased the number of acres a single operator could harvest in a day from less than one in 1928 to as many as 15 by 1960. Both pull-behind and tractor-mounted corn pickers were used, and most harvested just one or two rows at a time (Figure 7). By 1955, the USDA estimated there were 650,000 corn pickers on American farms.

Figure 7. Harvesting corn with a tractor-pulled corn picker in the 1930s.

Combine harvesters that cut and threshed the grain with the same machine were used for small grain harvest for several decades before they were adapted for corn harvesting in the 1950s. Early versions harvested two rows, expanding to four and six rows by the end of the 1960s. The introduction of on-farm systems for drying, aerating, and mixing shelled grain in the early 1960s eliminated the need for storing corn on the ear in cribs before shelling and grinding. As agricultural engineers solved the technical challenges of harvesting tough corn stalks, the adoption of the combine was rapid. By the mid-1960s, annual sales of corn heads for self-propelled combines exceeded the sales of mounted corn pickers.

> *Combine harvesters that cut and threshed grain with the same machine were used in small grains for several decades before they were adapted for corn in the 1950s.*

SINGLE CROSS HYBRID ERA (1960s–1990s)

Changes in corn production methods and productivity continued to accelerate with the introduction of single-cross corn hybrids in the late 1960s. Between the late 1960s and the late 1990s, corn yield increased by an average of 1.6 bu/acre/year. The dramatic increases in corn yield can be attributed to both genetic improvements and advancements in farming technology and management practices. Genetic advancements included the development of improved hybrids with greater yield potential and enhanced resistance to stressors like drought. Agronomic and management improvements included higher planting densities, advanced fertilization and irrigation practices, more effective weed control, and improved machinery.

More farmers began growing corn in rotation with soybeans as breeders released a larger assortment of high yielding soybean varieties. In 1966, soybeans were harvested on 37.5 million acres (a record at the time) with a yield of 25.4 bushels per acre. By 1997, the harvested acreage had nearly doubled to approximately 70 million acres. The northern Great Plains, particularly North and South Dakota, saw substantial increases in soybean acreage during the 1990s, driven by improved genetics and rising crop prices. This period also saw further decline in oat acreage, from around 18 million acres in 1966 to approximately 5 million acres in 1997.

In the 1960s, conventional tillage methods for growing corn involved intensive plowing, disking, and harrowing to prepare a smooth, firm seedbed as well as mechanical weed control (Figure 8). Growing awareness of the soil erosion caused by intensive tillage led to the adoption of conservation tillage methods beginning in the 1970s and accelerating in the 1980s and 1990s. This shift was also driven by advancements in equipment technology, the development of corn hybrids with greater resilience to cold, damp seed beds, and greater use of chemicals for weed, insect, and disease control. U.S. farm policy during the 1980s and 90s encouraged the use of conservation practices, especially on highly erodible land. Conservation tillage techniques included reduced tillage, no-till, ridge tillage, and mulch-till, all of which aimed to leave more crop residue on the soil surface to protect it from erosion.

Corn planters saw significant advancements in size, efficiency, and technology during the single cross hybrid era (Figure 9). The late 1960s marked a move away from seed plates, with John Deere introducing the 1200 and 1300 series of plateless planters in 1968, and Allis-Chalmers producing the first commercially successful no-till planter system in 1966. The 1970s brought air-powered metering systems, such as International Harvester's Cyclo Air

Figure 8. The 1970s and 1980s saw a shift away from intensive tillage using implements such as the moldboard plow shown here and greater adoption of reduced tillage and no-till.

planter in 1971, and larger, more precise planters like John Deere's 7000 and 7100 MaxEmerge models introduced in 1975. Kinze also introduced the first rear-folding planter toolbar in 1975, making larger planters easier to transport between fields. The 1980s and 1990s continued this trend with planters growing to 16 and 24 rows, and manufacturers focusing on improving seed placement accuracy. By the 1990s, most corn growers were planting corn in 30-inch row spacing. The number of seeds planted per acre in the U.S. Corn Belt saw a steady increase from around 20,000 seeds/acre in the late 1960s to around 30,000 seeds/acre in the late 1990s.

Farm tractors underwent significant improvements in power, comfort, safety, and efficiency during the single cross hybrid era. Power output increased substantially, with larger four-wheel-drive and articulating tractors becoming more common to handle larger implements. While late 1960s models often had less than 100 horsepower, by the mid-90s, some tractors were exceeding 400 horsepower. Although introduced earlier, front-wheel assist technology became more widespread in the 1980s, offering improved traction and power delivery for heavy tillage work (Figure 10).

Figure 9. During the single cross hybrid era, corn planters increased considerably in size, efficiency, and accuracy.

Figure 10. Tractors with front wheel assist became widely available during the 1980s.

The 1960s and 1970s experienced a dramatic expansion in fertilizer use, driven by new hybrids and low nitrogen costs. However, fertilizer use peaked in 1981 and then moderated, with improved efficiency and genetic advancements allowing for higher yields without increased nitrogen. Environmental concerns about nutrient loss and pollution led to early efforts to recommend lower nitrogen rates and explore new management practices. Technological and regulatory milestones, such as the introduction of nitrogen stabilizers and advanced application equipment, further influenced fertilization practices during this period. A key development was the discovery of the nitrification-inhibiting nitrapyrin in the late 1950s by Dow Chemical Company scientists. This led to the commercial introduction of the N-Serve stabilizer in 1976.

The amount of irrigated U.S. land dedicated to corn cultivation increased substantially during this era, growing from less than 2 million acres in 1966 to more than 10 million acres, accounting for 15% of total corn acres, by 1997. Irrigated corn production in the United States shifted from primarily relying on flood-based systems to a much wider adoption of more efficient technologies, particularly center-pivot irrigation. This expansion occurred alongside a broader move eastward in irrigated agriculture, allowing farmers in the traditionally drier Great Plains and newer areas to achieve more consistent and higher yields.

A major shock occurred in the early 1970s, when a widespread outbreak of southern corn leaf blight (SCLB) resulted in significant yield losses. Advances in genetics led to the creation of cytoplasmic-sterile breeding lines and fertility-restoration genes, eliminating the need for manual detasseling of corn plants to produce hybrid seeds. However, the shift to uniform hybrid corn varieties increased genetic vulnerability to widespread epidemics. The introduction of Texas male-sterile cytoplasm (cms-T) in the 1950s, which was widely adopted by the late 1960s, made the corn crop highly susceptible to a new virulent race of the SCLB fungus. This led to a devastating epidemic in 1970, causing significant yield losses. The epidemic was one of the costliest agricultural issues in North American history, destroying 15% of the U.S. corn crop and causing an estimated $1 billion in losses. In response, seed companies returned to manual detasseling for corn seed production.

The southern corn leaf blight outbreak of 1970 destroyed around 15% of the U.S. corn crop, causing over $1 billion in losses.

Western corn rootworm (WCR), maize dwarf mosaic virus (MDMV), and gray leaf spot (GLS) emerged or became more prevalent during the single hybrid era, further challenging corn production. The range of WCR underwent a major expansion and developed new adaptations. After causing damage in Nebraska in

Figure 11. International Harvester axial-flow rotary combine introduced in the late 1970s.

the 1940s, the pest expanded eastward, reaching Indiana by the 1970s and the east coast by the 1990s. During the 1990s, a new WCR variant capable of laying eggs in soybean fields and infesting rotated corn emerged in Illinois and Indiana. MDMV, an aphid-transmitted virus first identified in Ohio in 1962, caused significant yield losses in several corn-producing states, but became less of an issue with the introduction of resistant hybrids in the 1970s. GLS became more widespread with the increased use of reduced-tillage and no-till practices. Major outbreaks in the mid-1990s led to the development of hybrids with greater GLS resistance.

Corn harvest during this period was marked by increased machine size, performance, and automation, greatly enhancing harvest efficiency. The 1970s brought the rotary combine (Figure 11), with International Harvester and New Holland leading innovations. The 1980s saw significant improvements in automation and operator comfort. By the 1990s, early precision agriculture technologies like GPS and yield monitoring began to emerge. A 1960s-era corn picker attached to a tractor could harvest about five acres per day, while combines sold in the 1990s could harvest up to 70 acres per day.

Development of auger-unloading, two-wheel grain carts by several shortline manufacturers led to expanded use of on-the-go grain unloading from combines (Figure 10). These carts proved much more maneuverable and efficient than the more cumbersome four-wheel grain wagons, which were typically parked at the field margins to receive grain from the combine. The use of grain carts to shuttle corn from running combines to larger semi-trucks positioned near field entrances began to surpass the use of grain wagons in the late 1990s and greatly increased the speed and efficiency of harvest operations.

Figure 12. Two-wheeled grain carts with unload augers were an important innovation that increased the speed and efficiency of harvesting higher-yielding corn.

BIOTECHNOLOGY ERA (LATE 1990s–2000s)

The biotechnology era of corn production began with the introduction of insect-resistant Bt hybrids in 1996. A combination of yield protection from biotech traits and genetic gain through breeding increased the average rate of corn yield gain for this period to 2.3 bu/acre/year. During the biotechnology era, there was a significant shift towards conservation tillage techniques, particularly no-till farming, which coincided with the widespread adoption of herbicide-tolerant (HT) corn. This shift led to increased yields, improved soil health, reduced erosion, and lower costs. The adoption of no-till farming grew rapidly, while mulch-till and reduced tillage methods also became more prominent.

The adoption of genetically engineered (GE) corn expressing insecticidal proteins from *Bacillus thuringiensis* (Bt) revolutionized pest management for corn. Bt corn was planted on 19% of U.S. corn acres by 2000 and increased to approximately 63% by 2010. This technology significantly reduced the need for broad-spectrum insecticide applications, as Bt corn effectively controlled lepidopteran pests like ECB. The introduction of corn insect protection traits for corn rootworm began in the early 2000s, marking a significant shift toward biotechnology as a management tool against this devastating pest. This provided growers with a powerful, in-plant defense that reduced reliance on soil-applied insecticides, leading to improved root health, reduced crop lodging, and increased yield potential.

> *Bt corn – introduced in 1996 – was planted on 19% of U.S. corn acres by 2000 and increased to approximately 63% by 2010.*

Corn planter technology also continued to evolve during this era from mechanical systems to sophisticated, electronically controlled equipment capable of precision planting. GPS guidance systems transformed planting practices, reducing operator fatigue and enabling extended work hours. Variable-rate technology allowed farmers to adjust seeding rates based on field conditions, while improved seed metering and placement technologies, such as vacuum meters and advanced monitoring systems, ensured accurate seed placement. Additionally, advancements in downforce technology and bulk seed handling systems further optimized planting efficiency and consistency.

The use of seed treatment expanded dramatically in the early 2000s, particularly with the widespread adoption of neonicotinoid insecticides and advanced fungicides. This was driven by a combination of factors, including increased corn market prices, a shift toward conservation tillage practices that left more crop residue harboring pathogens, and earlier planting in colder, wetter soils. Seed treatments offered protection against early-season insect pests like wireworms and seedling diseases such as *Pythium* and *Fusarium*, which could threaten stand establishment and vigor.

By the early 2000s, precision agriculture technologies became mainstream, integrating new technologies with traditional practices to enable site-specific, data-driven decisions. The adoption of GPS guidance, real-time yield monitoring, and on-board data processing transformed how farmers managed their crops. Yield monitors on combines, which tracked harvested crop volume, became standard, generating yield maps that helped farmers identify and address low-performing field areas (Figure 13). Precision farming tools improved nutrient use efficiency by allowing more targeted fertilizer applications.

Figure 13. Yield monitors were introduced in the 1990s and became standard equipment in the 2000s.

ADVANCED BREEDING TECHNOLOGIES ERA (2010s–PRESENT)

While much of the public focus on biotechnology has been on transgenic crops, other molecular technologies have contributed to substantial advances in plant breeding and seed product development in recent decades. Foremost among them have been the use of molecular markers and doubled haploid techniques. The corn seed products resulting from these technologies became widely available to farmers in the second decade of the 21st century (Figure 14).

Field preparation for corn production has continued to evolve towards more sustainable and data-driven practices since 2011. Significant growth in no-till and reduced tillage practices led to conservation tillage reaching 76% of all U.S. corn acres by 2021. Strip-tillage became more common, offering comparable yields to intensive tillage but at lower costs. The use of cover crops significantly increased, driven by environmental conservation efforts and government incentives.

Corn planter technology has continued to evolve during this era, transitioning from mechanical controls to fully integrated, data-driven systems focused on precision, high-speed planting, and automation. Key advancements included electric drive seed meters, high-speed seed delivery systems, and active downforce control. Additionally, in-cab displays and real-time sensing technologies provided operators with detailed metrics and high-definition maps, enabling instant diagnostics and adjustments.

Figure 14. Optimum® AQUAmax™ corn hybrids were the first seed product concept delivered using DNA markers covering the entire corn genome to improve quantitative traits.

Optical spray technology came on the scene in the 2010s. Initially focused on "green-on-brown" systems for fallow ground, it advanced to "green-on-green" systems capable of operating within crops. This evolution was driven by advancements in machine learning and camera technology, enabling greater accuracy and efficiency. Early systems like WEED-IT and WeedSeeker used simple optical sensors to detect chlorophyll and trigger specific nozzles. By 2017, technologies like Blue River Technology's "See & Spray" used AI and machine learning for more precise weed targeting.

Corn disease management has seen significant advancements since 2011 due to the emergence of new diseases like tar spot and bacterial leaf streak, as well as the re-emergence of diseases such as southern rust, fungal stalk and ear rots, and corn stunt. Key strategies included the development of hybrids with improved resistance, the identification of specific resistance genes, and the use of advanced breeding tools like genome-wide association studies. Fungicide applications have become more common, with newer fungicide products containing multiple modes of action to combat resistance.

SECOND CENTURY OF HYBRID CORN (2026–)

Continued advancements in agricultural technology and breeding are expected to boost corn yields even further over the coming decade. Opportunities in corn product development include using gene editing to speed up as well as to reduce the cost of the breeding process, stacking genes for resistance to the major corn diseases, novel modes of action for insect resistance, and creation of short-statured hybrids that can withstand extreme weather events. New knowledge of the corn genome and physiological processes will be used to improve yield potential, agronomic traits, and end-use qualities. Protecting the corn crop from diseases and pests as well as stimulating crop growth will continue to shift from chemical to biological solutions, whether incorporated directly into corn hybrids or applied to the soil, seed, or plants.

Innovations in corn production technology will center on precision agriculture, leveraging AI, robotics, internet of things (IoT) sensors, drones, and artificial intelligence to optimize every aspect of production from planting through harvest, storage, and delivery to the end user. Greater automation will result in autonomous harvesters and tractors, enhanced real-time data from integrated sensors and satellite imagery, and data-driven decisions powered by machine learning for predictive pest control and resource management. This shift will be used to increase yields, reduce waste, and improve sustainability in corn production, making production more efficient, profitable, and environmentally friendly. Most farms will continue to be under family ownership, but they will increasingly require a team of employees with expertise in business management, agronomy, technology, logistics, and marketing.

New Opportunities with Winter Canola

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KEY POINTS

- In 2023, Corteva Agriscience, Bunge, and Chevron U.S.A. announced a commercial collaboration to introduce proprietary winter canola hybrids that produce plant-based oil with a lower carbon profile.
- Farmers in the Southern U.S. have the opportunity to increase revenue by introducing winter canola into their cropping systems.
- Winter canola can be planted on acres that would have otherwise been left fallow over the winter, in rotation with wheat or other winter crops every two to three years.
- Planting is the most critical management stage for establishing a high-yielding winter canola crop.
- Winter canola requires an extended period of cold temperatures to induce flowering the following spring: a process called vernalization.
- Key management practices for winter canola during the spring are nitrogen and fungicide applications.

A NEW REVENUE OPPORTUNITY

As agricultural markets face growing complexity and uncertainty, farmers have a new opportunity to secure contracts through an innovative partnership. In 2023, Corteva Agriscience, Bunge, and Chevron U.S.A. announced a commercial collaboration to introduce proprietary winter canola hybrids that produce plant-based oil with a lower carbon profile. The goal of this collaboration is to increase the availability of vegetable oil feedstocks for the growing renewable fuels market. Demand for biofuels in North America and Europe is expected to reach 22 billion gallons by 2040. The companies introduced the winter canola crop into the Southern U.S. with an intention to create a new revenue opportunity for farmers to meet this growing demand.

Figure 1. More than 2.7 million acres of canola are currently grown in the United States.

This "field to fuel" partnership secures a market for farmers who plant Pioneer canola seed. Bunge agrees to buy the harvested seed and process the oil. Chevron obtains the oil for processing into renewable fuels. Farmers know they have a secure market for their crop before it is even planted, and it's grown as a winter rotation crop on ground that might have otherwise been fallow, creating an additional source of income. The program launched in 2023 with a pilot of 5,000 acres. In the second year, the program expanded to 35,000 acres, and in 2025 approximately 115,000 acres were contracted.

There are several benefits that make growing winter canola hybrids a wise choice, from its high yield potential to enhanced reliability across farming environments to help better manage financial risks. It can be used as a feedstock to produce renewable diesel, biodiesel, and sustainable aviation fuel as replacements for petroleum-based chemicals. By pairing unique genetics with recommended agronomic practices, this crop can achieve lower carbon intensity levels while bringing opportunities to adopt sustainable practices and benefit the entire cropping system. And because it is incorporated into the crop rotation as part of a double cropping system, it doesn't take acres away from food production.

"There hasn't been a new cropping system in the United States in quite some time to this size and degree… it would maybe be soybeans back in the 70s…otherwise I can't think of one."— Chad Berghoefer, Global Product Director for Biofuels

INTRODUCTION TO WINTER CANOLA

Canola is in the Brassicaceae plant family, closely related to mustard and cabbage. Canadian plant breeders developed canola in the 1960s and 1970s from rapeseed plants to eliminate undesirable components and improve the oil profile. Canola contains about 45% oil, which is more than corn (~4%) or soybean (~19%).

More than 2.7 million acres of canola are currently grown in the U.S., primarily in the Northern Plains, Pacific Northwest, and Southern Great Plains. There are two types of canola: spring and winter, named as such for when they are planted. Spring canola is planted in early spring (March) and harvested around September. This type accounts for the majority of U.S. canola production. Winter canola is planted in the fall (September), overwinters, and is harvested in June. Under ideal conditions, winter canola can yield 20-30% more than spring canola. It is grown in warmer areas like the Southern Great Plains. In the Pacific Northwest, both spring and winter types of canola are grown. In the Northern Plains, spring canola is typically grown, while in the Southern Plains, the winter type is more common.

Under ideal conditions, winter canola can yield 20-30% more than spring canola.

ADDING WINTER CANOLA TO CROPPING SYSTEMS

Winter and spring canola are similar in terms of their biological makeup, although winter canola has better tolerance to cold and freezing. Winter canola can be planted on acres that would have otherwise been left fallow over the winter. It can be used in rotation with wheat or other double cropping systems every two to three years. Winter canola should not entirely replace winter wheat in a double-cropping system. It is best implemented in rotation with winter wheat, as allowing two to three years between canola plantings in a field helps prevent the buildup of canola disease pathogens.

Canola has two main advantages in double cropping systems compared to wheat. Canola generally matures earlier than wheat, which can allow earlier planting of the spring crop. Canola also leaves less residue in the field than wheat, which makes no-till planting of the summer crop easier.

Fueling Growth in Winter Canola
- Agriscience Explained Podcast

Winter canola also has some considerations compared to winter wheat, both in terms of suitable environments for production and management practices. Winter canola is slightly more sensitive to low soil pH; significant yield losses for canola can be seen below a pH of 5.7, whereas for wheat, the significant impact occurs below 5.5. Canola is less tolerant of water-logged soil and won't grow well on land with poor drainage or prone to flooding. The growing point of the canola plant is above ground, making the plant more susceptible to physical damage, environmental conditions (such as early season freezes), and leaf-eating insects during early growth and development.

In terms of management practices, canola has slightly greater demands for nitrogen and sulfur than wheat. It is also sensitive to herbicides typically used in wheat production, so any sprayers used in wheat must be thoroughly cleaned and rinsed.

Figure 2. For winter canola, the ideal seedbed is firm, moist, and granular, allowing for good seed-to-soil contact.

AGRONOMIC MANAGEMENT

PLANTING

Planting is the most critical management stage for establishing a high-yielding winter canola crop. Winter canola is susceptible to poor stand establishment if good seed-to-soil contact is not achieved. For winter canola, the ideal seedbed is firm, moist, and granular, allowing for good seed-to-soil contact at a depth of ½ to 1 inch, preventing crusting and ensuring emergence. Winter canola prefers well-drained soils vs. soil types that can crust, flood, or are prone to stay saturated.

Because of the importance of good seed-to-soil contact, conventional tilled ground is preferrable over no-till. Soil should be firm and finely tilled. A moderate amount of crop residue on the soil surface is desirable to help reduce soil erosion, but it is important to ensure residue does not interfere with seed-to-soil contact. Tillage also helps to ensure a clean, weed-free field for planting. In some instances, a preemergence herbicide is recommended to control grasses including volunteer corn.

Seed is typically treated with insecticide to protect plants from pests such as crucifer flea beetle (*Phyllotreta cruciferae*), striped flea beetle (*Phyllotreta striolata*), and cutworms. Insecticide seed treatments such as Lumiderm® offer up to 35 days of protection for critical stages of seedling growth.

Planting dates are important for establishing a successful winter canola crop. Late planting can result in small plants with inadequate reserves to maximize winter survival. Planting too early can also impact winter survival, as excessive fall growth may elevate the growing point of the plants too far above the soil surface, increasing the chance of winterkill. Optimal planting windows differ by geography (Figure 3).

Figure 3. Recommended planting windows for winter canola.

Planting in the early part of the range for a region can result in an approximately 10 bu/acre increase in yield (Figure 4). In a Corteva Agriscience field study conducted across 10 Mid-South and Southern locations, yield loss per day of delay after September 15th was 0.6 bu/day (Figure 4). Seeding rate has a lower impact on yield, but higher seeding rates yielded approximately 2-3 bu/acre more than lower rates. Seeding rate should target a plant stand of 6-7 plants/sq. ft. The number of seed in lbs/acre needed to achieve this stand will depend on seed size (Table 1).

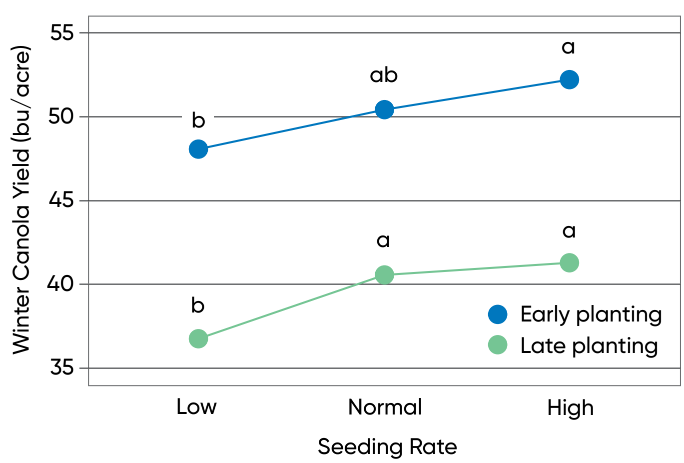


Figure 4. Effect of planting date and seeding rate on winter canola yield from small plot experiments at 10 locations in Arkansas, Illinois, Missouri, Mississippi, and Tenessee. Seeding rates were: Low = 3plts/sq ft, Normal = 7plts/sq ft, High = 11 plts/sq ft. Planting dates were: Early ~September 15th, Late ~October 12th.

Table 1. Recommended canola seeding rates based on row spacing and seed size.

Seeds/Pound	Row Spacing (inches)		
	7.5 - 15	20	30
	Seeding Rate (lbs/acre)		
70,000 - 80,000	4.2	2.7	2.4
80,000 - 90,000	3.3	2.4	2.1
90,000 - 100,000	3.0	2.1	1.8
100,000 - 110,000	2.7	1.9	1.6
110,000 - 120,000	2.5	1.7	1.5

Winter canola will sprout in about 5-7 days under the right conditions and requires around 600 GDUs to reach between 5-8 leaves with a stem diameter of ¼-1/2 inch, a height of 6-12 inches, and an extensive root system, all of which are ideal for overwintering. The crown should be close to the ground to decrease winter damage. In the rosette stage, the stem thickens and produces smaller leaf cells with a high concentration of soluble substances that increase freeze tolerance. Overwintering is a critical stage for winter canola because it requires an extended period of cold temperatures to induce flowering the following spring. This process is called vernalization.

Overwintering is a critical stage for winter canola because it requires an extended period of cold temperatures to induce flowering the following spring.

VERNALIZATION

Vernalization requires exposure to temperatures between 32°-50°F for a duration of 4-10 weeks. Successful vernalization will help ensure timely flowering and optimal yield, while incomplete vernalization can result in delayed flowering and reduced seed set. Leaves often discolor, turn purple and die in the winter (Figure 5). Much of the leaf tissue freezes and dies but, as long as the crown does not die, the plants will survive. Winter canola can withstand temperatures as low as -5°F degrees for 3-5 days, or longer with snow cover (Figure 6). Growth resumes in early spring with new leaves appearing from the plant crown. A cluster of flower buds will become visible at the center of the rosette and rise as the stem rapidly bolts.

Figure 5. Canola leaves often discolor, turn purple and die during the winter.

Figure 6. A field planted to winter canola on January 16 (top) following 7 inches of snowfall, and the same field on January 29 (above).

SPRING MANAGEMENT

In early spring, the winter canola restarts growth. Key management practices during the spring are nitrogen and fungicide applications (Figure 8). Total nitrogen application of 120-160 lbs/acre as a split application was found to promote yield and lower the nitrogen input by approximately 50 lbs (Figure 7). The first application can be done in late winter while plants are still dormant. The application can include sulfur (15 lbs/acre) and boron (1 lb/acre). Plants will start to grow when the temperature reaches 40°F. The second

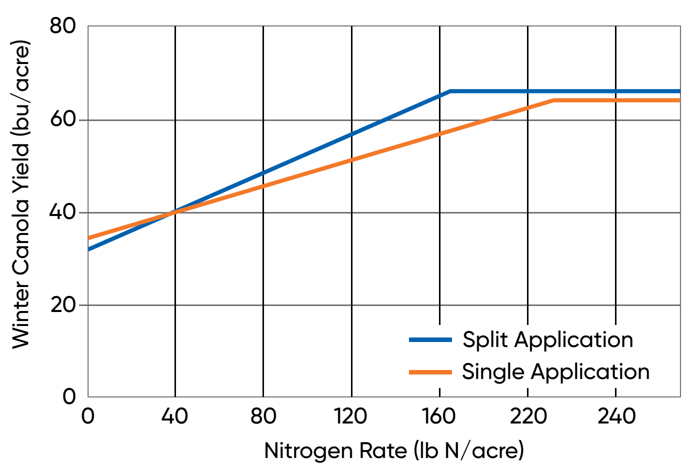


Figure 7. Effect of single and split nitrogen application on winter canola yield at small plot experiments in 10 locations in Alabama, Arkansas, Illinois, Mississippi, Missouri, and Tennessee.

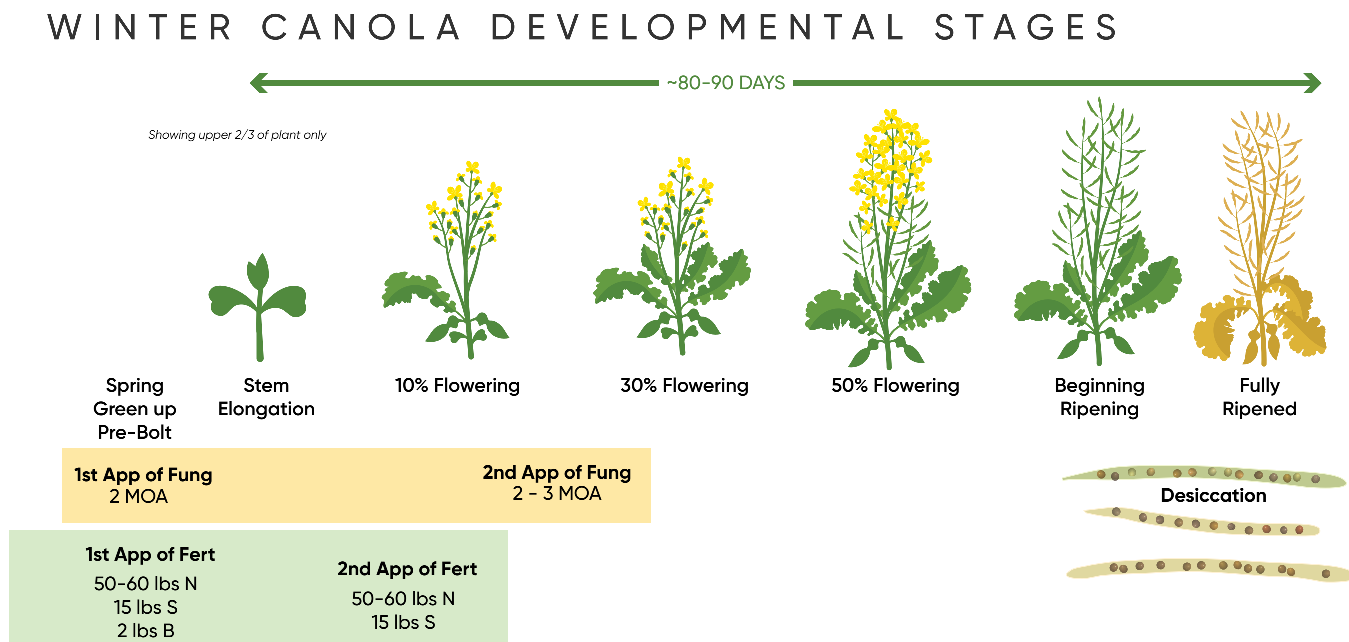


Figure 8. Spring management recommendations for winter canola by crop growth stage.

nitrogen application can be done approximately one month after the first application when plants are at the 50% flowering stage.

Timely fungicide applications will protect the crop from damaging pathogens such as white mold (*Sclerotinia sclerotiorum*). The first application should occur at approximately 10% flowering with a single mode of action fungicide. The second application is approximately 21 days later with a dual mode of action fungicide.

DESICCATION AND HARVEST

Approximately 70 days after the first flower buds open, canola seeds reach their maximum dry weight. Harvest timing for winter canola is typically between late May and early June. Use of a desiccant is recommended to ensure even moisture and maturity for ease of harvest. Desiccant should be applied when 75-80% of seeds have changed color (Figure 9). Lower pods may contain completely mature, black seeds, whereas very top pods will contain seeds with a mix of maturation stages and appear green, brown, or black. Reglone® is a common desiccant labeled for winter canola and is applied at 1.5-2 pt/acre. Reglone is activated by sunlight and will only desiccate plant material that it comes in contact with, so coverage is important. It's best to apply on cloudy days or evenings to allow for good coverage. Slight adjustments to harvest equipment may be needed. Canola is harvested at a speed of 2-3 mph.

Figure 9. Desiccant should be applied when 75-80% of seeds have changed color. Lower pods will be slightly more mature while upper pods will have a mix of brown and green seeds.

FUTURE INNOVATION FOR WINTER CANOLA

As the global population climbs to 10 billion people, the demand for energy grows with it. The path to meeting the demand will include a mix of energy sources, with renewable fuel supplying an increasing proportion of energy needs each year. The demand for renewable energy sources is driven by consumer sentiment, regulatory requirements, and government incentives. The use of renewable fuels helps lower greenhouse gas emissions while meeting increasing energy demands. Today, about 40% of the U.S. corn crop and about 30% of U.S. soybean oil are used to produce biofuels. As demand continues to grow, new agricultural feedstocks are needed, with increased seed crushing and energy refinery capacity.

While current winter canola hybrids already yield well, breeding efforts continue to create new hybrids even better adapted to the southern growing regions. Corteva is continuing to breed for high yield, high oil, shatter-resistance, disease-resistance, and compatibility with no till systems. Additionally, more options for seed treatments that include fungicides are undergoing registration.

As Chad Berghoefer, global product director for biofuels pointed out, "There are not many times in ag when you get a four-way win. The grower is winning from additional income that is coming in and another cropping system ready to diversify, we win from selling additional seed that would have otherwise been fallow ground, and Bunge and Chevron are winning from a renewable fuels standpoint…this doesn't happen very often in ag."

The Future of Wheat is in Hybrid Genetics

DANIEL WIERSMA, M.S., WHEAT GLOBAL PRODUCT MANAGER

KEY POINTS

- Wheat is a globally important crop that needs innovative technology to advance yield potential in the future.
- Hybrid wheat systems have been explored since the 1960s but have struggled to achieve scalability in commercial production.
- Corteva Agriscience has developed a novel wheat hybridizing system aiming to bring hybrid wheat to market by the end of the decade – marking a significant innovation milestone.
- Hybrid technology is expected to deliver an initial genetic gain of 10% or more, outperforming leading wheat varieties in the market today.
- Leveraging Corteva's deep expertise in hybrid genetics, wheat breeders are poised to accelerate its genetic rate of gain in the years ahead.

WORLDWIDE IMPORTANCE OF WHEAT

Wheat (*Triticum aestivum* L.) is among the most important global crops. It is planted on more than 600 million acres and produces more than 800 million metric tons of grain annually. Figure 1 shows relative production in various regions and countries of the world. The highest yielding areas of the world include Western Europe and parts of North America.

Revolutionary Plant Breeding: Breakthrough Unlocks Hybrid Wheat
- Agriscience Explained podcast

Wheat is used primarily for human consumption, providing high nutritional value including carbohydrates (calories) and proteins along with important minerals and vitamins. Wheat grain provides approximately 20% of the protein and calories in our global diet (Erenstein et al., 2022).

Wheat is a key crop for food security in many parts of the world and grain movement around the world through exports and imports is high, accounting for around one third of global grain trade.

WHEAT INNOVATION IS NEEDED

Wheat breeders across both public and private sectors have been developing improved varieties since the early 1900s. Thanks to genetic gains and better agronomic practices, global wheat grain production more than doubled between the 1960s and 2010 (FAOSTAT, 2025). However, recent research by Boehm et al. (2022) found that grain yield for hard red winter (HRW) wheat varieties adapted to the Northern Great Plains has stagnated since about 2008.

Recent research found that yield of hard red winter wheat varieties adapted to the Northern Great Plains has stagnated since about 2008.

In 2024, Corteva scientists initiated a study designed to measure the rate of genetic yield gain for HRW wheat. The study analyzed 44 HRW varieties released since the early 1900s, grown across nine locations in Kansas. Results showed a modest yield improvement of just 2.2 bu/acre per decade (Figure 2). This is lower than the 3 bu/acre per decade yield gains estimated from USDA yield data for Kansas farmers that reflects productivity gains achieved through the combination of improved genetics plus crop management practices.

These findings highlight the need for new innovations in wheat to enhance yield potential and yield stability – especially as global demand continues to rise.

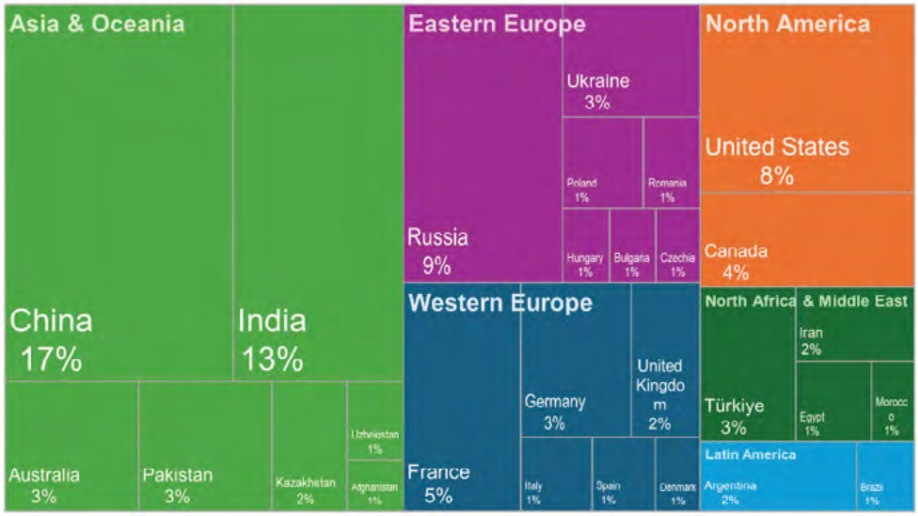


Figure 1. Global wheat production (% of total production) by region and country (FAOSTAT, 2025).

20% OF PROTEIN AND CALORIES
provided by wheat globally.

2ND MOST
traded grain commodity in the world second to corn, accounting for 1/3 of total grain trade.

NORTH AMERICA
grows about 1/8 of global wheat production.

HYBRID BREEDING – A PROMISING PATH FOR WHEAT

Hybrid breeding has been a powerful driver of yield improvements in major crops like rice (*Oryza sativa* L.) and corn (*Zea mays* L.). As a prime example, the Pioneer Hi-Bred Company (now a part of Corteva Agriscience) increased corn yield potential by 600% over the past 100 years through continuous genetic advancements.

Studies of experimental wheat hybrids in Europe and the United States suggest that yield increases of 10-25% and an improvement in yield stability are achievable. With today's advanced genetic tools and access to a broad germplasm base, even greater improvements are within reach.

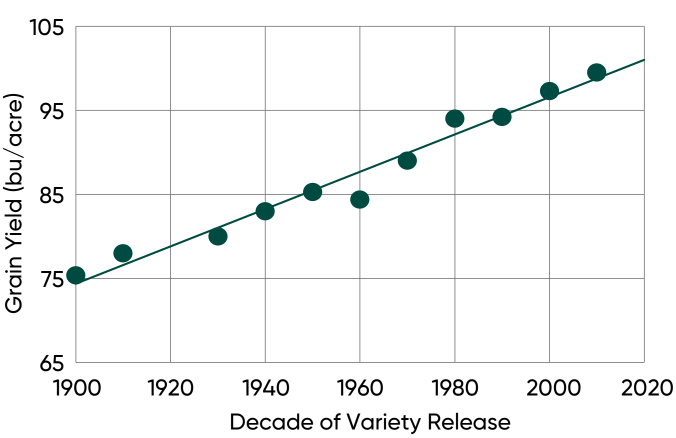


Figure 2. Average grain yield of HRW wheat varieties by decade of variety release. 2025 harvest of 44 varieties at 9 research locations in Kansas.

Despite these promising benefits, hybrid wheat has faced challenges. The complexity of cross-pollination and the relative costs and scalability of hybrid seed production have slowed progress. While producing hybrid wheat at scale is a major technological challenge, it's a critical step toward sustainably increasing global food production for a growing population and a changing climate.

WHEAT BREEDING AND HYBRIDIZATION

The primary goal of hybrid plant breeding is to combine the strengths of two different parents to create plants with superior traits. This improvement in yield and other characteristics is known as heterosis or hybrid vigor.

IMPORTANT TERMS

Heterosis: Also called hybrid vigor, it is the effect of having superior performance/characteristics from a cross between two different parent lines as compared to the performance of each individual parent.

Genetic gain: A measure of year-to-year improvement of newly developed varieties for grain yield and other traits of interest.

Male sterile: Plants producing ineffective pollen or no pollen and used in breeding for making hybrid seeds

Aleurone: The outermost layer of cells found in the endosperm of wheat providing crucial physiological function and contributes to the grain's nutritional profile, including antioxidants.

HOW DOES HYBRIDIZATION WORK IN WHEAT?

Wheat plants are naturally self-pollinating. Each flower contains both male (anthers) and female (pistil) parts. When heading begins, pollen is released from the anthers and fertilizes the pistil of the same plant.

To create new varieties, breeders manually cross-pollinate wheat by physically removing the anthers from a flower (a process called emasculation) and applying the pollen from another plant. While effective on a small scale, the method isn't practical for large-scale hybrid wheat production.

To produce hybrid wheat on a commercial scale, breeders must prevent self-pollination and encourage outcrossing between two inbred parents. This requires a system that disables the plant's natural ability to self-fertilize.

To produce hybrid wheat on a commercial scale, breeders must prevent self-pollination and encourage outcrossing between two inbred parents.

Beginning in the 1960s, several methods were explored to achieve this, focusing on making sterility systems where plants do not produce viable pollen. A recent review by Revell et al. (2025) outlines three primary approaches for reliable and scalable pollination control in wheat.

1. **Cytoplasmic Male Sterility (CMS)** involves altering the plant's mitochondrial (cytoplasm) DNA, so it doesn't produce pollen. This is the most widely use system used by wheat breeders today. However, it has some drawbacks:
   - It requires a third parent to restore fertility, making it a 3-line system.
   - It works only with a limited range of wheat germplasm.
   - It results in low seed set in hybrid seed production fields.
2. **Chemical Hybridizing Agents (CHA)** are a class of chemicals that cause male sterility when applied to wheat. They have been used on a limited basis because of the narrow window for the CHA chemical application and instability due to environmental conditions.
3. **Nuclear Male Sterility (NMS)** is a newer male sterility system developed by scientists at Corteva Agriscience. Using the Male Sterile 45 (MS45) gene, this method relies on genetic changes in the plant's nucleus to induce male sterility (Singh et al., 2018, Rhode et al., 2025).

Corteva's novel MS45 seed production technology system offers several advantages for producing hybrid wheat:

- **No need for fertility restoration:** Unlike other systems, it uses normal male plants and doesn't require genetic manipulation to restore fertility in the female line.
- **Easy maintenance of female lines:** The female "maintainer" lines reproduce through self-pollination.
- **Color-based seed sorting:** The MS45 gene of the maintainer line is tightly linked to a gene for blue aleurone expression (seeds with a blue hue). This allows seeds to be sorted by color to isolate red male-sterile seeds from blue maintainer seeds. The red male-sterile seeds are then planted together with male pollen-producing seed to grow F1 hybrid seed.
- **Proven performance:** Corteva's hybrid wheat system consistently delivers strong hybrid vigor and stable performance across all tested environments.
- **Non-GMO approach:** All breeding is done using conventional methods – no genetic modification (GMO) or gene-editing is involved.

HYBRID WHEAT SYSTEM DEPLOYMENT

To successfully produce and deploy hybrid wheat, three key elements must be in place:

- First, breeders need a reliable pollination control system, allowing them to cross two inbred parent lines effectively.
- Second, germplasm resources must be developed to take full advantage of hybrid vigor – boosting yield and other agronomic or disease traits.

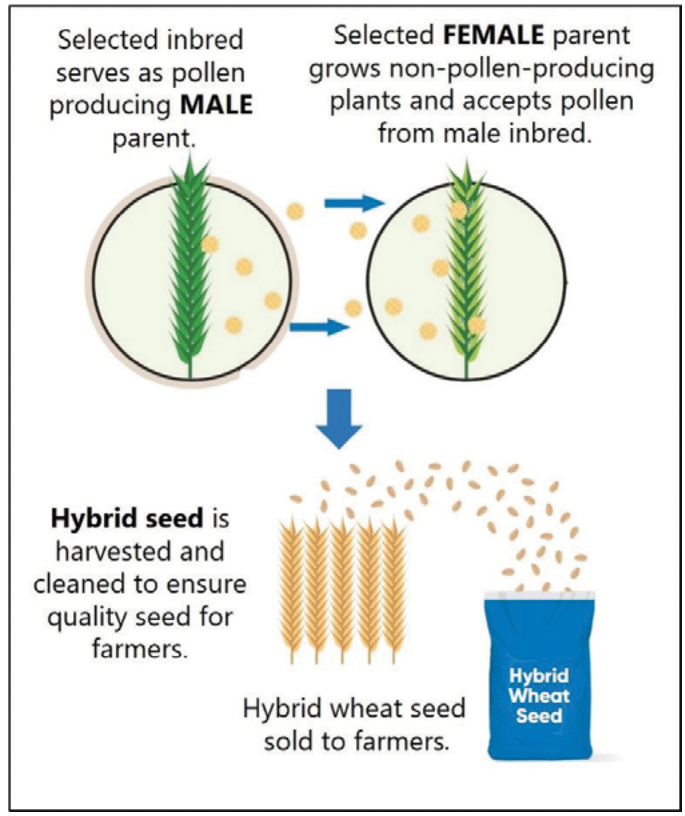


Figure 3. System for the hybrid wheat seed production stage where fertile male and non-pollen producing female seeds are planted in the same field to create hybrid offspring.

- Third, the seed production process must be scalable to cover millions of acres and remain cost-effective for both farmers and seed companies investing in the technology (Figure 3).

The biggest factor influencing the economics of hybrid wheat is the cost of producing hybrid seed. A key part of this process is timing – known as "nicking" – which ensures that the female plant is ready to receive pollen when the male is shedding it. Ideally, the female parent flowers two to five days earlier than the male parent (Schmidt et al., 2024), and the male plant should be taller to help pollen better reach the female flowers.

The biggest factor influencing the economics of hybrid wheat is the cost of producing hybrid seed.

NEW ENABLING TOOLS FOR WHEAT BREEDING

For centuries, wheat has fed civilizations, yet its genetic complexity remained a stubborn frontier. With its hexaploid genome—six sets of chromosomes tangled in a labyrinth of genetic code—wheat posed a genetic challenge that defied easy analysis and use.

That changed in 2018 with the completion and publication of the wheat genome (Appels et al., 2018), a landmark achievement in agricultural science. With a new roadmap of where genes are located, scientists at Corteva were able to engineer a novel sterility system for producing hybrid wheat.

The use of genomic prediction tools allows breeders to unravel the complexity of selecting for multiple traits.

But the genome did more than enable hybridization of wheat. It helped transform breeding itself. Marker-assisted selection became more targeted, more precise and more intentional. Breeders could now target specific genes to improve disease resistance, drought tolerance and other favorable traits for wheat.

The use of genomic prediction tools, integrating large datasets and predictive models, allows breeders to unravel the complexity of selecting for multiple traits. What was once a slow, intuitive process became a data-driven sprint – accelerating Corteva's wheat breeding progress.

EXPECTED BENEFITS OF HYBRID WHEAT

Higher yields: Early generation hybrids have 10% or greater yield potential compared to elite commercial varieties in moderate to high yield environments (Figure 4). Under water-limited stress, the advantage of hybrids over leading varietal wheat products is 20% or greater (Figure 5).

Improved stability: Hybrids offer more consistent performance across diverse growing conditions, reducing risk potential for farmers.

Enhanced disease resistance: Combining disease resistance genes from both parent inbred lines accelerates protection against key diseases.

Sustainability: Hybrids can deliver higher yield potential using the same inputs as varietal wheat, making them a more sustainable option.

Better input response: Hybrids may offer greater potential to respond to water, fertilizer, or other crop inputs.

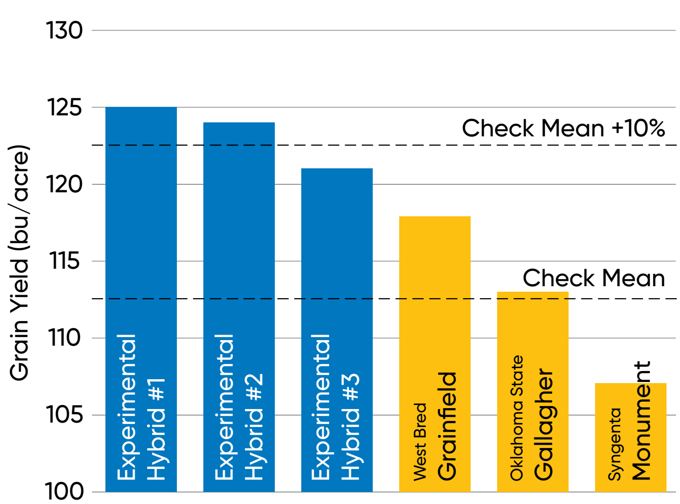


Figure 4. Yield comparison of experimental hybrid HRW wheat lines and elite commercial varieties planted in 2024 and harvested in 2025 at multiple Kansas research locations.

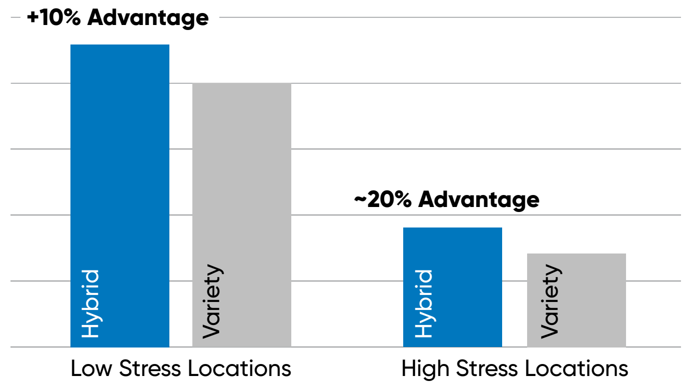


Figure 5. Comparison of hybrid performance versus leading commercial check varieties of HRW wheat in low-stress and high-stress (water-limited) environments.

Corteva Agriscience yield trial testing; 2 years of testing with 6-10 locations/year in each of the market classes. HRW testing in NE, KS, CO, OK.

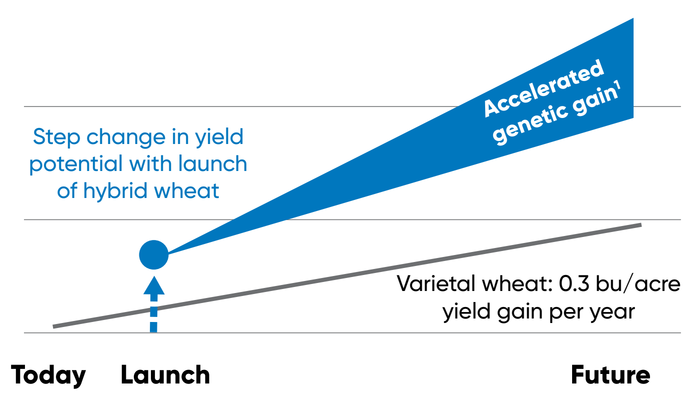
Market acceptance: For widespread adoption, hybrids must meet expectations for high grain yield, disease resistance, and lodging while meeting industry standards for grain quality.

THE PROMISE OF HYBRID WHEAT

Hybrid technology, paired with cutting edge genetic tools, is reshaping how we select for the traits that matter most.

In the unfolding story of agricultural innovation, hybrid wheat marks a pivotal chapter. With its introduction, wheat producers are on the brink of a transformation. Hybrid technology, paired with cutting edge genetic tools, is reshaping how we select for the traits that matter most – yield, agronomics, quality, and resilience. These tools don't just improve precision, but they help accelerate the pace of progress. (Figure 6).

Corteva's first generation of hybrid wheat will debut in the HRW wheat class, followed by Soft Red Winter (SRW) and Hard Red Spring (HRS) wheat classes by the end of the decade. But the real story lies in the pipeline – where breeders are already refining the characteristics of male and female lines to enhance pollination success and unlock even greater yield potential. It's a quiet revolution, rooted in biology, driven by data, and poised to reshape the future of wheat.



[1] Represents Corteva's conservative estimates based on current breeding program and use of hybridization and advanced breeding tools for wheat.

Figure 6. Change in yield potential with hybrid wheat.

Genome Editing for Crop Improvement

JEFFRY SANDER, PH.D., PROGRAM MANAGER, GENOME EDITING TECHNOLOGIES

MARIA FEDOROVA, PH.D., GLOBAL GENOME EDITING TECHNICAL LEAD

JESSE MUNKVOLD, PH.D., PROGRAM LEADER, GENE EDITED BREEDING

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Genome editing is an advanced breeding tool that allows scientists to make precise, intentional changes to an organism's DNA through addition, removal, or alteration of specific genes.
- Genome editing can be used to rapidly and efficiently create improved crop varieties that are indistinguishable from those that could be obtained using traditional breeding technologies.
- The field of genome editing made a significant leap forward with the development of the CRISPR-Cas system as a gene editing tool in the early 2010s.
- Corteva Agriscience is establishing a CRISPR-Cas advanced breeding platform to develop seed products for greater environmental resiliency, productivity, and sustainability.
- Corteva's genome editing breeding platform is enabling the rapid development of crops with enhanced disease resistance and improved drought tolerance, supporting yield stability across diverse environments.
- One of the essential enablers of any innovation is the regulatory framework governing its use, and agricultural applications of genome editing are no exception.
- Science-based, risk-proportionate, and globally harmonized policies for genome-edited crops are essential for translating this innovation into real-life improvements, benefiting producers and consumers globally.

A NEW ERA OF CROP IMPROVEMENT

Throughout its 100-year history, Pioneer has been a leader in driving increased agricultural productivity through crop improvement. Following its founding in 1926, what was then known as the Hi-Bred Corn Company led a revolution in corn breeding that used hybridization to dramatically increase yields. With the introduction of agricultural biotechnology in the 1990s, it was demonstrated that desirable traits from non-native sources could be introduced into crops species. For example, the introduction of transgenic Bt traits from soil bacteria provided corn the ability to protect itself from damaging pests, thus improving the quantity and reliability of corn yields.

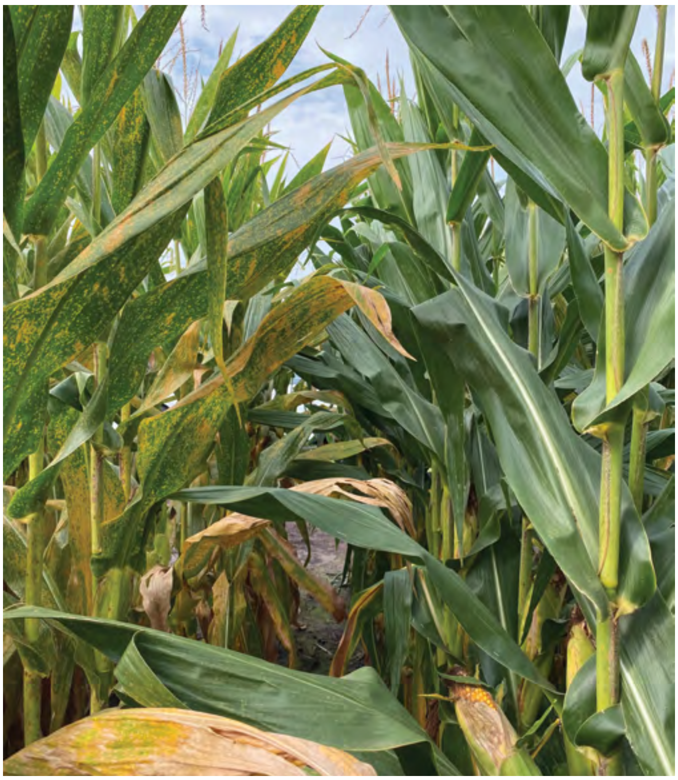


Figure 1. A gene-edited corn hybrid with multi-disease resistance (right) next to a conventional isoline hybrid (left) showing contrasting severity of southern rust (*Puccinia polysora*) infection. (Johnston, Iowa; September 3, 2025.)

Most recently, breakthroughs in the field of genome editing have been bringing forth a third revolution to crop improvement to be used alongside existing technologies. Genome editing is the process of introducing targeted and precise changes to DNA and other genomic features determining plant characteristics and diversity. This ground-breaking technology is expected to help develop innovative and sustainable solutions for growers similar to those realized through conventional plant breeding practices, but with even greater quality, accuracy, and with more efficient development timelines.

Much of the excitement in genome editing is centered around CRISPR-Cas technology (commonly called simply CRISPR), which has been rapidly adopted due to its advantages over earlier genome editing tools in quality, efficiency, and technical flexibility. CRISPR has many potential applications extending well beyond agriculture and has garnered wide mainstream media attention as research in this area has rapidly expanded. Two of the scientists who led the development of CRISPR as a gene editing tool were awarded the Nobel Prize in Chemistry in 2020 for their work – only eight years after the initial paper describing their work was published (Jinek et al., 2012), highlighting the immediate impact of their discovery.

The purpose of this article is to provide a brief overview of what genome editing in plant breeding is, how it works, and how Corteva Agriscience is using this technology to facilitate a new era of crop improvement.

GENOME EDITING

Genome editing is an advanced breeding tool that allows scientists to make precise, intentional changes to an organism's DNA through addition, removal, or alteration of specific genes. Gene edited products are different than those with transgenic traits – commonly referred to as genetically modified organisms, or GMOs – because these beneficial changes mimic genetic variation found in nature and can be achieved without introducing DNA from another organism. Scientists can achieve these beneficial changes more efficiently using genome editing than other technologies that are currently available.

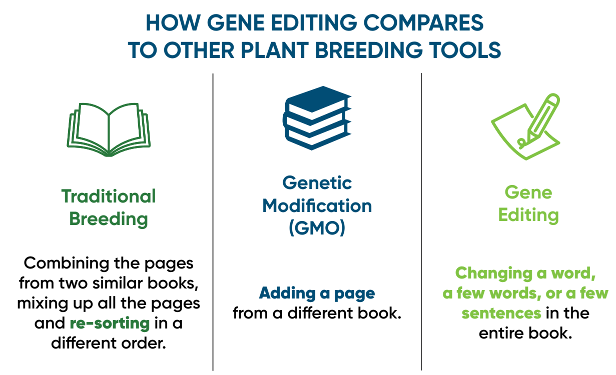


Figure 2. A useful analogy for plant breeding tools is the process of editing text in a book. Genome editing is a precise and effective way to make a beneficial change to an organism – like changing one word, a few words, or a few sentences in an entire book.

While the actual implementation of genome editing is more complex, it is conceptually similar to editing a text document using a word processor. In this analogy, the genome editing tool is the cursor that can be pointed to the desired location within the text. Placement of this cursor enables one to delete, change or insert letters or even words at the selected location, thereby improving the text. In the same way a plant's own genetic sequences can be targeted using genome editing and purposefully adapted to provide desired characteristics.

Genome editing can be used to rapidly and efficiently create improved crop varieties that are indistinguishable from those that could be obtained using traditional breeding technologies. For example, gene editing can be used to move disease-resistance alleles from lower-yielding, non-commercial genetics directly into high-yielding elite varieties. Traditional plant breeding methods can achieve the same result, but require an expensive, less precise, and time-consuming backcrossing process. In contrast, genome editing preserves the integrity of the elite genetic background by introducing only the desired allele and does so within a single generation.

WHAT IS CRISPR?

The field of genome editing made a significant leap forward with the development of the CRISPR-Cas system as a gene editing tool in the early 2010s (Gasiunas et al., 2012; Jinek et al., 2012). CRISPR (clustered regularly interspaced short palindromic repeats) is a naturally occurring adaptive immune system found in many types of bacteria and archaea where it defends against viruses. It works by acquiring short sequences of viral DNA into the bacteria's genome, forming a genetic memory of past invaders. When the virus attacks again, RNA transcribed from these sequences guides the Cas protein to destroy the matching viral DNA. Scientists have repurposed this system to a gene editing tool, by directing Cas enzymes to recognize and modify specific genomic sequences.

CRISPR is a naturally occurring adaptive immune system found in many types of bacteria and archaea.

CRISPR was not the first genome editing system. The zinc-finger nuclease (ZFN) was the most widely used platform in the 2000s (Urnov et al., 2010; Gaj et al., 2016), followed by transcription activator-like effector nucleases (TALENs) in the early 2010s (Joung and Sander, 2013; Gaj et al, 2016). However, high cost, technical complexity, and limited design flexibility restricted broader adoption of these platforms. In contrast, CRISPR is more robust and significantly easier to design and use. This enables scientists to create edits more rapidly and cost-effectively and allows for the simultaneous modification of multiple genes.

Over the last decade, many CRISPR-Cas systems have been discovered and characterized including novel variants identified by scientists at Corteva Agriscience (Bigelyte et al., 2021; Urbaitis et al., 2022). Despite the diversity of these systems (e.g. sequence, structure, size, temperature) they share the common feature of a programmable RNA(s) that is capable of guiding a Cas protein to matching DNA sequences.

CRISPR-CAS FACILITATED CROP IMPROVEMENT

Higher organisms, including plants, continuously encounter DNA breaks from external sources such as sunlight and internal processes that release free radicals. They have developed efficient mechanisms for repairing the multitude of DNA breaks that occur in each cell every day. DNA break repairs are generally classified as non-homologous end joining or homology directed repair (Figure 3).

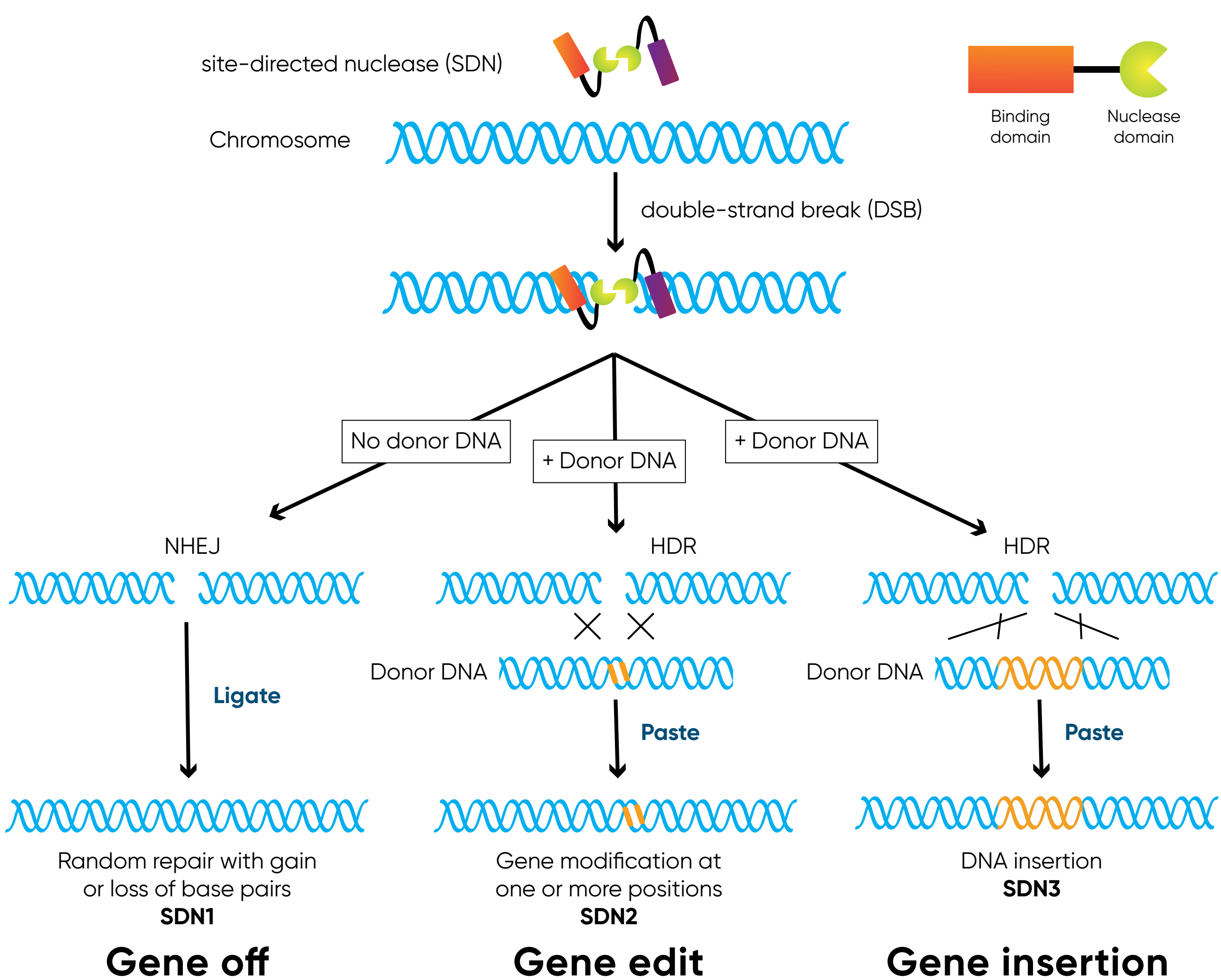


Figure 3. CRISPR-Cas facilitated DNA repair and basic CRISPR genome editing applications (from Podevin et al., 2013). Repair without a template occurs through the nonhomologous end joining (NHEJ) pathway and can be used to disrupt the function of a gene, effectively deleting it. Repair using a template through the homology-directed repair (HDR) pathway can enable precise alterations and insertions from the template DNA sequence into the genome.

Non-homologous end-joining (NHEJ) is the dominant DNA repair pathway in plants. It reconnects DNA ends introducing insertions or deletions. These changes can modulate gene expression or even turn genes off completely. Homology-directed repair (HDR) uses a second intact DNA strand, with sequence that matches those flanking the break, to precisely repair the break, incorporating any sequence variation between the flanking regions.

Initially, genome editing applications relied on programmable molecular scissors such as CRISPR-Cas to cut DNA at specific targets, leveraging cellular repair pathways like NHEJ and HDR to delete, modify, or insert genes. More recent advances have introduced a new generation of applications capable of mimicking and mining more of nature's diversity. For example, Corteva scientists pioneered a method using two targeted breaks within a single chromosome to re-invert a large DNA segment that that had long been reversed relative to the standard orientation, thus restoring its ability to participate in recombination through traditional breeding (Schwartz et al., 2020). In a separate unpublished study, Corteva demonstrated the targeted relocation of a chromosomal segment from one corn chromosome to another in the same plant. These studies demonstrated that structural rearrangements such as inversions and translocations, first revealed through early sequencing of plant genomes, can be replicated using genome editing.

> *Recent advances in genome editing have introduced a new generation of applications capable of mimicking and mining more of nature's diversity.*

Next generation genome editing platforms have been expanded to go beyond double-strand breaks. New tools recruit enzymes that modify DNA without requiring double-strand breaks. For example, they can now enzymatically copy sequence from an RNA template into the genome using a single-strand nick (Anzalone et al., 2019; Ferreira da Silva et al., 2024). Other approaches recruit base-editing enzymes that introduce precise sequence changes without the need to cut DNA at all (Collantes et al., 2021). These innovations are enabled by CRISPR-Cas platforms and their ability to recognize and bind specific DNA sequences with precision. These next generation technologies are highly efficient and well-suited for multiplexing, making it possible to obtain dozens of gene edits simultaneously (Figure 4).

AGRICULTURAL APPLICATIONS OF GENOME EDITING

Corteva Agriscience is establishing a CRISPR-Cas advanced breeding platform to develop seed products for greater environmental resiliency, productivity, and sustainability. CRISPR-Cas has numerous potential agricultural applications including improvements to yield, disease resistance, and drought tolerance, as well as improvements beneficial to the end user such as output characteristics and nutritional content.

MULTI-DISEASE RESISTANT CORN

Corteva is using CRISPR genome editing technology to improve the genetic resistance of corn hybrids to multiple major diseases by combining and repositioning corn disease resistance genes. Global corn genetics offer a rich source of natural disease resistance genes; however, these genes may be in varieties that are lower-yielding or not adapted to the target growing environment. Additionally, these genes are often located on different chromosomes, far apart from each other. Combining the desired disease resistance genes in the same modern elite inbreds through conventional breeding is very time and resource consuming and may result in a genetic linkage

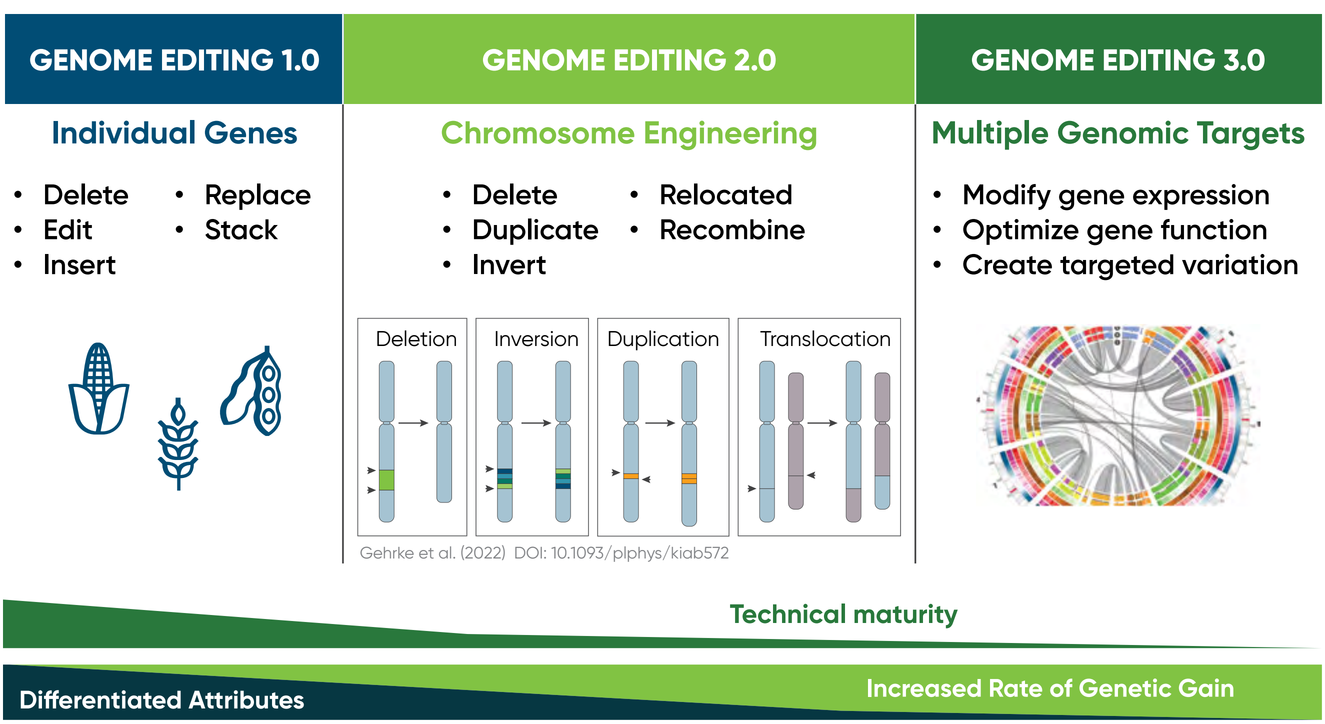


Figure 4. The next generation of genome editing technologies allow for more complex modifications like multiplexed gene activation or large-scale chromosome engineering. These newer systems are more precise and efficient, enabling scientists to edit larger sections of the genome, replace segments of DNA, or activate multiple genes at once.

drag. Using CRISPR genome editing technology, the desired native disease resistance genes are co-located together and efficiently moved into modern, high-yielding corn varieties.

Using CRISPR genome editing technology, desired native disease resistance genes are co-located together and efficiently moved into modern, high-yielding corn varieties.

Corteva's first multi-disease resistant product will protect against gray leaf spot (*Cercospora zeae-maydis*), northern corn leaf blight (*Exserohilum turcicum*), southern corn rust (*Puccinia polysora*), and anthracnose stalk rot (*Colletotrichum graminicola*). This genome editing strategy is highly adaptable, enabling deployment across other crops, targeting additional diseases, and extending to geographies worldwide.

IMPROVED DROUGHT TOLERANCE IN CORN

Drought stress is the primary yield-limiting factor in corn production in most regions of the world and improved drought tolerance has long been a focus of corn breeders. Drought tolerance is a complex trait involving multiple physiological processes. Nevertheless, ethylene – a gaseous plant hormone that influences plant growth and development – is known to play an important role in modulating plant response to abiotic stress, including water deficits and high temperatures.

One of the first demonstrations of this hormone's impact on drought tolerance in corn was via manipulation of the ethylene biosynthesis gene: ACS6. Transgenic studies showed that downregulation of this gene could reduce ethylene levels and improve grain yield under drought stress conditions (Habben et al., 2014). Another ethylene associated gene, ARGOS8, is a naturally occurring negative modulator of corn's native ethylene response. This association led Corteva scientists to pursue increasing the expression of this gene as a means to increase drought-tolerance in corn hybrids. Over 400 corn inbreds were initially evaluated for native variation of expression of the ARGOS8 gene; however, despite extensive efforts using years of traditional breeding methods, the expression levels in all these lines were less than needed to have a meaningful effect on drought tolerance. Scientists then employed CRISPR-Cas gene editing technology to increase the expression level of the ARGOS8 gene by using a promoter from another native maize gene (GOS2). Field evaluations showed that, compared to the wild type, CRISPR ARGOS8 variants increased grain yield by 5 bu/acre under flowering drought stress conditions and did not exhibit yield loss under well-watered conditions (Shi et al., 2017).

CRISPR ARGOS8 variants increased grain yield by 5 bu/acre under flowering drought stress conditions and did not exhibit yield loss under well-watered conditions.

GENE EDITING AS A BREEDING TOOL

Plant breeding programs heavily depend on recombination—the natural reshuffling of traits that occurs when two varieties are crossed—to identify offspring with the most favorable trait combinations. This enables the development of high-performing commercial varieties with enhanced yield and other agronomic traits. Genetic recombination is naturally limited in any new breeding cross, with on average only one to two DNA crossovers occurring per chromosome. This recombination can be further limited where naturally occurring DNA rearrangements have taken place within the genome of one parent but not another.

Advancements in DNA sequencing technologies have made it possible to sequence entire genomes and compare them across different varieties of the same crop. Corteva Agriscience research on corn has uncovered multiple natural instances of large-scale chromosomal rearrangements that spontaneously occur in all 10 chromosomes, such as large deletions, duplications, translocations, or inversions of DNA. These types of large-scale chromosomal rearrangements are not unique to corn – they are known to occur in many plant species. One such spontaneous DNA rearrangement that Corteva scientists observed in certain inbred lines was a large inversion of the central part of chromosome 2. The inversion covers 75.5 Megabases of the DNA sequence, which is about one-third of the chromosome. This inversion was detected in 3 out of 66 sequenced inbred lines and happened spontaneously at some point in their breeding history. Discovery of this spontaneous inversion helped explain why breeders had not observed genetic recombination in this region after crossing these three inbreds with other inbreds.

Corteva Agriscience research on corn has uncovered multiple natural instances of large-scale chromosomal rearrangements that spontaneously occur in all 10 chromosomes, such as large deletions, duplications, translocations, or inversions of DNA.

Corteva scientists decided to test if it would be possible to 're-invert' this chromosomal fragment using CRISPR-Cas genome editing technology, so that its orientation would match this region in most other inbreds. Since no genes were deleted, edited, or inserted – just a fragment of chromosome inverted – there is no discrete phenotype. The effect of re-inversion had to be confirmed by analyzing if recombination of characteristics can now occur in this region. Recombination in this chromosomal region has been successfully confirmed using molecular markers (Schwartz et al., 2020), which will allow breeders to unlock useful genetic variation contained in this region.

In complementary work, Corteva scientists have also used CRISPR-Cas genome editing to increase the rate of recombination in the corn genome. Targeting genes known to modulate the frequency of recombination in plants, researchers used CRISPR-Cas to turn off these genes in corn inbreds and then measured the amount of recombination when crossed with other lines. In these crosses, recombination was increased up to five-fold with no negative effects on plant performance. By increasing genetic recombination in this way, Corteva plant breeders can significantly increase the number of new genetic combinations to evaluate, including rare combinations that may lead to increased yield and other improved agronomic performance.

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REGULATORY LANDSCAPE FOR GENOME EDITING IN PLANTS

One of the essential enablers of any innovation is the regulatory framework governing its use, and agricultural applications of genome editing are no exception. Regulatory policies for biotechnology were established in various countries over 20-30 years ago, at the dawn of plant genetic engineering when it was used to insert DNA 'foreign' to the recipient genome (DNA from a different species, e.g. bacteria). These biotechnology policies govern cultivation, food, and feed uses of transgenic crops, such as Bt corn and soybean. Most countries set their policies in alignment with The Cartagena Protocol on Biosafety - an international agreement aimed to ensure the safe handling, transport and use of living modified organisms (LMOs, commonly known as GMOs – genetically modified organisms). LMO/GMO is defined as a "living organism that possesses a novel combination of genetic material obtained through the use of modern biotechnology" (Secretariat of the Convention on Biological Diversity, 2000). Seen as inherently different from conventional (non-transgenic) crops, GMO crops require onerous safety assessment in most countries and regulatory approvals before their testing and commercial cultivation.

Regulatory policies for biotechnology were established in various countries over 20-30 years ago, at the dawn of plant genetic engineering.

Crop genome editing using CRISPR is a little over ten years old and one of the most recent biotechnology innovations. It allows the introduction of targeted changes to plant's genome without leaving any foreign (transgenic) DNA sequences. Similar genetic changes can arise in plants spontaneously or by using conventional breeding techniques (e.g., chemical or irradiation mutagenesis or genetic crosses) – and thus, can occur in conventional crops. This has presented a fundamental question: do such genome-edited plants possess a "novel combination of genetic material," are therefore GMOs, and subject to onerous GMO regulation? Or are such genome-edited plants much more similar to, and therefore as safe as, conventional varieties?

Regulators and policy makers have been tasked with addressing very important questions. How should the existing biotechnology regulations be adapted to account for genome editing? What is the appropriate regulatory policy framework to facilitate innovation while protecting human health and the environment?

Corteva Agriscience supports the position of International Seed Federation that plant varieties developed through the latest plant breeding methods, such as CRISPR genome editing, should not be differentially regulated if they are similar to or indistinguishable from varieties that could have been produced through earlier breeding methods. It is the characteristics of the product itself, and not the tool used to create it, that determines product safety.

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Gene Editing: Pathway to Progress

- Agriscience Explained podcast

Regulatory policies for genome editing in plants have made tremendous progress in the past decade. A growing number of countries consider certain outcomes of genome editing as not resulting in a "GMO" and thus, consider such genome-edited crops as being equivalent to conventional crops. Global harmonization of regulatory policies is extremely important since many crops are internationally traded agricultural commodities. For example, offering genome-edited corn hybrids to the U.S. farmers would need to consider the regulatory status of the resulting grain in major U.S. corn export markets. Therefore, regulatory policies that are aligned between countries are essential for bringing genome editing innovations to market.

Global harmonization of regulatory policies is extremely important since many crops are internationally traded agricultural commodities.

The regulatory landscape for plant genome editing is continuously evolving. New examples of genome-edited crops with enhanced disease resistance, increased yields, resilience to abiotic stress, or improved nutritional value constantly emerge, showcasing the value of this plant breeding innovation to help address global food security and climate change challenges. This puts pressure on the regulatory policies to keep up with technological progress, but not all governments have formulated their regulatory position yet. The Global Farmers statement on plant breeding innovations, endorsed by 30 international farmer and agricultural industry organizations, appeals: "Farmers urge governments to remove regulatory impediments and uncertainty to advance plant breeding solutions for rural communities, food security and sustainable development." Science-based, risk-proportionate, and globally harmonized policies for genome-edited crops are essential for translating this scientific innovation into real-life improvements, benefiting producers and consumers globally.

High Night Temperature Effects on Corn Yield

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Research has shown that above-normal night temperatures can reduce corn yield.
- Yield losses can be a product of both reduced kernel number and reduced kernel weight, depending on the timing of high night temperature stress.
- Nighttime temperatures are currently increasing at a faster rate than daytime temperatures, which has prompted extensive new research on the effects of elevated nighttime temperatures on yields in several crops.
- The effects of high night temperatures on plants are complex and can involve multiple physiological processes.
- The primary physiological basis for the negative effect of high night temperatures on corn yield is an increased rate of cellular respiration during the nighttime hours.
- Research indicates that conditions in which the overnight low temperature remains above 70°F are likely to be detrimental to corn yield.
- Yield reductions can be significant, depending on the timing, severity, and duration of heat stress.

NIGHT TEMPERATURES AND CORN YIELD

Many agronomists and corn growers are aware of the general concept that above-average night temperatures during pollination and grain fill can be detrimental to corn grain yield. Average summer temperatures in much of the Corn Belt are commonly warmer during the day and much warmer during the night than those to which corn was originally adapted in its native region. The genetic lineage of corn can be traced back the Central Highlands of Mexico (Galinat, 1988), specifically the Tehuacán Valley and Balsas River Valley. Summer climate in this region is characterized by relatively mild daytime high temperatures, cool nights, and abundant sunshine (Figure 1). The first research in the U.S. Corn Belt that demonstrated negative effects of elevated night temperatures on corn yield was conducted in the late 1960s (Peters et al., 1971), and it has been generally known among corn producers and agronomists since then that warm nights can reduce corn yield.

What is less understood though, is how yield is impacted through effects on specific plant processes and yield components. Abiotic stress effects on crops can be complex, with the timing, duration, and severity of the stress all being important factors in determining the ultimate impact on yield. Until recently, very few studies had been conducted on this question, making it difficult to pin down precise effects of high night temperatures on corn yield and answer important questions regarding the degree and duration of heat stress that corn can endure before yield is affected. In recent years, however, a surge of new research in this area has brought more insights into how and why high night temperatures can affect corn yield.

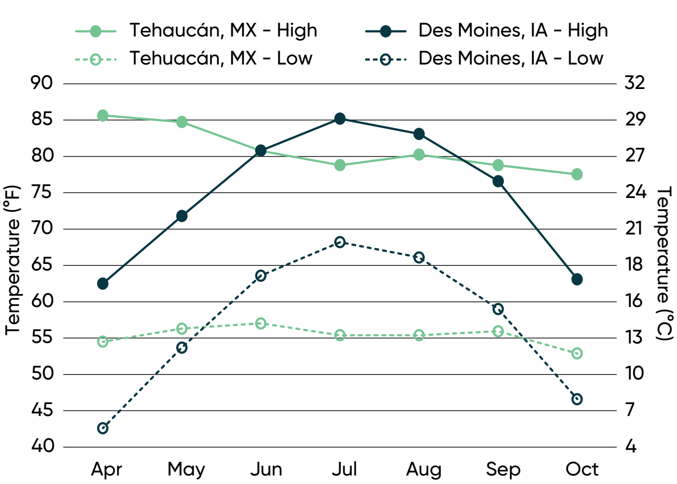


Figure 1. Average daily high and low temperatures for Tehuacán, Puebla, in the Central Highlands of Mexico near where corn was first cultivated, and for Des Moines, IA, in the heart of the modern U.S. Corn Belt.

INITIAL RESEARCH

The first experimental evidence that high night temperatures can have a detrimental effect on corn yield came from a field experiment performed by researchers at the University of Illinois in the late 1960s (Peters et al., 1971). In this study, small climate-controlled enclosures were constructed and placed over corn plants at night to alter air temperature. Nighttime temperature treatments were imposed at flowering and maintained through physiological maturity. In this study, corn grown with an average night temperature of 85°F yielded 40% less grain than corn grown with the average ambient night temperature of 62°F (Table 1).

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

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

Although the impact on corn yield was substantial in this study, the real-world insights that could be drawn from it were limited – it was a single year, single location study with only one high temperature treatment applied over the entire reproductive period. Corn yield was the only response variable reported, with no data on specific yield components. The elevated night temperature treatment applied in the study was also unrealistically high for the central United States. So, while this study clearly demonstrated that elevated night temperatures *could* reduce corn yield, it provided little insight into the risk of yield loss associated with above average night temperatures within a range likely to be experienced under real world conditions.

EFFECTS ON YIELD COMPONENTS

Subsequent studies built upon the work done by Peters et al. and examined the effects of high night temperatures on corn yield components. Research conducted a decade later at the University of Guelph focused specifically on the effects of elevated temperature during the grain fill period (Badu-Apraku et al., 1983). In this study, corn plants were grown in pots outdoors and then moved into controlled-temperature growth chambers 18 days after silking. Results showed that grain yield per plant was significantly affected by temperature regime (Table 2).

The lowest temperature regime (77°F day, 59°F night) resulted in the greatest grain yield per plant as well as the longest grain fill duration. Increasing the night temperature to 77°F significantly reduced yield per plant. Increasing the day temperature to 95°F also resulted in lower yield per plant, regardless of night temperature.

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

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

* Interval from 18 days after silking to physiological maturity.
Values followed by the same letter are not significantly different at $\alpha = 0.05$.

Since temperature treatments were applied after kernel set, yield reductions in this study were entirely attributable to differences in kernel weight.

A study conducted in Argentina in the 1990s showed that high night temperatures could negatively affect yield through reductions in kernel number as well (Cantarero et al., 1999). This study examined the effects of elevated night temperature (9°F above ambient) over a period extending from one week before silking to three weeks after silking. Results showed that kernel abortion in heated plots was 8% higher than in the control plots. Ears in the heated plots had an average of 34 kernels per row at harvest, compared to 37 kernels per row in the control plots.

RENEWED RESEARCH INTEREST

Until relatively recently, the total body of research on the effects of high night temperatures on corn yield remained relatively sparse. A handful of studies had demonstrated that elevated night temperatures could significantly reduce corn yield and that those reductions could be a function of lower kernel number or lower kernel weight, depending on the timing of the heat stress. However, despite understanding the theoretical importance of night temperatures, it remained difficult to translate that knowledge into assessing real-world impacts. Temperature in the field is dynamic, and determining the timing, intensity, and duration of nighttime heat stress necessary to impact yield was difficult with only a few studies to go on.

Until relatively recently, the total body of research on the effects of high night temperatures on corn yield remained relatively sparse.

In the past decade, however, there has been a surge of new research in this area (Hein et al., 2024; Kettler et al., 2022; Kettler et al., 2024; Niu et al., 2021; Wang et al., 2020). Understanding the real-world effects of warmer nights on crop yield has taken on increased importance due to the reality of rising global temperatures. As temperatures have increased around the world, night temperatures have increased at a faster rate than daytime temperatures (Davy et al., 2016). In the U.S., nighttime temperatures during the summer months of June, July, and August have increased by an average of 3.1°F since 1970 (Climate Central, 2025). Figure 2 shows summer night temperature increases for several U.S. locations in major corn-producing areas. Detrimental effects of high night temperatures have been observed in several crops, including wheat (Garcia et al., 2015; Garcia et al., 2016; Hein et al., 2019), rice (Bahuguna et al., 2016; Welch et al., 2010), quinoa (Lesjak and Calderini, 2017), and barley (Garcia et al., 2015; Garcia et al., 2016). The prospect of widespread yield declines across multiple major crops due to rising night temperatures has generated concern about potential implications for global food security (Sadok and Jagadish, 2020).

CORN YIELD DETERMINATION

Corn yield reduction from heat stress can be associated with reductions in both source and sink capacity. Impact on yield depends on the growth stage of the corn at the time stress occurs. The most critical period for corn yield determination is the roughly 4- to 5-week window bracketing silking when kernel number is set. Approximately 85% of total grain yield is related to the total number of kernels produced per acre (Otegui et al., 1995). Kernel number is closely associated with crop growth rate during this critical period. Any stress during this time that reduces the net photosynthetic rate and assimilate availability can reduce the number of kernels the plant sets and negatively impact yield. Even if the stress is temporary and the plant recovers, the damage to yield will be done because the plant's sink capacity has been reduced. Once kernel number has been set, stress can continue to impact yield through grain fill by reducing kernel weight. Stalk quality can also be impacted if the stress forces the plant to increase its reliance on remobilized carbohydrates to complete grain fill.

The most critical period for corn yield determination is the roughly 4- to 5-week window bracketing silking when kernel number is set.

EFFECTS OF HIGH NIGHT TEMPERATURES ON CORN

The effects of high night temperatures on plants are complex and can involve multiple physiological processes (Sadok and Jagadish, 2020). The primary physiological basis for the negative effect of high night temperatures on corn yield is an increased rate of cellular respiration during the nighttime hours, which increases carbohydrate consumption and reduces the amount of carbon assimilate available for translocation to the grain (Kettler et al.

INCREASE IN SUMMER NIGHT TEMPERATURES 1970–2024

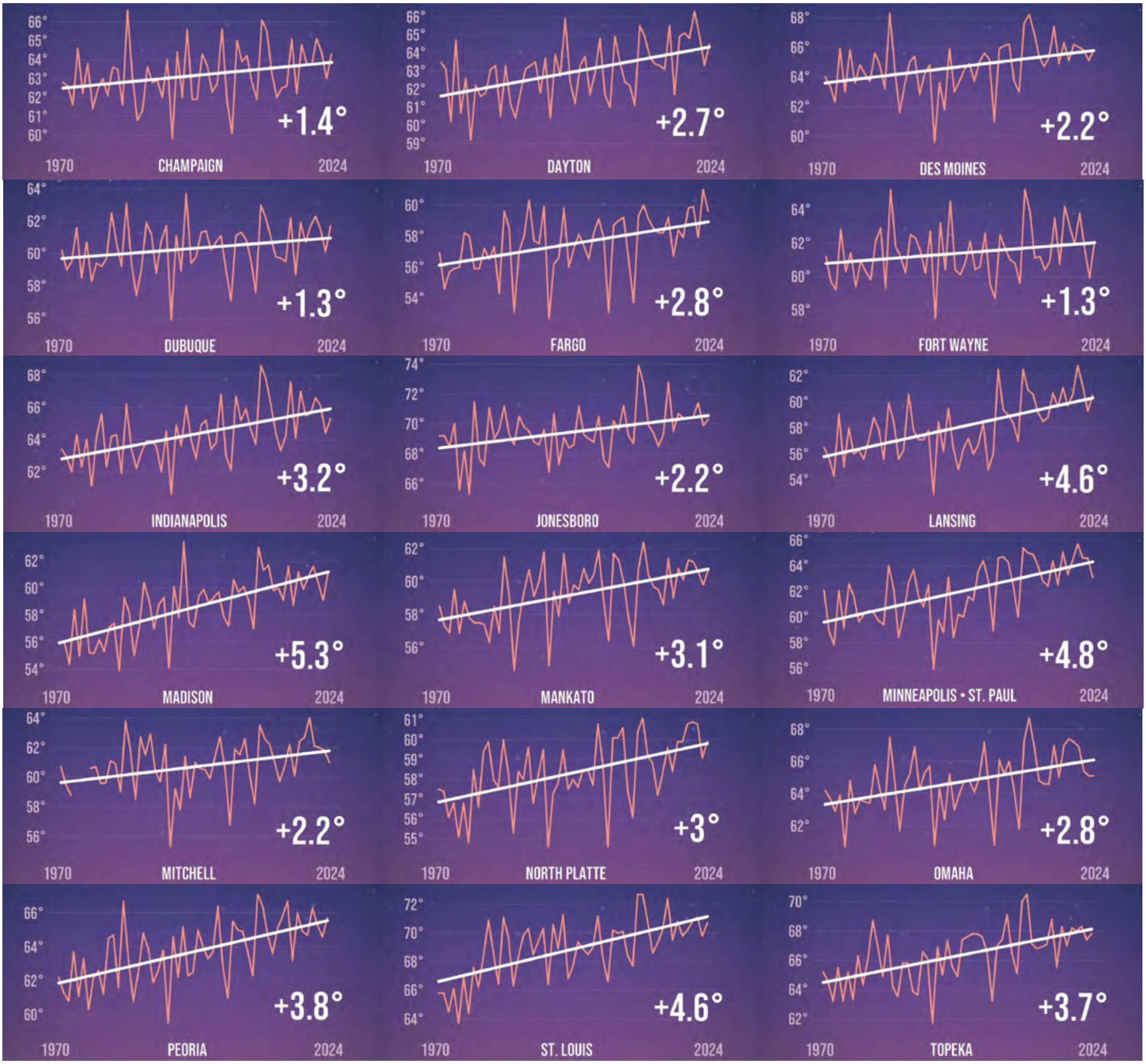


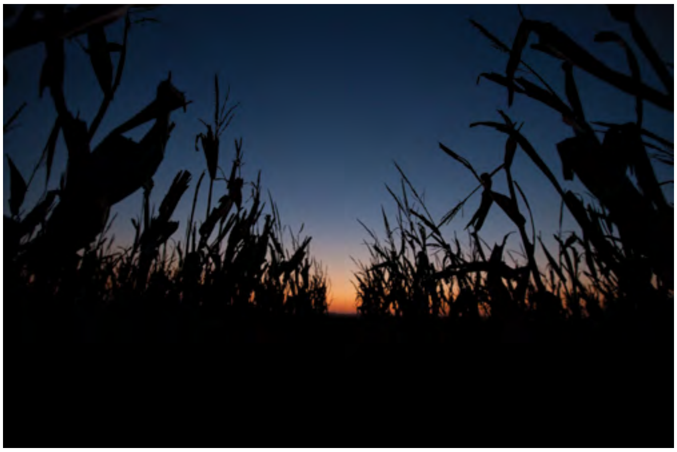
Figure 2. Change in average summer (June, July, August) minimum temperatures from 1970 to 2024 in several U.S. cities located within major corn-producing areas. All charts produced by and used with permission of Climate Central (climatecentral.org) based on data from NOAA (ACIS).

The primary physiological basis for the negative effect of high night temperatures on corn yield is an increased rate of cellular respiration during the nighttime hours.

2022; Niu et al., 2021; Sunoj et al., 2016; Wang et al. 2020). Increased respiration rates associated with high night temperatures have been documented in wheat (Impa et al., 2019) and rice (Mohammed and Tarpley, 2009) as well. High night temperatures can also accelerate corn development rate, which can shorten the length of the grain filling period (Badu-Apraku et al., 1983; Cantarero et al., 1999; Niu et al., 2021). Other effects of high night temperatures on plants can include accelerated leaf senescence (Lesjak and Calderini, 2017), increased water stress (Sadok and Jagadish, 2020), reduced pollen shed and pollen viability (Wang et al., 2020), and reduced photosynthetic rates (Tombesi et al., 2019).

INCREASED CELLULAR RESPIRATION

Cellular respiration is the process by which cells break down sugar to obtain energy for various cellular functions. Cellular respiration consumes carbon assimilated through photosynthesis to obtain the energy necessary to maintain and increase plant biomass.



Respiration can be subdivided into growth respiration and maintenance respiration. Growth respiration is the expenditure of carbon that contributes to the growth of the plant. Maintenance respiration provides energy to processes that do not directly contribute to an increase in plant biomass or plant weight. The two are distinguished based on the relative growth rate of the plant; at a zero growth rate, all respiration contributes to maintenance.

The proportion of respiration contributing to plant growth tends to be greater in younger developing tissues, whereas respiration in mature tissues is mostly for plant maintenance. Maintenance respiration also tends to be greater in the roots than in the above ground portions of the plant. Respiration provides the energy necessary to drive critical plant processes, but respiration can also consume assimilated carbon with little or benefit to the plant. A lower rate of respiration relative to photosynthesis has generally been viewed as favorable for maximizing agricultural productivity and grain yield.

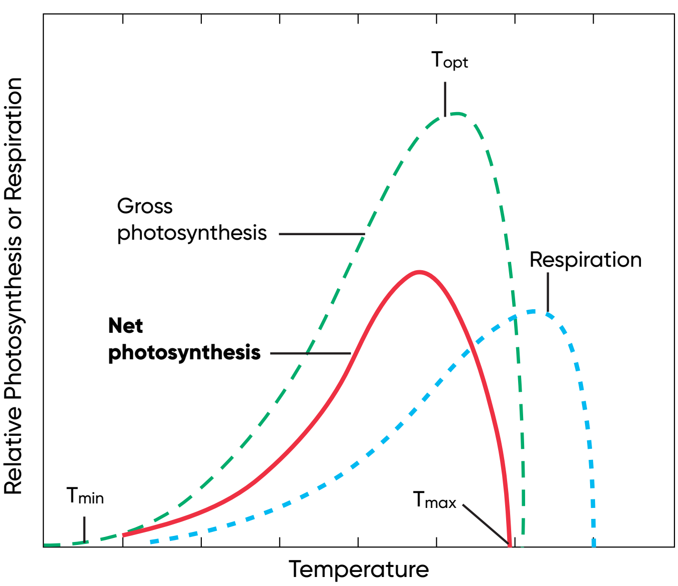


Figure 3. Generalized model of temperature effects on rates of gross photosynthesis, respiration, and net photosynthesis. Net photosynthesis in corn is optimized at 86 °F. (Figure adapted from Hopkins, 1999.)

Both processes are temperature-dependent – photosynthesis and respiration are slow at cooler temperatures, increase as the temperature increases, and cease when the temperature gets too high. The optimum temperature (T_{opt}) for respiration is greater than that for photosynthesis. Net photosynthesis is a measure of carbon assimilated through photosynthesis minus carbon expended through respiration and has a T_{opt} lower than that of gross photosynthesis. Grain yield is more closely associated with the rate of net photosynthesis (the red line in Figure 3).

If night temperature increases, the total expenditure of energy through respiration increases, while the input of energy from photosynthesis remains the same.

Higher night temperatures increase the rate of respiration during the nighttime hours. If the daytime temperature remains the same and the nighttime temperature increases, the total expenditure of energy through respiration increases, while the input of energy from photosynthesis remains the same. The end result is that net photosynthesis decreases, and less assimilated carbon is available for grain fill. This concept is illustrated in Figure 4, which compares plant dry weight accumulation over successive days between warmer and cooler night temperature conditions, assuming equivalent temperatures during the day.

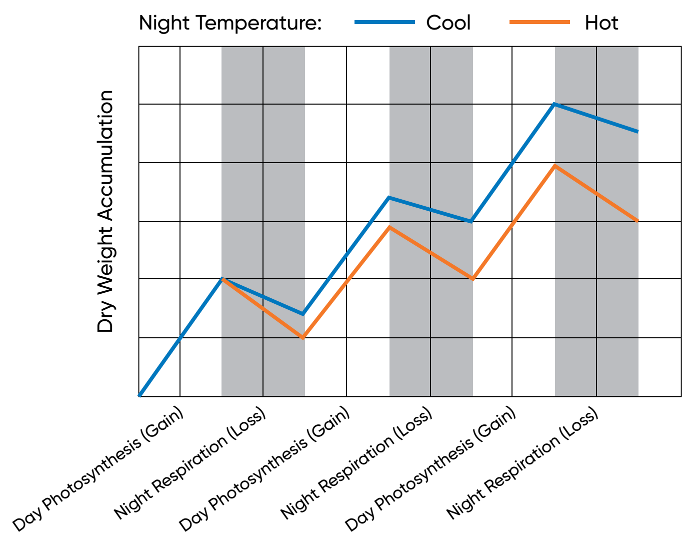


Figure 4. Dry weight accumulation related to night temperature. Growth involves accumulation of dry weight from photosynthesis during the day and loss from respiration at night. (Adapted from Hoeft, et al., 2000.)

ACCELERATED PHENOLOGY

Research has shown that high night temperatures can reduce corn yields by accelerating phenological development resulting in a shorter grain fill period. Phenological development in corn is linked to the accumulation of heat units above a base threshold. For corn, the base level is 50°F and the upper threshold is 86°F. Growing degree unit (GDU) accumulation for a given day is calculated by the formula:

$$\text{GDU} = \left(\frac{\text{Daily Max Temp °F} + \text{Daily Min Temp °F}}{2} \right) - 50\text{°F}$$

Higher temperatures increase GDU accumulation and increase the rate of thermal time that drives plant development. For example, a maximum temperature of 86°F and minimum temperature of 65°F results in a daily GDU accumulation of 25.5. However, a day with the same maximum temperature but a minimum temperature of 72°F results in a daily GDU accumulation of 29.

Accelerated phenology can impact corn yield in a couple of ways. First, it can reduce plant growth rate during the critical period around silking by reducing net photosynthesis relative to thermal time, which can reduce kernel set. Second, it can reduce the duration of the grain fill period. Shortening the length of time between silk emergence and maturity reduces the number of days that the corn plant is engaged in photosynthesis during grain fill, effectively reducing the amount of energy the corn plant can convert into grain yield. Based on long-term average daily minimum and maximum temperatures for Des Moines, IA, a 111 CRM hybrid that reaches 50% silk on July 10 would be predicted to reach physiologically maturity on September 2. A 2-week period following silking during which night temperatures are 5°F above normal would shorten the time to maturity by 2 days.

A 2-week period following silking during which night temperatures are 5°F above normal would shorten the time to maturity by 2 days.

Multiple studies – particularly those in which heat treatments were applied over most or all of the grain fill period – have observed a reduction in the time to physiological maturity. Earlier leaf senescence and physiological maturity were both noted as outcomes of elevated night temperature in the initial University of Illinois study in the late 1960s (Peters et al., 1971). Research conducted by Badu-Apraku et al. (1983) showed that duration of the grain fill period and grain yield per plant were both significantly affected by temperature regime (Table 2). Niu et al., (2021) found a one to three-day reduction in time to physiological maturity when temperatures were raised 4-5°F above ambient over the entire reproductive period.

INCREASED WATER LOSS

Another potential impact of higher night temperatures on corn is greater water loss due to increased evaporative demand (Sadok and Jagadish, 2020). Higher temperatures create a greater vapor pressure deficit (VPD) between the saturated leaf interior of plants and the ambient air. This causes the transpiration rate of plants to increase, placing a greater demand on soil water supply and potentially accelerating the onset of drought stress. VPD increases exponentially with temperature, so relatively small changes in temperature can substantially increase water demand, even though VPD at night is considerably lower than during the day.

Higher temperatures create a greater vapor pressure deficit between the saturated leaf interior of plants and the ambient air.

It was long believed that stomata on the plant leaves were typically closed during the night, which would render any increase in nighttime VPD irrelevant, since transpiration could not occur if the stomata were closed. Recent research has shown this is not the case though. A study in wheat found that nighttime transpiration rates could be as much as 55% of daytime rates under high nighttime VPD conditions (Claverie et al., 2018). A study in corn found nighttime transpiration rates as high as 18% of daytime rates (Tamang and Sadok, 2018), demonstrating that nighttime VPD can have a non-negligible effect on water loss. Another corn field study found increased evapotranspiration and lower soil moisture levels with higher night temperatures, which exacerbated drought stress in one year of the study and led to earlier leaf senescence (Niu et al., 2021).

A common misconception regarding high night temperature effects on corn is that plants must expend energy to cool themselves. While transpiration of water does have a cooling effect on the plant, it is a passive process driven by physical forces that does not require any energy expenditure on the part of the plant. Any increase in energy use associated with high nighttime temperatures is unrelated to cooling the plant.

A common misconception regarding high night temperature effects on corn is that plants must expend energy to cool themselves.

RECENT RESEARCH

Research on the effects of elevated night temperatures have varied in their methodology, including the manner in which heat treatments were applied, as well as the timing, duration, and intensity. Some studies have involved growth chambers in which plants were subjected to fixed and constant day and nighttime temperature regimes (Badu-Apraku et al., 1983; Wang et al. 2020). Other studies involved semi-enclosed structures in the field used to maintain a dynamic temperature treatment at a specific level above the ambient temperature (Hein et al., 2024; Kettler et al. 2022; Kettler et al., 2024; Niu et al., 2021). Timing of high night temperature treatments has most commonly been targeted to the period bracketing or immediately after silking, although some studies have involved elevated night temperatures throughout grainfill, or even over the entire life of the plants. Although there is still much to be learned about the effects of high nighttime temperatures on corn, recent studies do provide insight into some key questions.

HOW HOT IS TOO HOT?

Heat stress effects on corn are incremental and cumulative, which makes it difficult to delineate a specific temperature threshold above which corn yield can be negatively affected. However, research suggests that conditions in which the overnight low temperature remains above 70°F are likely to be detrimental to corn yield. A field study in which corn was subjected temperatures 4-5°F above ambient over the entire grain fill period – increasing the average nighttime low from 66° to 70-71°F – found an average yield reduction of 8% over two years (Niu et al., 2021). Kettler et al. (2024) proposed 73°F as a threshold temperature for nighttime heat stress in corn based on previous research that found a significant increase in respiration above this level (Kettler et al., 2022).

Conditions in which the overnight low temperature remains above 70°F are likely to be detrimental to corn yield.

HOW MUCH CAN YIELD BE AFFECTED?

High night temperatures can significantly reduce corn yield, depending on the severity and duration of heat stress. Niu et al. (2021) found that even a relatively small increase in temperature (from 66° to 70-71°F) could significantly reduce yield (-8%) when it extended over the entire reproductive period. Hein et al. (2024) found a 13.8% reduction in yield, or 2% per °F.

Yield effects of heat treatments applied over shorter durations depend on the intensity of heat. A field study in which night temperatures 4-8°F above ambient (corresponding to an increase of nighttime minimum temperature from 68°F to 73°F) were applied for 15 days following silking found significant effects on respiration, crop growth rate, and kernel number, but no significant reduction in yield (Kettler et al., 2022). Badu-Apraku (1983) found that increasing the nighttime temperature from 59°F to 77°F over a period extending from 18 days after silking through maturity reduced corn yield by 18%. A two-year field study in Argentina found that high night temperature treatments applied for a period of 15 days immediately after silking did not significantly affect yield, but heating applied for a 30-day period did, decreasing yield by around 15% (Kettler et al., 2024).

DO HYBRIDS DIFFER IN RESPONSE TO HIGH NIGHT TEMPERATURES?

Research has found that hybrids can differ in their response to high night temperatures and that hybrids adapted to temperate environments tend to be more susceptible to nighttime heat stress than tropical hybrids. Most studies have only involved one or two hybrids; however, a recent field study conducted in Kansas included 12 hybrids (Hein et al., 2024). This study involved an increase in night temperature of 7°F over the entire reproductive period (corresponded to an increase in the average nighttime minimum temperature from approximately 70°F to 77°F). Results showed an average of 8% lower kernel weight and 14% lower yield (Figure 5). However, results significantly differed among hybrids, with individual hybrid yield response ranging from -28% to +4%, indicating the potential for selecting hybrids with a greater tolerance to high nighttime temperatures.

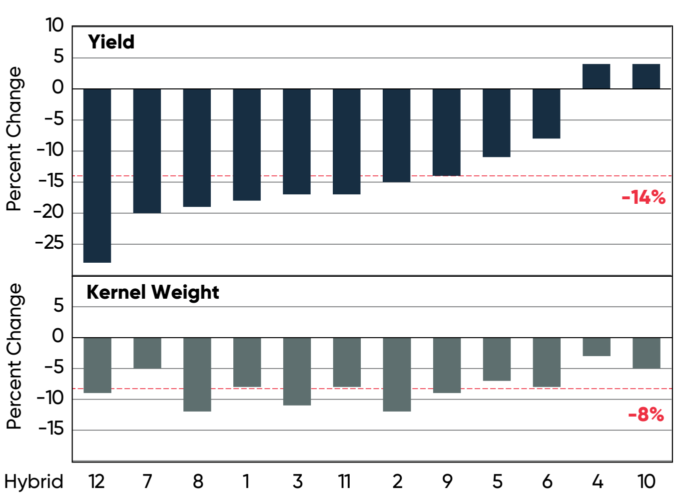


Figure 5. Effect of high night temperature on yield and kernel weight of 12 different temperate hybrids (Hein et al., 2024).

Summer Night Temperatures in 2009 and 2010

The 2009 and 2010 growing seasons in the Midwest provided an interesting case study on the impact of night temperatures on corn yield.

In 2009, many farmers in the Midwestern United States produced record corn grain yields. However, in 2010, even with adequate rainfall, corn grain yields were much lower. In the states of Nebraska, Kansas, Iowa, Missouri, and Illinois, the average minimum night temperatures during July and August of 2009 were about 5° to 8°F lower than the average minimum night temperatures in 2010.

The difference in night temperatures was likely a primary driving factor behind the difference in yield outcomes between the two seasons (Elmore, 2010).

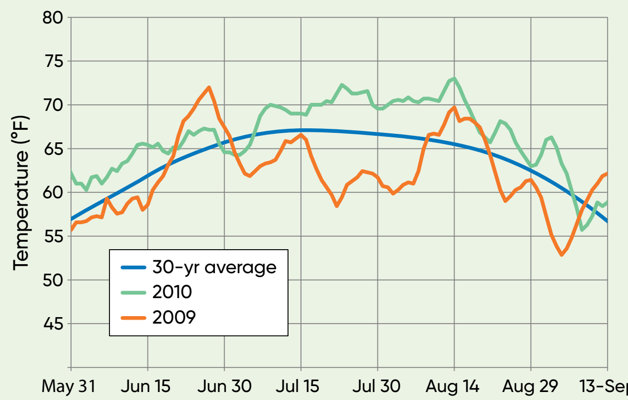


Figure 6. Daily minimum temperatures (7-day moving average) for Des Moines, IA, in 2009 and 2010, and 30-yr average minimum daily temperatures (1981-2010).

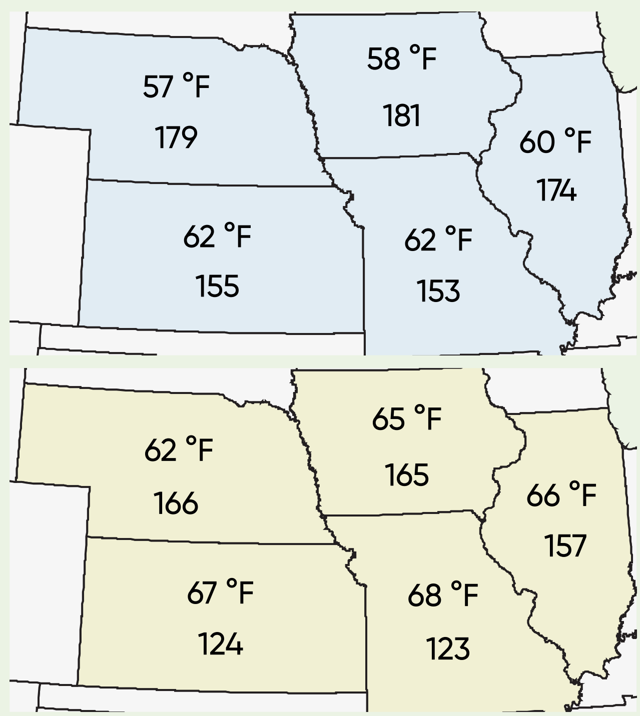


Figure 7. Average minimum temperatures experienced in July-August of 2009 (top) and 2010 (above) and average yields (bu/acre) in Iowa, Illinois, Missouri, Kansas and Nebraska. Data from NCEI NOAA, USDA NASS.

Effects of Flooding on Soil Composition and Plant Nutrient Content in Corn

JACKSON PRESTON, FIELD EXPERIMENTATION INTERN

REBECCA HENSLEY, M.S., SENIOR RESEARCH ASSOCIATE

KEY FINDINGS:

- Corn's recovery from flooding is dependent upon temperature and how long the soil stays saturated; survival rate drops quickly at extended warm temperatures.
- Flooding reduces soil nitrogen availability and impairs nutrient uptake in corn, resulting in multiple nutrient deficiencies.
- Nutrient losses can occur despite fertilizer applications, highlighting the importance of management strategies.

FLOODING EFFECTS ON CORN

- Flooding is a major abiotic stress in U.S. Corn Belt production, causing reduced oxygen in the root zone, impaired nutrient uptake, and potential yield loss.
- Corn's recovery from flooding depends on the temperature and how long the soil stays saturated, with survival dropping quickly at warm temperatures.
- Young corn (before V6) is especially vulnerable with prolonged saturation causing root death, nitrogen loss, and reduced yield potential.
- Since weather is a key uncontrollable factor in corn yield, understanding corn's response to extreme stress, like flooding, is essential for supporting farmers and improving management decisions.
- Late spring and early summer 2025 provided excessive post-planting rainfall in central Indiana (11.5 inches recorded between planting and flowering), which caused standing water and crop stress.

2025 STUDY BACKGROUND

- An opportunistic study of flooding effects was conducted in a research field located near Windfall, Indiana in 2025 after excessive rainfall rendered the experiment originally planned for the site unusable (Figure 1).
- The original experiment involved crop growth model validation and included numerous corn hybrids planted at different populations, and – most importantly – blocks that received a 300 lbs N/acre nitrogen application or zero nitrogen application.
- Starting on April 30, consistent rainfall in both May and June resulted in 9.62 inches of rainfall on the field with extended periods of excessive ponding.
- Average rainfall during this time for the area is around 4.49 inches. In July another 1.92 inches of rainfall received again resulting in excessive ponding.

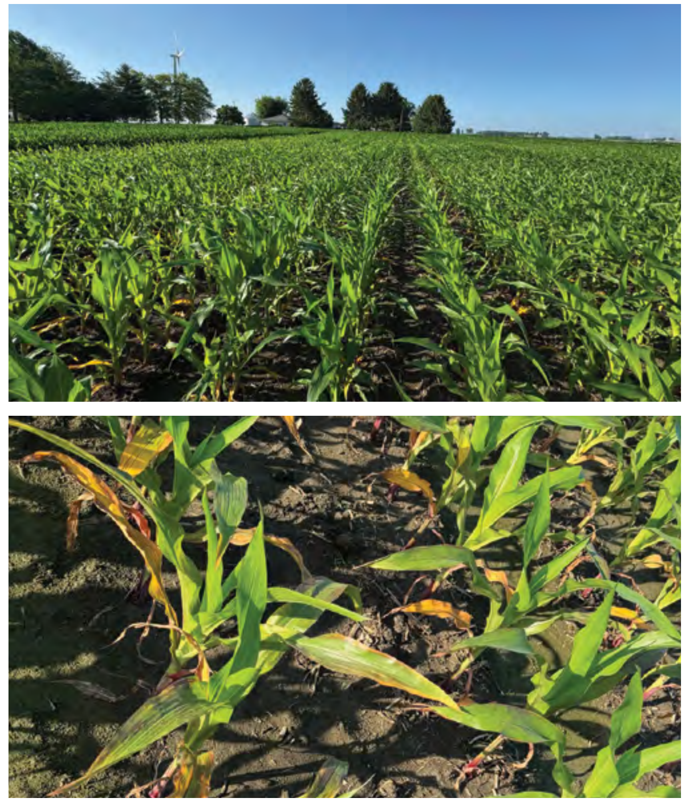


Figure 1. An opportunistic study of flooding effects was conducted in a research field located near Windfall, Indiana in 2025 after excessive rainfall rendered the experiment originally planned for the site unusable.

METHODOLOGY

- The original experiment area was split into blocks that received a 300 lbs N/acre nitrogen application or zero nitrogen application.
- Planting and application of 300 lbs/acre of pre-emergence nitrogen occurred on April 28, with 50% emergence on May 8.
- Each nitrogen block contained planting densities of 22,000 and 44,000 plants/acre.
- The field had 396 lbs/acre potash and 297 lbs/acre of MAP-monoammonium phosphate applied on February 20.
- Sampling areas in the 300 lbs N/acre and 0 lbs N/acre nitrogen blocks with differing levels of flooding damage were identified by NDVI maps by using drone flight imagery on June 17th.
- Figure 2 shows the boxes that indicate the areas of "poor", "average", and "good" crop condition. These were determined based on the images and confirmed in the field by how the plants physically looked in these areas.

Figure 2. NDVI imagery of the experiment field taken on June 17, June 30, and July 30 showing sampling areas representing poor, average, and good crop conditions within the 300 lbs N/acre and 0 lbs N/acre blocks.

- Drone images were collected again on June 30 (image 2) and July 15 (image 3) as we continued to monitor the site.
- Leaf samples (V11 and R1) and soil samples (R1) were collected from these plots and sent to the lab for analysis.
- As shown in Figure 1, significant nutrient deficiency, stunting, and saturated soils were observed in late June.
- Combine yield was recorded on October 2.

RESULTS

- Flooded areas had lower soil nitrate (NO_3-N) and ammonium (NH_4-N), indicating significant nitrogen loss from leaching and denitrification (Figure 3).
- Soil $N0_3$-N levels are considered very low when values are less than 5 ppm, low from 6-10 ppm, medium from 11-20 ppm and high from 21-35 ppm.
- The lowest NH_4-N value recorded was in the plots with zero nitrogen applied pre-emergence; here values were consistently around 2 ppm.
- Post-application NH_4-N generally decreases or remains stable, except in some good-performing plots.
- The highest NO_3-N value was 9 ppm in the 300 lbs N/acre applied plots that were least affected by the flooding ("good" crop condition) while the 300 lbs N/acre applied plots in the flooded area had NO_3-N values ranging from 6.5 to 3.5 ppm still putting all areas of the field in the low to very low category.
- Corn plants from flooded plots showed lower concentrations of nitrogen, reflecting impaired nutrient uptake under saturated conditions (Figure 4).
- These nutrient losses and deficiencies were observed even where fertilizer was applied, as confirmed by tissue analysis, drone imagery, and field observations of increased crop stress through the R1 growth stage.
- At the V11 growth stage, we would expect to see leaf tissue values ranging from 3.5 to 5%. The average nitrogen value at V11 for 300 lbs N/acre was 2.2% while 0 lbs N/acre was 1.7%, showing that there was not much of an advantage to the 300 lbs N/acre rate in the flooded area.
- Overall, the plants were deficient at this time point, affecting crop growth and development.
- Corn yield differences were observed between 0 and 300 lbs N/acre areas, which were expected.
- Hybrid differences within each nitrogen treatment were also observed, possibly indicating differences in flooding stress tolerance.
- Yield differed among the good, average, and poor areas of the 300 lb. treatment block (Table 1).

Table 1. Average corn yield in the good, average, and poor condition areas of the 300 lbs N/acre block.

Sampling Area	Yield (bu/acre)
Good	251
Average	234
Poor	201

CONCLUSION

- Flooding reduces soil nitrogen availability and impairs nutrient uptake in corn, resulting in nitrogen deficiencies.
- Nutrient losses can occur despite fertilizer applications, highlighting the importance of all management strategies.
- Recommendations would include split nitrogen applications, use of nitrogen stabilizers, or rescue nitrogen application pre flowering via aerial application.
- Improvements in field drainage may help reduce nutrient loss and crop stress in flood-prone areas.
- Plant tissue analysis is important for monitoring the effectiveness of fertilizer applications, especially after heavy rainfalls.
- Pairing tissue tests with soil samples provides an understanding of nutrient availability and uptake.
- Significant yield loss is likely to occur in portions of fields where excessive ponding occurred for more than one to two days.
- Depending on the timing of the rain and how much growing season is left, replanting portions of the field may be justified.

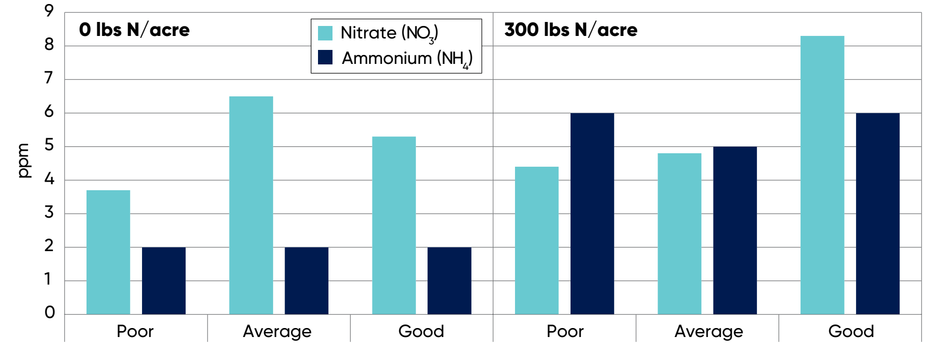


Figure 3. Soil nitrate (NO_3) and ammonium (NH_4) levels in the poor, average, and good crop condition areas of the 0 lbs N/acre and 300 lbs N/acre blocks sampeld at the R1 crop growth stage.

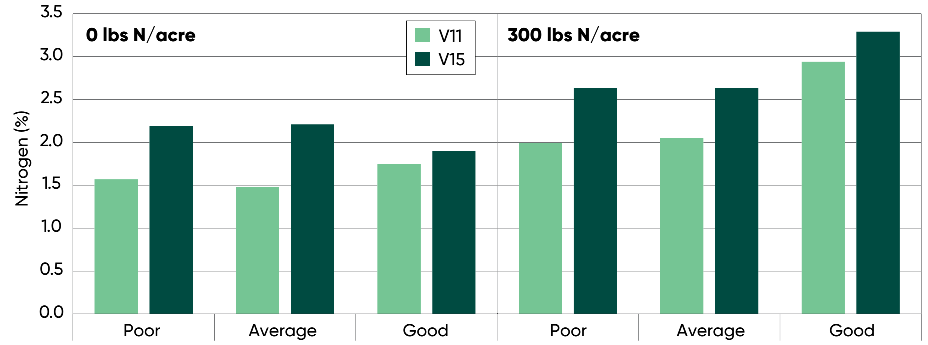


Figure 4. Corn leaf nitrogen levels of plants sampled at the V11 and V15 growth stages in the poor, average, and good crop condition areas of the 0 lbs N/acre and 300 lbs N/acre blocks.

Rootless Corn Syndrome

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Rootless corn occurs when unfavorable soil conditions around the crown of the plant prevent nodal roots from developing normally.
- Rootless corn often becomes apparent between the V3 and V8 growth stages when plants fall over due to their underdeveloped root systems.
- Typically, the best solution to rootless corn is a soaking rain that provides enough moisture around the crown of the plant to sustain the development of new nodal roots.

WHAT IS ROOTLESS CORN SYNDROME?

- Rootless corn syndrome, also referred to as floppy corn, occurs when the nodal root system fails to develop properly, which can cause plants to fall over (Figure 1).
- Affected plants can have few nodal roots or none at all, in which case they will only have the mesocotyl and seminal root system holding them to the ground.
- Rootless corn most commonly becomes apparent between the V3 and V8 growth stages. Affected plants will often appear healthy and vigorous at first but eventually fall over when the underdeveloped root system is no longer able to anchor the growing plant.
- Plants that remain unable to initiate nodal root development may wilt and eventually die.

Figure 1. Rootless corn syndrome caused by shallow planting followed by dry soil conditions.

CORN ROOT DEVELOPMENT

- A corn plant produces two root systems – the seminal root system and the nodal root system (Figure 2).
- The seminal root system is comprised of the radicle and up to three pairs of lateral seminal roots. The seminal roots originate from within the seed embryo and sustain the corn seedling for the first couple of weeks after emergence.
- The nodal roots are the main root system that sustains the plant through the growing season. Nodal roots develop sequentially from individual nodes above the mesocotyl.
- The nodal roots begin development at the junction of the mesocotyl and coleoptile, which is normally ¾ inch below the soil surface for corn planted at adequate depth.
- Roots from the first five stem nodes typically emerge below ground with the first four packed tightly together and the first noticeable internode between nodes four and five.

Figure 2. Left: V1 corn plant prior to nodal root development with only seminal roots. Right: V2 corn plant with nodal roots beginning to develop above the seed.

CONTRIBUTING FACTORS

- Rootless corn occurs when unfavorable soil conditions around the crown of the plant prevent nodal roots from developing normally. There are a number of factors that can contribute to poor nodal root development:
- **Extremely Dry Soil** – Prolonged hot and dry weather early in the season can dry out the soil near the surface, particularly in fields with minimal surface residue.

Figure 3. A corn plant showing rootless corn syndrome that has been dug up showing the seed, mesocotyl, and seminal roots.

- Nodal roots emerging into extremely dry soil can desiccate and die if they are unable to reach soil moisture. Affected roots will appear shriveled and discolored (Figure 3).
- **Shallow Planting** – Planting too shallow causes nodal root initiation to occur closer to the soil surface than at the usual ¾ inch depth, which increases the risk of nodal root initiation into hot and dry soil. Corn should never be planted less than 1 ½ inches deep.
- **Heavy Rain After Planting** – Excessive rainfall after planting can cause subsidence of the soil around the furrow or erosion that removes soil from around the crown of the plant, both of which can increase the risk of poor nodal root development.
- **Compacted Soil** – Compacted soil around the seed can create a physical barrier to root elongation and inhibit nodal root development. This can result from sidewall compaction caused by planting into wet soil.
- **Exposed Crown** – Seed furrows that are not adequately closed or that reopen as soil dries after planting can expose the crowns of developing plants and cause newly initiated roots to desiccate. Loose and/or cloddy soil around the seedling can have the same effect (Figure 5).

Figure 4. A corn plant exhibiting rootless corn syndrome. The mesocotyl is visible anchoring the plant to the ground but nodal roots have failed to develop.

MANAGEMENT OPTIONS

- There is little that can be done to remedy rootless corn once it has occurred.
- In some cases, interrow cultivation may help enable nodal root development by throwing soil around the base of the plants, but this may not be helpful if the soil is already extremely dry and can be difficult to do without burying plants that have already flopped over.
- Typically, the best solution to rootless corn is a soaking rain that provides enough moisture around the crown of the plant to sustain the development of new nodal roots (Figure 6).

Figure 5. Corn plants in field that had severe rootless corn syndrome showing up in many plants. The planter furrow opened back up due to extremely hot and dry conditions following planting. Depth gauge shows that the depth of the "crack" is 2.5 inches - clear down to the depth of the seed.

Figure 6. Corn plants that experienced rootless corn syndrome. The plant on the left was able to recover and successfully developed new nodal roots following a rainfall, while the plant on the right was not able to recover.

Tassel Wrap in Corn

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KEY POINTS

- Tassel wrap – a developmental abnormality of corn in which the uppermost leaves remain wrapped around the emerging tassel instead of unfurling normally – was observed in several states in 2025.
- The widespread occurrence of tassel wrap in 2025 was primarily driven by environmental conditions, with abundant moisture and heat unit accumulation in the growth stages leading up to pollination likely playing a key role.
- Field observations by Corteva scientists suggest that genetic factors also contributed, with corn hybrids characterized by erect leaf architecture in the upper canopy and very aggressive earlier silking more likely to experience tassel wrap.
- In most cases, tassel wrap does not ultimately affect yield; however, reduced kernel set and yield loss can occur if it persists long enough to negatively affect pollination.
- In fields affected by tassel wrap, it is advisable to wait until mid-grain fill stages to evaluate effects on kernel set and its potential yield impact.

TASSEL WRAP IN 2025

In July of 2025, a phenomenon commonly referred to as "tassel wrap" was observed across several states in which the uppermost leaves on corn plants remained wrapped around the emerging tassel instead of unfurling normally. The tassels wrapped in leaves were often partially or completely obstructed in their ability to shed pollen in a timely manner. In most cases there was little or no impact on kernel set. In some cases, this obstruction persisted long enough to negatively affect pollination and result in reduced kernel set.

Tassel wrap was observed in at least 15 different Midwestern and Southern states in 2025 (Squire and Held, 2025; Corteva data). Numerous hybrids with a range of different trait technologies from multiple different seed brands were affected. Within specific geographies it was not uncommon for tassel wrap to be more prevalent within certain hybrids (Licht, 2025; Quinn, 2025) and fields planted within specific windows (Karhoff et al., 2025; Licht, 2025; Quinn, 2025; Roozeboom et al., 2025). Iowa State associate professor Dr. Mark Licht reported that affected fields had tassel wrap on anywhere from 20% to 80% of plants, with less than 50% of plants affected in most cases (Licht, 2025).

POTENTIAL CONTRIBUTING FACTORS

Agronomists believe this issue was primarily associated with a later than normal manifestation of rapid growth syndrome – a phenomenon that normally appears earlier in the vegetative stages in which an abrupt acceleration in plant growth causes the plant leaves to become tightly wrapped as new leaves emerge faster than existing leaves are able to unfurl (Karhoff et al., 2025; Licht, 2025; Quinn, 2025). When rapid growth syndrome occurs during vegetative growth, it typically resolves on its own and has little or no impact on yield.

A sudden acceleration in growth can cause the leaves in the whorl to become twisted or tightly wrapped, as the inner leaves grow faster than the outer leaves can unfurl.

Rapid growth syndrome is relatively common in corn and is brought on when environmental conditions suddenly shift from unfavorable to very favorable for corn growth (Jeschke, 2020). When rapid growth syndrome occurs earlier in the growing season, it is most commonly associated with a shift from cooler to warmer temperatures, but it can also involve a shift from overcast to sunny conditions, an increase in soil water availability, or any combination of these factors that cause the plants to sharply transition from slow to rapid growth. This sudden acceleration in growth can cause the leaves in the whorl to become twisted or tightly wrapped, as the inner leaves grow faster than the outer leaves can unfurl. Rapid growth syndrome most commonly occurs at the V5-V6 growth stage but can be observed as late as V12. Occurrences of rapid growth syndrome late enough in the season to impede tassel emergence are less common.

In addition to a rapid acceleration in growth, other environmentally driven factors may contribute to the occurrence of tassel wrap as well. Environmental conditions during late vegetative growth can cause a shortening of the upper internodes. This can lead to a

Figure 1. Tassel wrap in a Missouri corn field; July 2, 2025.

compression in leaf structure and less room for tassel extension, particularly in cases where corn is shorter overall. Environmental conditions that cause plants to produce smaller tassels with fewer branches may contribute as well, as there is less tassel mass to push the flag leaf open. Fields experiencing tassel wrap in 2025 were noted in some cases as having smaller tassels with fewer branches (Licht, 2025; Quinn, 2025).

GENETIC AND ENVIRONMENTAL FACTORS IN 2025

Field observations by Corteva scientists suggest that occurrences of tassel wrap in 2025 likely involved an interaction of multiple genetic and environmental factors. Hybrids with the most frequent occurrence of tassel wrap tended to have some combination of three characteristics: erect leaf architecture in the upper canopy, minimally branched tassels, and negative anthesis-silking interval. All three of these characteristics have been important in driving yield gain in corn and have been directly or indirectly selected for by corn breeding programs.

Occurrences of tassel wrap in 2025 likely involved an interaction of multiple genetic and environmental factors.

The shift toward more upright leaves in corn hybrids that began early in the 1960s has been important for supporting greater plant densities and maximizing radiation use efficiency by enabling light penetration deeper into the canopy (Duvick et al., 2004). Smaller tassels with fewer branches have provided a more optimal allocation of biomass in the plant, favoring photosynthesizing tissues and harvestable yield. And shortening the anthesis-silking interval (the amount of time between pollen shed and silk emergence) has been critically important in improving drought tolerance in corn. All these changes have occurred across US commercial germplasm through selection for higher yields and have not been unique to Corteva/Pioneer.

Figure 2. Comparison of tassels from three hybrids grown side by side. The middle tassel displays tassel wrap, with pollen being released within the upper leaves and only the tip of the tassel exposed. The tassels on either side show normal development and pollen shed.

Of these three characteristics, erect leaf architecture in the upper canopy and very aggressive earlier silking appear to be closely associated with occurrences of tassel wrap problems affecting pollination during 2025.

While hybrid characteristics no doubt contributed to tassel wrap, its uniquely widespread occurrence in 2025 clearly demonstrates that abnormal environmental conditions were the dominant driving factor. Above-average total rainfall appears to be the environmental anomaly in 2025 that correlates most to tassel wrap occurrence (Figure 3), specifically more rainfall and lower vapor pressure deficit from V7 to V14 (Figure 5). Greater water availability is known to induce more rapid plant growth and earlier appearance of silks relative to pollen shed. Much of the area that experienced tassel wrap also had below average GDU accumulation earlier in the season (Figure 4), so the shift from slow growth to rapid growth conditions may have been a factor.

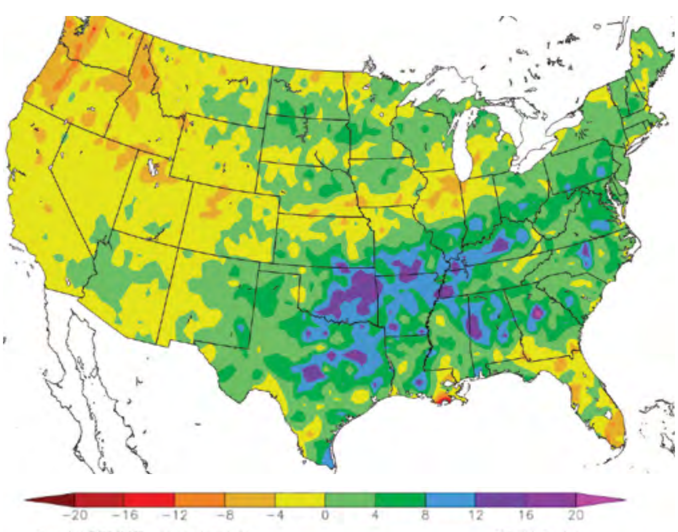


Figure 3. Precipitation anomaly for the 120-day period from March 26 to July 23, 2025 (High Plains Regional Climate Center). Areas with the greatest prevalence of tassel wrap in the southern Corn Belt and Midsouth tended to have greater than normal precipitation, although cases were also being reported in northern regions with precipitation closer to normal.

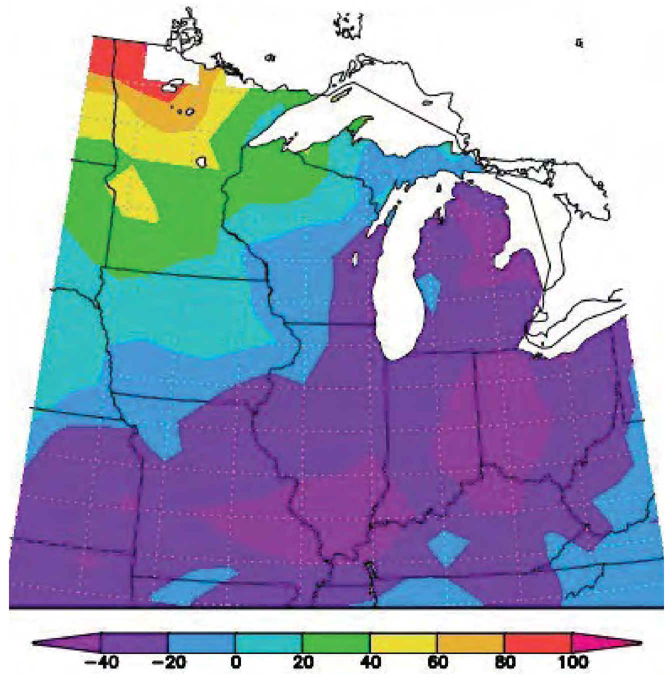


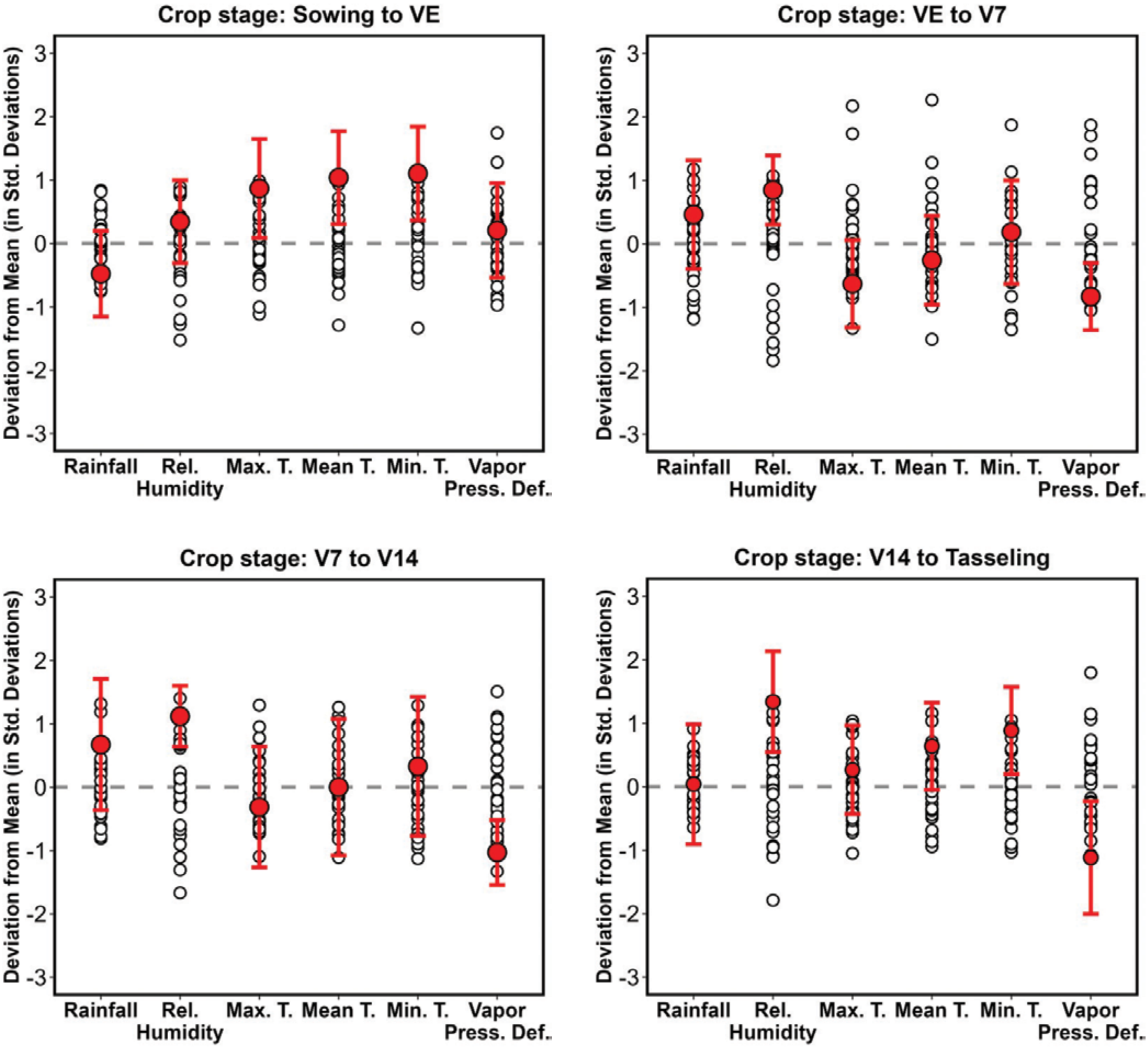
Figure 4. Growing degree unit accumulation deviation from normal for the period of May 1 to 27, 2025 (Midwestern Regional Climate Center).

IMPACT ON POLLINATION

Successful pollination depends on the synchronization of pollen shed with the presence of receptive silks. Silks on a corn ear typically emerge over a period of four to eight days. This process is sequential, with silks from the basal portion of the ear emerging first, followed by silks from the middle and tip of the ear. Silks grow about 1 to 1.5 inches a day and will continue to elongate until fertilized. Silks are receptive to pollen for up to 10 days after they emerge from the husk, but their receptivity is highest during the first four to five days. After about five days, silk receptivity begins to decline, and after 10 days, it decreases rapidly due to natural senescence of the silk tissue.

When normal tassel emergence and pollen shed is impeded by leaves remaining wrapped around the tassel, the result can be a delay in pollen shed relative to silk emergence and a reduction in pollen load, both of which can reduce kernel set and – ultimately – yield. This was the case in at least some of the fields impacted by tassel wrap in 2025.

Silks are receptive to pollen for up to 10 days after they emerge from the husk, with greatest receptivity during the first 4 to 5 days.



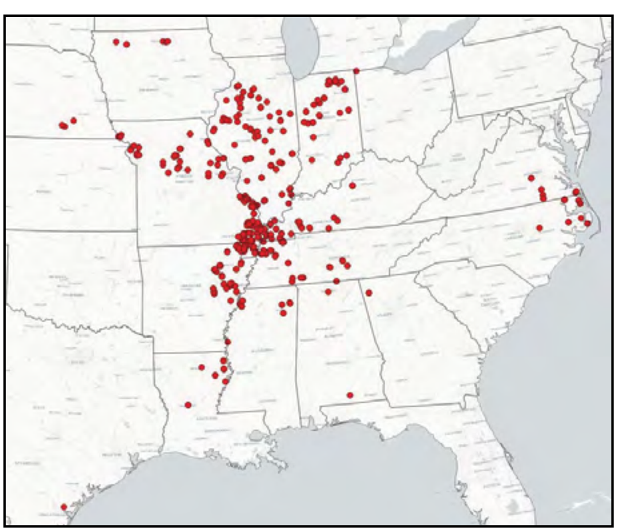


Figure 5. Weather conditions in 2025 compared to the previous 30 years for a set of locations with reported tassel wrap incidents. The data illustrate rainfall, relative humidity, mean temperature, maximum and minimum temperatures, and vapor pressure deficit across key growth stages—planting to tasseling, planting to emergence, emergence to V7, V7 to V14, and V14 to tasseling—for 64 reported tassel wrap cases across the U.S.

ENVIRONMENTAL FACTORS AND DEVELOPMENT ISSUES

Although the 2025 growing season saw the most widespread occurrence of tassel wrap in recent memory, similar situations have occurred in recent years in which an acute stress event or an unusual confluence of environmental conditions during the critical period around silking in corn resulted in occurrences of abnormal crop development appearing over a wide area. Recent examples include 2021, when corn plants producing multiple ears on the same shank were observed across multiple states (Jeschke, 2021) and 2016, when abnormalities in ear development occurred across much of the Western and Central Corn Belt (Jeschke, 2016a, 2016b, 2016c).

In 2021, the development of multiple ears per shank was believed to be associated with a hormonal imbalance triggered by some sort of early season stress that disrupted the apical dominance of the primary ear, followed by favorable growing conditions that allowed secondary ears to develop. Abnormal ear development in 2016 seemed to be associated with a confluence of multiple stress factors, including a rapid transition from cold to hot temperatures, an extended period of low solar radiation, and high winds that damaged plants as they were nearing pollination.

The occurrence of abnormal development issues in corn is partly attributable to the basic biology of the corn plant itself, and the ability of environmental stresses that affect the plant during critical developmental stages to have a lasting effect on plant development. It is not unusual for instances of abnormal development to show up more in some hybrids than in others. In some cases, this may have more to do with crop phenology – the exact stage of development the crop was in when exposed to the environmental conditions that triggered abnormal development – which is a function of hybrid maturity, planting date, and GDU accumulation.

In cases like the one shown in Figure 2, the wrapped tassels begin shedding pollen while still wrapped in the upper leaves. Pollen loses viability as soon as it comes into contact with water. The pollen shed inside the wrapped leaves is lost and not able to contribute to pollination once the tassel was able to emerge. The tassels will ultimately expand from the leaves and will shed pollen, but significantly later.

Pollen shed across a field of corn typically lasts 10 to 14 days, with around a 4-day period when pollen shed is at its peak. Pollen shed from an individual plant occurs over a shorter period – typically not more than 7 days. Plant-to-plant variability in the timing of peak pollen shed, along with the sheer volume of pollen produced (estimates range from 2 million to 25 million grains per plant), typically provides a margin of safety for achieving complete pollination. Even if unfavorable conditions disrupt pollination for a few days, there is still usually enough time and pollen available to complete pollination without issue.

When pollen shed is impeded for more than a few days, it is possible that incomplete pollination can result. This can be due to insufficient pollen availability during the window of silk receptivity. Since silks continue to elongate until they are fertilized, early emerging silks that remain unfertilized will continue to grow. The resulting mass of silk growth can sometimes obstruct fertilization of newly emerged silks from ovules further up the ear.

Earlier silking respective to pollen shed has been a direct focus of corn breeders for a long time, especially because of its positive effect on drought tolerance. Old hybrids, with lower drought tolerance, tended to extrude silks later than pollen shed when under drought stress, limiting their ability to yield due to limited exposure of silks to pollen availability. Modern high-yielding hybrids have been bred to extrude silks earlier than pollen shed, even under severe drought conditions. The shift in earlier silking has been a key trait responsible for the greater drought tolerance of modern germplasm.

PREVIOUS EXPERIENCES WITH TASSEL WRAP

The widespread nature of tassel wrap in 2025 meant that many corn growers and agronomists were likely seeing it for the first time, but more limited occurrences were observed by Corteva scientists in previous years, affecting different geographies each year. Prior experience with tassel wrap has shown that, while some hybrid genetics may be more prone to it, all genetics can be affected by it with the right environmental factors. Some older hybrids that experienced tassel wrap in 2025 had never shown it before.

Some older hybrids that experienced tassel wrap in 2025 had never shown it before.

In previous years, the vast majority of fields experiencing tassel wrap ultimately saw no impact on corn yield. In cases where the duration of tassel obstruction was sufficient to affect pollination, the most common outcomes were missing kernels concentrated near the base of the ear or on one side of the ear and unevenness of early kernel growth resulting from the fertilization of individual ovules occurring over a longer period of time.

Figure 6. Ears from a field where tassel wrap resulted in incomplete pollination sampled on July 11 (left) and July 25 (right). Ears sampled on July 11 show missing kernels and inconsistent kernel size and color due to variation in fertilization timing. Ears sampled on July 25 show more consistent kernel color and compensatory growth where kernels adjacent to gaps have expanded into the empty space.

The effect of uneven pollination timing can look worse than it actually is if evaluated too early after fertilization. Ovules that are fertilized a few days later than those adjacent to them will be smaller and lighter in color through the early stages of kernel growth but will even out somewhat as grain fill proceeds (Figure 6). The effect of missing kernels can also not be as bad as it may initially appear.

Figure 7. Tassel wrap in a Missouri corn field; July 7, 2025.

Although missing kernels generally have a negative effect on yield, the plant does have some capacity to compensate for missing kernels through greater kernel weight. Kernels adjacent to gaps will expand into the empty spaces, and kernel weight overall can be greater as the plant allocates the same amount of photosynthate over a smaller number of kernels. Ears with poor pollination at the base often have lower tip kernel abortion. The percentage yield loss will be lower than the percentage of missing kernels (Table 1). In fields affected by tassel wrap, it is advisable to wait until mid-grain fill stages to evaluate effects on kernel set and its potential yield impact.

Missing kernels generally have a negative effect on yield but the plant does have some capacity to compensate for missing kernels through greater kernel weight.

Table 1. Estimated reduction in plant yield associated with incomplete pollination (Borrás et al., 2004; Westgate et al., 2003).

Kernel Loss (%)	Yield Loss (%)
10	2.5 - 4.6
20	7.2 - 11.8
30	18.8 - 20.3
40	30.1 - 30.4
50	41.2 - 42.0

CONCLUSIONS

Each growing season brings a unique set of conditions and challenges and 2025 has been no exception. Abnormal environmental conditions, especially abundant water availability leading up to pollination, were likely the main cause of the higher-than-normal occurrence of tassel wrap in 2025. Earlier silking relative to pollen shed driven by extraordinarily good growing conditions might have exacerbated the problem. The wide geographic range of reported occurrences, as well as the fact that it showed up across numerous different hybrids, trait technologies, and seed brands, clearly points to environmental conditions as the primary driver.

Fields experiencing tassel wrap in previous years usually saw no effect on yield; however, reductions in kernel set associated with tassel wrap were observed in some cases in 2025. Fields that experienced tassel wrap should be evaluated around mid-grain filling so the end effect on kernel set is fully visible. Kernel weight compensation will occur on ears with missing kernels, which means that yield loss will not be directly proportional to the number of missing kernels.

Corn Stunt Disease in the U.S.

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Corn stunt is one of the most economically important diseases affecting corn in South America but is less known in the U.S. because it is generally confined to the southernmost parts of the country.
- The primary causal organism for corn stunt disease is *Spiroplasma kunkelii*, a bacterial pathogen commonly referred to as corn stunt spiroplasma (CSS).
- *S. kunkelii* is transmitted by corn leafhoppers (*Dalbulus maidis*), which acquire the pathogen by feeding on infected plants and spread it by feeding on healthy plants.
- Infected plants can have dramatically shortened internodes resulting in the characteristic plant stunting.
- Ears of infected plants are smaller than normal and do not fill properly.
- Management of corn stunt disease is focused on preventing infection by managing the insect vector.

Understanding Corn Stunt
- Forward-thinking Farming webinar

CORN STUNT: A MAJOR DISEASE OF CORN

Corn stunt is one of the most economically important diseases affecting corn in the Americas and the Caribbean. As the name implies, corn stunt disease is characterized by severely stunted plants that often produce multiple small ears with loose or missing kernels. Yield loss associated with corn stunt disease can be severe – over 70% – and major outbreaks have impacted yields in Brazil and Argentina in recent years.

Corn stunt disease is less known in the U.S. because it is generally confined to the southernmost parts of the country. Outbreaks have occurred previously in the U.S. – in Florida in 1979-1980 and in California in 2001. However, an unprecedented outbreak that impacted corn in several states in 2024 has led to some concern that occurrence of corn stunt disease could become more frequent and widespread.

CAUSAL PATHOGENS

The primary causal organism for corn stunt disease is *Spiroplasma kunkelii*, a bacterial pathogen commonly referred to as corn stunt spiroplasma (CSS). *Spiroplasma* is a genus within Mollicutes, a class of small bacteria that share the common feature of not having a cell wall, unlike most bacteria. Mollicutes are parasites of various animals and plants, living on or in the host's cells.

S. kunkelii is transmitted by corn leafhoppers (*Dalbulus maidis*), which acquire the pathogen by feeding on infected plants and spread it as they subsequently feed on healthy plants. This bacterial pathogen is transmitted singly or in combination with maize bushy stunt phytoplasma (MBSP), maize rayado fino virus (MRFV), and/or sugarcane mosaic virus. Because of the multiple pathogens involved, corn stunt disease is often referred to as a disease complex.

Figure 1. Corn plants exhibiting symptoms of corn stunt disease in Texas in 2024.

DISEASE SYMPTOMS

The initial symptoms of corn stunt are small chlorotic stripes that develop at the base of the leaves. Over time, these chlorotic stripes expand and coalesce, extending further toward the leaf tips on older leaves. As infected plants age, they may develop a reddish or reddish-purple color, although this can vary by hybrid and environmental conditions (Figure 1). Eventually, leaves on infected plants may die prematurely.

Infected plants can have shortened internodes resulting in the characteristic plant stunting. Plants infected early in their development may reach a final height of only 5 feet (1.5 m) (Figure 2), whereas infection later in the season may cause little or no stunting. Infection can cause a proliferation of secondary shoots in leaf axils, and plants may develop multiple small ears.

Ears of infected plants are smaller than normal and do not fill properly. Ears often have blank spaces, and kernels that do develop are loosely attached to the cob, a condition sometimes referred to as "loose tooth ears" (Figure 3).

Figure 2. Corn plants in a field in Puerto Rico with severely shortened internodes resulting from corn stunt disease. The degree of stunting indicates that infection occurred early in development.

Figure 3. Ears on corn plants infected with corn stunt disease displaying characteristic symptoms — reduced ear size, poor kernel fill, and blank spaces.

Figure 4. Corn plants in a field in southern Texas in 2024 showing corn stunt symptoms consistent with infection later in the season. Foliar symptoms are present but there is minimal stunting. Foliar symptoms progress from leaf chlorosis and reddish coloration along the midribs (left) to premature death of leaf tissue (right).

Symptoms of corn stunt disease observed in the U.S. are generally less severe than those associated with corn stunt disease in South America and the Caribbean due to the timing of infection. Outbreaks of corn stunt in the U.S. are largely driven by leafhopper populations moving northward from Mexico, which results in infection later in the growing season compared to places like Brazil where corn leafhopper populations are present year-round, and infection can occur much earlier.

The corn stunt disease outbreak in Texas and Oklahoma in 2024 was driven by corn leafhopper feeding that likely started during late vegetative growth stages. Infected plants showed foliar symptoms but had little or no stunting since infection occurred after vegetative growth was completed or nearly completed (Figure 4). Ear symptomology ranged from total kernel abortion to reduced kernel fill and smaller ear size (Figures 5 and 6).

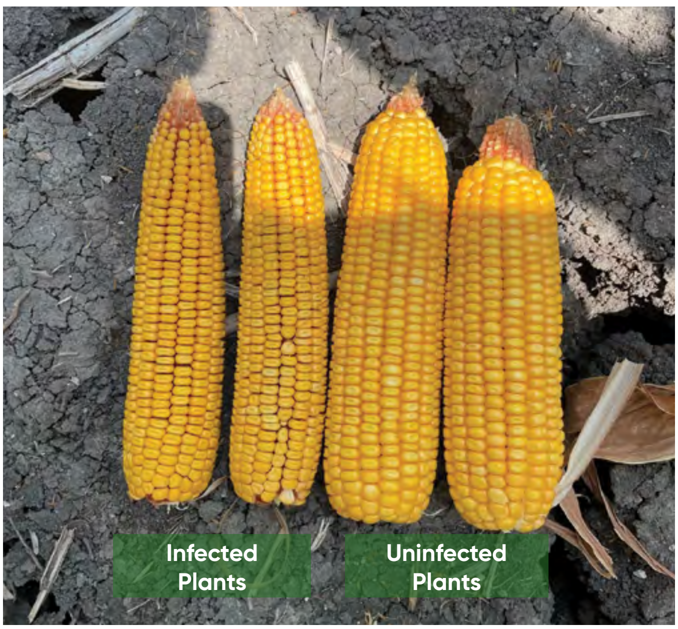


Figure 5. Ears from corn stunt infected and uninfected plants showing poorly filled kernels on the infected plant ears.

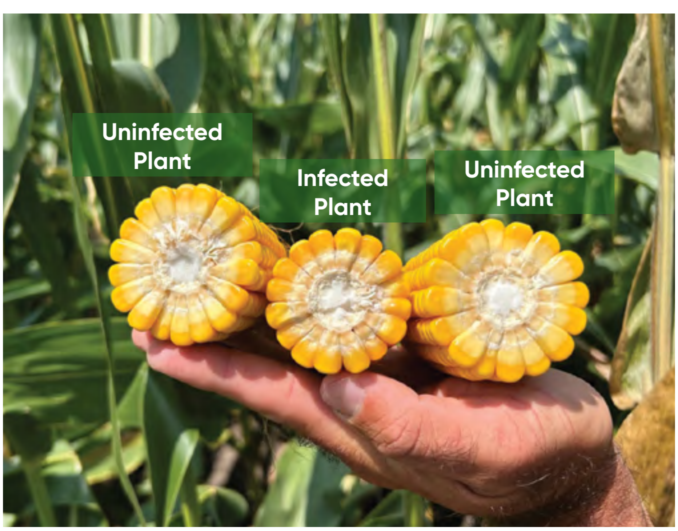


Figure 6. Ears from corn stunt infected and uninfected plants showing reduced kernel depth and ear girth of infected plants.

DISEASE LIFECYCLE

Although a complex of pathogens is associated with corn stunt disease, *Spiroplasma kunkelii* appears to be the major component of this disease. *S. kunkelii* is transmitted by leafhoppers, mainly corn leafhoppers (*D. maidis*) but the Mexican corn leafhopper (*D. elimatus*) has also been reported as a vector. Corn leafhoppers spread the disease by carrying the spiroplasma from diseased corn to healthy corn as they feed on the phloem sap of corn plants. Corn stunt pathogens are not transmitted through seed; the only way for a plant to become infected is through leafhopper feeding.

S. kunkelii lives in the phloem sieve tubes of infected host plants. Disease symptoms appear about 3 weeks after corn is infected. The exact mechanism or mechanisms by which the pathogens associated with corn stunt disease damage the plant are not fully understood.

Multiplication of the bacterium occurs both in the plant and in the insect hosts. Multiplication ceases when the temperature drops below 64°F (18°C). Spiroplasmas overwinter within adult leafhoppers, and when they resume activity in early spring, they can be infective.

CORN LEAFHOPPERS

HOST SPECIES

The most critical factor in the corn stunt disease pathosystem is not the pathogen, but rather the vector – the movement and proliferation of leafhoppers have been shown to drive corn stunt outbreaks. *D. maidis* has a limited host range, feeding only on corn, its wild relatives in the genus *Zea* and grasses in the closely related genus *Tripsacum*. *D. maidis* likely originated in the high valleys in the central region of Mexico, where it evolved alongside the wild ancestors of corn native to this region.

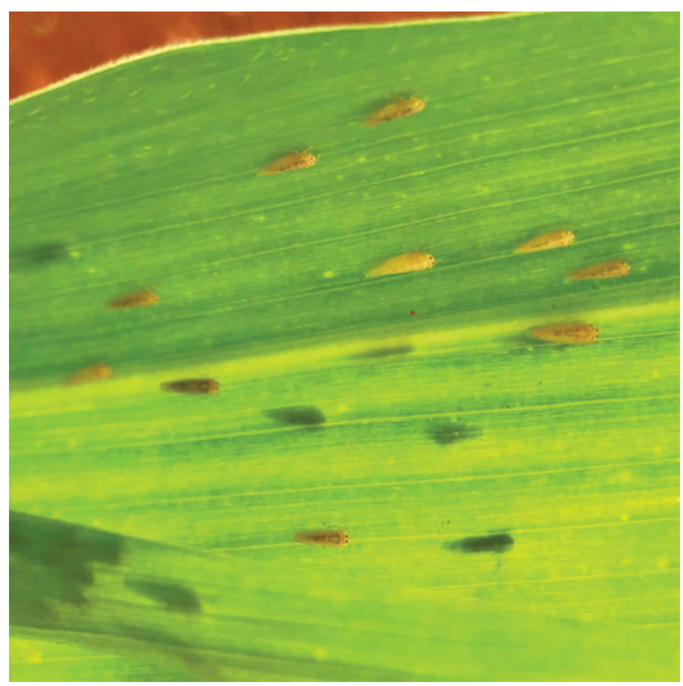


Figure 7. Adult corn leafhoppers (*D. maidis*) on a corn leaf.

Figure 8. *D. maidis* adults. Photos courtesy of and used with permission of Ashleigh M. Faris, Ph.D., Oklahoma State University.

A Corteva Agriscience study of potential alternate hosts – including sorghum, sugarcane, johnsongrass, pearl millet, soybean, and several species of pasture grass – found that corn was the only host plant on which leafhopper reproduction occurred. Other grass crops such as wheat and sorghum, as well as Bermudagrass, can serve as a reservoir for leafhopper populations – giving them a place to persist when no corn is available – but reproduction only occurs on corn.

MOVEMENT INTO THE U.S.

Outbreaks of corn stunt in the U.S. are likely driven by leafhopper populations moving up from Mexico, where corn is under continuous cultivation. Leafhoppers populations can move with prevailing winds, sometimes over long distances. Previous outbreaks of corn stunt disease in southern Florida are believed to have been caused by leafhopper populations carried in with tropical storms. The spread of leafhoppers further north into the U.S. is limited by cold temperatures and lack of secondary hosts to provide a year-round source of food. Direct plant damage caused by corn leafhopper feeding is rarely significant – the primary economic importance of the corn leafhopper is its role as a disease vector.

LIFECYCLE

D. maidis begins as an egg and then undergoes five nymphal instars before reaching adulthood (Figure 8). Females insert eggs into the mesophyll of the upper surface of corn leaves, often in the whorls of corn seedlings. The first nymphal instar will hatch around 8 to 10 days after oviposition. First instars are less than 1 mm long and last instars are around 4 mm long. Each nymphal stage averages 3 to 4 days, with the total time to adulthood averaging 14 to 16 days.

Adult longevity averages 60 to 80 days. Mature females oviposit an average of 15 eggs per day for most of their adult life. Corn stunt pathogens are not transmitted through leafhopper reproduction.

Corn leafhoppers do not enter any type of overwinter dormancy; populations survive as active adults. Under optimal conditions, corn leafhopper adults can survive without reproducing for up to three months.

BIOLOGY AND ECOLOGY

The number of corn leafhopper generations per year can vary greatly based on environmental conditions and host availability. Temperature has a significant influence on corn leafhopper development and reproduction. *D. maidis* requires 648 degree-days above a threshold of 41°F (4.9°C) to complete its lifecycle. The optimum temperature range for corn leafhopper reproduction is 72 to 77°F (20 to 22°C); at temperatures below this range, reproduction sharply declines.

In the least favorable environments, a minimum of two generations of corn leafhoppers will develop on a single corn crop. In areas with favorable temperatures where corn is grown throughout the year – particularly corn under irrigation – corn leafhoppers can go through more than 12 generations per year. In areas with year-round corn production, the corn leafhopper maintains breeding populations throughout the year, which can allow populations to grow very large.

MANAGEMENT CONSIDERATIONS

LEAFHOPPER CONTROL

There are no management tools available to combat the pathogen complex that causes corn stunt disease, so management is focused on preventing infection by managing the insect vector. Field experience with managing corn leafhoppers thus far is largely from South America where corn stunt disease is a much more persistent and serious threat to corn. Yield loss potential depends on growth stage of corn when infected; the earlier infection occurs, the greater the impact on yield.

Outbreaks of corn stunt disease in the U.S. have generally occurred later in the growing season, driven by corn leafhopper populations that moved northward from Mexico. The corn stunt outbreak in California in 2001 was a notable exception, where symptoms appeared earlier in the season. In this case, it was suspected that the mild winter of 2000-2001 allowed local overwintering of a population of corn leafhoppers carrying *S. kunkelii*. The timing of the 2024 outbreak in Texas and Oklahoma was more typical of U.S. outbreaks, with symptoms appearing later in the season.

INSECTICIDES

Insecticides are commonly used in South America to prevent the spread of corn stunt disease by controlling corn leafhoppers. In Brazil, corn is commonly treated three to six times per crop for control of corn leafhoppers. Insecticide seed treatments containing clothianidin or imidacloprid can provide control of corn leafhoppers following emergence, but seed treatment efficacy does not last beyond the V3 growth stage. The threshold is for foliar insecticide treatment is the presence of corn leafhoppers. A Corteva Agriscience greenhouse study found that as few as two leafhoppers per plant feeding for just one day was enough to compromise corn yield. Reinfestation can occur quickly, so multiple applications may be necessary if feeding begins early. Feeding often begins along the edges of fields as leafhoppers move in, so treatment may be focused on field margins.

Figure 9. Corn leafhoppers require the presence of living corn plants to feed and reproduce. Volunteer corn can serve as a "green bridge" that allows leafhopper populations to persist in a rotational crop such as soybeans.

CULTURAL PRACTICES

The key factor for corn leafhopper reproduction is the presence of corn plants on which to feed and reproduce, so cultural control practices are largely focused on eliminating the continuous presence of corn (referred to as a "green bridge"). Crop rotation, narrowing the planting window, and controlling volunteer corn are all practices that have been employed to manage corn leafhopper populations. However, given the mobility of corn leafhoppers, efforts to eliminate green bridges would need to be employed at an area-wide scale to be impactful.

GENETIC RESISTANCE

Corn hybrids can differ in their resistance to corn leafhopper feeding. Resistance works via reduced feeding preference (antixenosis) or survival (antibiosis), both of which reduce the duration of insect-plant interaction, which reduces the inoculation efficiency of *S. kunkelii*. In countries such as Brazil, where corn stunt disease is a persistent threat, hybrids are rated for their resistance to leafhoppers and susceptible hybrids are not advanced to commercial status. Corn hybrids resistant to corn leafhopper feeding have been an important tool for management of corn stunt disease in Brazil; however, experience has shown that hybrid resistance can be overcome by intense leafhopper feeding pressure. Given the infrequency of corn stunt outbreaks in the U.S., no such ratings for corn hybrids have been developed here.

FUTURE OUTLOOK

Corn stunt has historically been a sporadic disease in the U.S. and limited to the southernmost corn production areas of the country; however, it could become a more frequent and widespread occurrence in the future. Prior to 2024, *S. kunkelii* had rarely been detected in field samples of corn outside of California, Florida, and Texas. In 2024, field samples positive for *S. kunkelii* were confirmed in 12 states, extending as far north as Minnesota, Wisconsin, and New York – extending beyond its previously documented range (Duffeck et al., 2025; Corteva Diagnostic Lab). Corn stunt was more limited in 2025 – with field samples testing positive for *S. kunkelii* in Texas, Arizona, Oklahoma, and Kansas – but still beyond its historic range (Table 1).

Table 1. States with positive detections of *S. kunkelii* by year since 2001 (Duffeck et al., 2025; Corteva Diagnostic Lab).

Year	State
2001	California
2014	Colorado
2015	Kansas
2016	Illinois, Kansas, Minnesota, Nebraska
2024	Alabama, Arkansas, Indiana, Kansas, Minnesota, Missouri, Nebraska, New York, Oklahoma, South Dakota, Texas, Wisconsin
2025	Arizona, Kansas, Oklahoma, Texas

The spread of corn stunt disease in 2024 was likely at least partly attributable to the impact of Hurricane Beryl, an unusually early-season hurricane that made landfall in Texas on July 8 and swept up through the Mid-South and Midwest before dissipating over the Northeastern U.S. and Ontario on July 11. Corn leafhoppers are known to spread long distances with prevailing winds and the first documented detection of corn stunt disease in New York would seem to correlate with the path of the storm system.

Expansion in the range of corn leafhopper populations to subtropical and temperate regions may also be a factor in the more frequent occurrence of corn stunt disease in the U.S. Rising temperatures increase the risk of corn leafhopper populations moving north from Mexico and creating more corn stunt outbreaks in the Southern U.S.

Currently, corn stunt disease appears unlikely to pose a persistent threat to corn production in the U.S. Corn Belt. Warm temperatures and the presence of a living host are both critical factors for the survival and reproduction of corn leafhoppers, neither of which are available year-round in the Corn Belt. However, more frequent incursions of corn leafhoppers and corn stunt disease into the Southern Plains could be possible.

Corn Stunt Disease and Corn Leafhopper Sampling in 2025

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KEY FINDINGS

- A comprehensive field sampling program was conducted in 2025 to monitor the incidence and distribution of corn stunt pathogens and the corn leafhopper vector.
- Corn leafhopper presence was confirmed in 185 counties across 16 states during the 2025 growing season.
- Only 3.8% of corn leafhopper specimens tested positive for corn stunt pathogens, indicating that leafhoppers spread more rapidly than the corn stunt pathogens they transmit.
- 2025 data strongly suggest that the 2024 corn stunt outbreak was an anomalous occurrence driven by unusual weather patterns that facilitated northward migration of the vector from its origin in Mexico.

BACKGROUND AND RATIONALE

- Corn stunt is one of the most economically important diseases affecting corn in South America.
- The primary causal organism for corn stunt disease is *Spiroplasma kunkelii*, a group of small bacterial pathogens commonly referred to as corn stunt spiroplasma (CSS).
- *S. kunkelii* is transmitted by corn leafhoppers (*Dalbulus maidis*), which acquire the pathogen by feeding on infected plants and spreading it by feeding on healthy plants.
- This bacterial pathogen is transmitted singly or in combination with maize bushy stunt phytoplasma (MBSP), maize rayado fino virus (MRFV). Sugarcane mosaic virus (SCMV) is often found to be part of the corn stunt disease complex, although this virus is transmitted by aphids.
- The presence of corn stunt is limited in the U.S. by the range of corn leafhoppers, which require living host plants to survive and do not typically overwinter in the U.S.
- Outbreaks of corn stunt in the U.S. are driven by leafhopper populations moving northward on prevailing winds from Mexico, where corn is under continuous cultivation and is the center of origin of the leafhopper.
- An unprecedented outbreak of corn stunt disease in 2024 that impacted corn in several states has led to some concern that occurrence of corn stunt disease could become more frequent and widespread.

Figure 1. Corn plants exhibiting characteristic foliar symptoms of corn stunt complex, including interveinal chlorosis, reddening, and stunting.

PROJECT OVERVIEW

- A comprehensive field sampling program was conducted in 2025 across Southern and Mid-South states to monitor the incidence and distribution of the corn leafhopper vector (*Dalbulus maidis*) and the associated pathogens, corn stunt spiroplasma (CSS), maize bushy stunt phytoplasma (MBSP), and maize rayado fino virus (MRFV).
- The primary goal of this program was to help understand the risk that corn stunt disease may pose to U.S. corn production going forward, and determine the risk of overwintering of corn leafhopper populations in the Southern U.S.
- This effort was conducted in partnership with Oklahoma State University, Kansas State University, and Texas A&M University, along with Pioneer Field teams and Corteva Plant Diagnostic Services.

METHODS

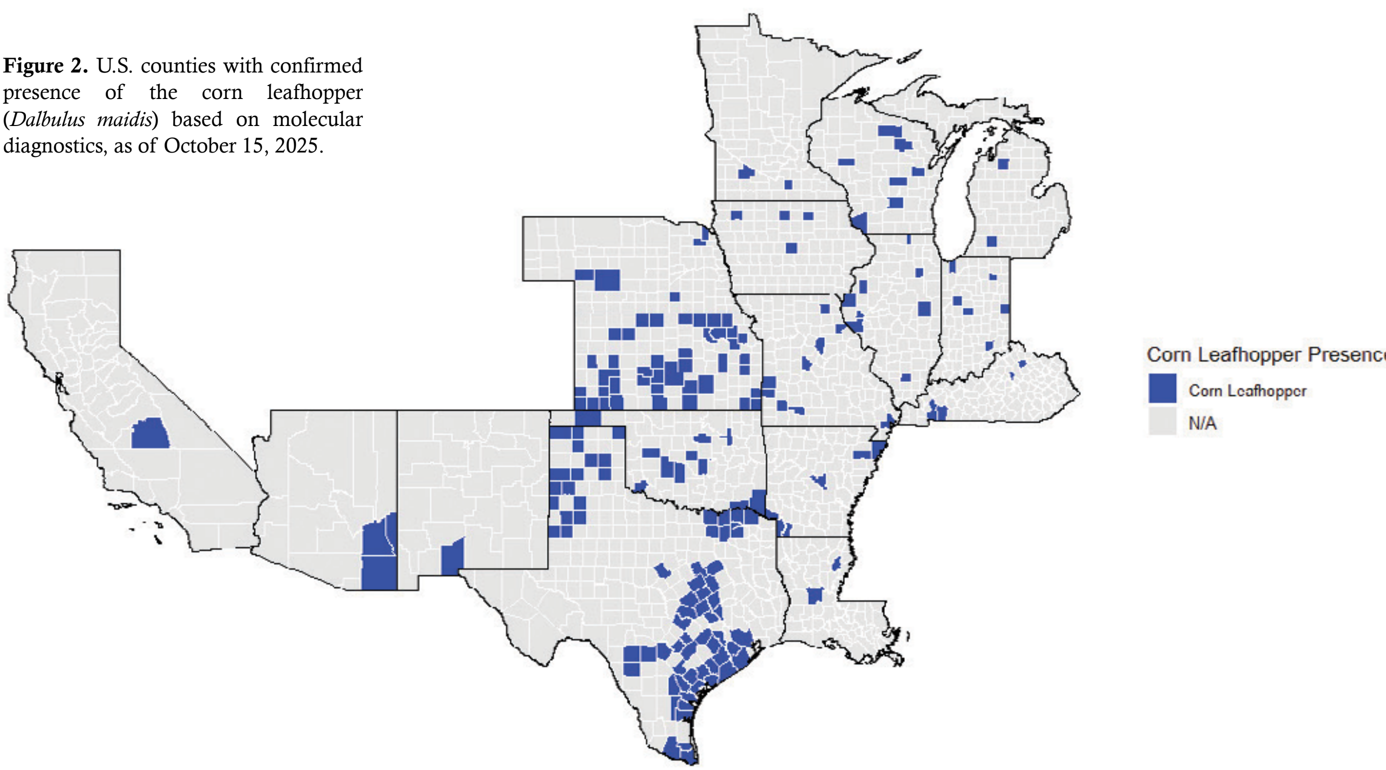
- Corn leafhoppers were collected using multiple trapping systems, depending on the collaborating institution. Trapping methods included PHEROCON AM/NB sticky traps, sweep nets, and vacuum sampling.
- Sampling frequency and intensity varied with the method:
  - **Sticky traps:** Three to six traps were placed in corn fields of interest. Traps were checked and replaced weekly, and the number of leafhoppers captured was recorded and submitted for analysis.
  - **Vacuum and sweep net sampling:** Conducted by academic partners following standardized protocols.
- Fields were selected based on pest pressure history, geographic location, collaboration with local farmers, and the presence of plants showing characteristic symptoms.
- Sampling was conducted by Pioneer field teams and academic partners from March to October 2025.
- Insect and plant samples were submitted to Corteva Plant Diagnostic Services for molecular analysis.
  - **Insects:** Analyses confirmed species identification as *Dalbulus maidis* and determined infection with corn stunt, maize bushy stunt, and maize rayado fino. Total DNA and RNA were extracted, and real-time PCR was performed using species-specific primers for leafhoppers and pathogens.
  - **Plants:** Leaf tissue samples were collected from symptomatic corn plants and tested for the presence of corn stunt maize bushy stunt, maize rayado fino, and sugarcane mosaic virus. DNA and RNA were extracted and analyzed by real-time PCR using species-specific primers.

RESULTS

CORN LEAFHOPPER ANALYSIS

- Over 2,400 insect samples were submitted to the Corteva Plant Diagnostic Services.
- 75.1% of submitted samples were confirmed by laboratory analysis as corn leafhopper (*Dalbulus maidis*).
- The aster leafhopper (*Macrosteles quadrilineatus*), which resembles corn leafhopper but does not transmit corn stunt pathogens, was frequently mistaken for corn leafhopper.
- Of the 1,814 specimens confirmed to be corn leafhopper, further analyses were performed to determine the presence of corn stunt, maize bushy stunt, and maize rayado fino.
- The vast majority of leafhoppers (96.2%) were negative for all target pathogens. Only 3.8% carried one or more of the diseases, with corn stunt being the most common, but only in 3.2% of the specimens.
- The first detection of corn leafhoppers in the USA in 2025 was in Texas in February and spread through most of the counties in the Rio Grande Valley in the following months.
- Through the growing season, corn leafhopper reports expanded throughout the country, and most of the reports came from Oklahoma, Kansas, Arkansas and Missouri.
- By the end of the 2025 growing season, corn leafhopper presence was confirmed in 185 counties across 16 states (Figure 2).
- Outside of Texas, corn leafhoppers were first detected in Oklahoma on June 23rd, then in Reno County, Kansas on July 9th, followed by Lawrence County, Missouri on July 10th.
- By July, corn leafhoppers were present across all major corn-growing regions in Texas, although populations remained lower than at this time in 2024.

Figure 2. U.S. counties with confirmed presence of the corn leafhopper (*Dalbulus maidis*) based on molecular diagnostics, as of October 15, 2025.



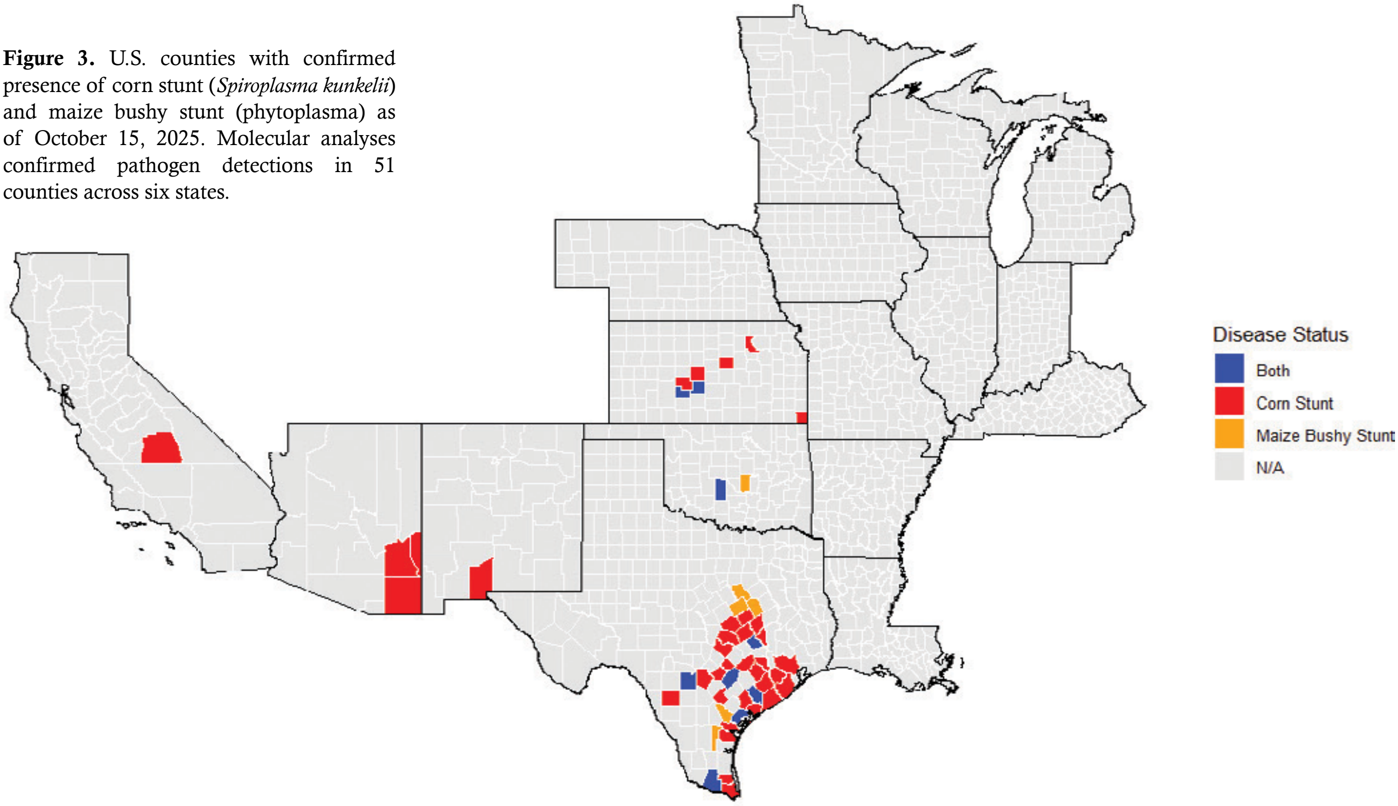


Figure 3. U.S. counties with confirmed presence of corn stunt (*Spiroplasma kunkelii*) and maize bushy stunt (phytoplasma) as of October 15, 2025. Molecular analyses confirmed pathogen detections in 51 counties across six states.

- By early August, we observed an expansion of corn leafhopper detections in the SE corner of Kansas and its expansion across central Oklahoma.
- Sporadic detections in Missouri, Arkansas, and Louisiana were also reported during August.
- By the end of August, corn leafhopper presence continued to expand and was detected in Nebraska (Clay County) and western counties of Kentucky, in addition to ongoing findings across Kansas, Missouri, and the Mid-South.
- Texas had high populations in the south, specifically in the Lower Rio Grande Valley, where the corn leafhopper is present year-round. After May, the population increased in the Upper Rio Grande Valley and North Texas.
- Additionally, field collections performed by academics led by Dr. Doris Lagos-Kutz of the University of Illinois also conducted corn leafhopper sampling using a suction sampling system (suctiontrapnetwork.org/) that covers most of the Midwest.
- According to their findings (Lagos-Kutz et al., 2025), the 2025 presence was significantly lower than in 2024. They are currently analyzing samples for the presence of the disease complex, and the results will be published in 2026. The counties where Dr. Lagos-Kutz team reported corn leafhopper presence are accounted for in Figure 2.
- Kansas State University also conducted winter trapping collections across 54 counties in Kansas. Traps were active from December 2024 through April 2025. A total of 53 corn leafhoppers were collected between November and January, with no captures from February to March, indicating that corn leafhoppers are not overwintering in the Midwest. Of the 53 insects collected, only two tested positive for corn stunt pathogen.

LEAF TISSUE ANALYSIS AND CORN STUNT CONFIRMATION

- Over 200 leaf tissue samples from plants displaying symptoms consistent with corn stunt disease were submitted to the Corteva Plant Diagnostic Services for analysis.
- Of the tissue samples submitted for analysis, 35% tested positive for corn stunt, 10% tested positive for maize bushy stunt phytoplasma, and 4% tested positive for both (Figure 3). No samples tested positive for maize rayado fino.
- The relatively low rate of pathogen detection in U.S. plant samples in 2025 may reflect both the low prevalence of infected vectors and misidentification of field symptoms when submitting samples.
- Disease presence (corn stunt or maize bushy stunt) was confirmed in symptomatic tissues from 51 counties across 6 states (AZ, CA, KS, NM, OK, and TX) (Figure 3).
- The first confirmed case of corn stunt occurred in Texas on May 5, 2025, in the Rio Grande Valley, coinciding with areas that experienced high leafhopper populations in 2024.
- Despite confirmed cases in Texas in May, corn leafhopper populations were lower than the previous year, averaging one adult per 10 plants according to academic partners.
- By mid-June 2025, corn stunt was confirmed in 20 Texas counties, primarily in the Rio Grande Valley.
- By the end of June, confirmations increased to 28 counties for corn stunt and 10 counties for maize bushy stunt; no maize rayado fino was detected.
- In early July, corn stunt was visually identified and later confirmed in Grady County, Oklahoma, marking the first case outside Texas in 2025.

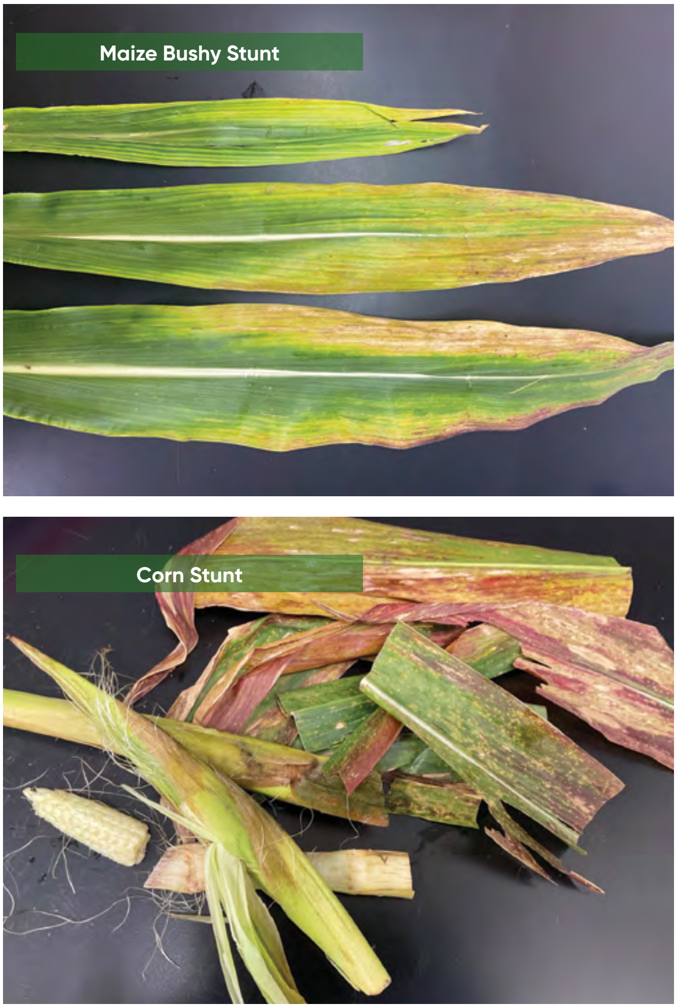


Figure 4. Laboratory images showing symptomatic corn tissues collected from confirmed cases of maize bushy stunt (top) and corn stunt spiroplasma (above). Samples display interveinal yellowing, reddening, and necrosis typical of disease progression.

- By August 4, maize bushy stunt was confirmed in Pottawatomie County, Oklahoma. No other Midwest states had reported disease at that time.
- The first Kansas case of corn stunt was confirmed on August 11 in Saline County. By the same period in 2024, 26 Kansas counties had confirmed infections.
- By the end of the 2025 season, only seven Kansas counties and three Oklahoma counties reported corn stunt, with no other confirmed cases in the broader Midwest.
- Arizona samples, received later in the season, showed corn stunt in three counties in September 2025.
- California samples were submitted in October from Uvalde County, confirming positive corn stunt detection at that time.
- Later in the season, a corn leafhopper population and corn stunt were detected in second-season corn in Texas (Figure 5). This is attributed to the migration of a leafhopper population from the maturing first crop to the second crop. While infection rates were higher compared to the summer, field observation indicated considerable variability, ranging from 10 to 50%.

DISCUSSION

- The 2024 outbreak of corn leafhopper raised major concerns regarding its dispersal, migratory behavior, and—most importantly—its potential to transmit corn stunt disease and affect U.S. corn production.
- Given that corn stunt outbreaks have been sporadic, and that the insect vector is not considered a major pest in U.S. corn systems, systematic data collection in 2024 was limited. Most field observations began late in the season, only after symptoms appeared in the field, which increased awareness ahead of 2025 and prompted earlier scouting for corn leafhoppers and corn stunt starting during the winter months.
- Although a coordinated sampling network was not established in 2024, data collected in 2025 through trials and the suction-trapping network (Lagos-Kutz et al., 2025) strongly suggest that the 2024 outbreak was primarily driven by unusual weather patterns that facilitated northward migration of the vector from its origin in Mexico.
- In contrast, the absence of similar conditions in 2025, combined with enhanced trapping and surveillance efforts, corresponded with markedly lower corn leafhopper activity and reduced disease pressure.
- Comparison between years clearly illustrates the contrast. By July 2024, corn leafhopper populations were well established in Kansas, and corn stunt was confirmed in 26 counties by the end of the season.

Figure 5. Later in the season, increased corn leafhopper populations and additional corn stunt cases were detected in second-season corn fields in Texas.

- In 2025, first detections again occurred in July but in much smaller numbers, even with a larger trapping network, and by October only seven Kansas counties had confirmed corn stunt cases. These findings reinforce that environmental conditions in 2024 played a decisive role in promoting corn leafhopper spread and disease transmission.
- The suction-trapping network also documented a consistent seasonal trend, with peak CLH abundance occurring in late September and October in both years, though populations were higher overall in 2025. This late season peak likely reflects either fall migration or local summer breeding. Regardless of source, corn leafhopper is not expected to overwinter in the Midwest due to its tropical biology. Eggs typically fail to hatch below 20°C, making winter survival unlikely.
- This was confirmed by the University of Kansas winter trapping efforts, which recorded no corn leafhopper captures between January and April.
- Quantitative PCR analyses confirmed that only a small proportion of corn leafhopper specimens carried pathogens associated with corn stunt. Thus, the presence of corn leafhopper does not necessarily indicate disease presence. Disease establishment depends on a complex interplay of biological and environmental factors.
- Unlike tropical regions, where infected corn is available year-round and sustains continuous transmission cycles, infected plants are not as common in the USA, explaining the low infection rates in corn leafhopper populations
- This analysis confirmed that leafhoppers spread more rapidly than the corn stunt pathogens they transmit. In 2025, corn leafhopper was reported in 16 states and 185 counties, yet only 3.8% of samples analyzed tested positive for corn stunt or maize rayado fino.
- This pattern aligns with disease incidence data: only 51 counties reported corn stunt, and 75% of those cases were concentrated in Texas, where temperatures and planting windows differ significantly from the Midwest and are more favorable for corns stunt spread.
- Although corn leafhoppers can acquire pathogens within approximately one hour of feeding, they require a latent period of about 20 days to become infective. This latency, combined with their migratory timing in the Midwest, limits the potential for disease transmission, since many insects that acquire pathogens after arrival may not survive long enough to infect new plants. Insects already infected before migration can transmit the pathogen sooner; however, the combination of biological latency and migratory timing effectively slows disease spread.
- Field studies from South America further indicate that corn is most vulnerable to infection up to the V8 growth stage. By the time corn leafhoppers typically arrive in the Midwest, most fields have already surpassed this stage, reducing the likelihood of corn stunt development.
- Yield data reflects these dynamics. In 2024, Kansas and Oklahoma reported yield losses ranging from 10% to 55% depending on disease severity and environmental factors. Some Oklahoma fields were unaffected, while others suffered substantial losses. In 2025, with lower corn leafhopper and disease incidence, similar yield impacts are not anticipated.
- Collectively, results from 2024 and 2025 demonstrate that the presence of the corn leafhopper does not necessarily lead to corn stunt outbreaks. The disease requires a combination of biological and environmental conditions, most of which are not prevalent in U.S. corn systems, suggesting that the overall risk of this pest–disease complex becoming a major issue remains low.
- Overall, these observations highlight the importance of continuous insect and pathogen monitoring to better understand the timing, frequency, and population dynamics of corn leafhopper and its role in corn stunt transmission.
- Establishing these parameters will be crucial for assessing future risks to U.S. corn production and guiding breeding, hybrid selection, and management strategies aimed at mitigating potential impacts.

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Southern Rust of Corn

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KEY POINTS

- Southern rust (*Puccinia polysora*) is a foliar disease of corn common to the Southeastern U.S. that is now occurring with increasing frequency in the Corn Belt.
- *P. polysora* requires a living host to survive, so it does not overwinter in the Corn Belt. Spores are carried north each year from tropical areas by prevailing winds.
- Southern rust has the potential to be much more damaging to corn than common rust due to its ability to rapidly develop and spread.
- Southern rust is favored by high temperatures (over 77 °F, 25 °C) and high relative humidity.

PATHOGEN FACTS

- Southern rust is a foliar disease of corn caused by the fungal pathogen *Puccinia polysora*.
- Southern rust does not occur as frequently in the Corn Belt as common rust (*P. sorghi*), but can be more destructive when infection does take place.
- Unlike other major foliar diseases of corn in North America, the rusts do not overwinter in the Corn Belt.
  - Rusts develop first in southern corn fields, and then may spread into primary corn-growing states.
  - Movement is by windblown spores that travel northward with prevailing weather systems.
- Southern rust is favored by high temperatures (over 77 °F, 25 °C) and high relative humidity, which tends to confine it to tropical and subtropical regions.
- Southern rust is generally more damaging to corn than common rust due to its ability to rapidly develop and spread.
- When conditions favorable for disease development persist for an extended period, severity can quickly reach epidemic levels.
- Yield impact depends on timing of infection, amount of leaf area damaged, and location of damaged leaves on the plant.

CROP DAMAGE

- Photosynthesis is reduced as functional leaf area decreases, which can reduce kernel fill and yield.
- Corn stalk quality can also be negatively affected as plants remobilize carbohydrates from the stalk to compensate for reduced photosynthesis.
- Later-planted corn is generally at higher risk for yield loss due to leaf diseases.
- If damage is confined to lower leaves or occurs after corn is well-dented, yield impact will be low.

Figure 1. Southern rust (*Puccinia polysora)* pustules on a corn leaf.

LIFE CYCLE

- Urediniospores are the primary infective propagule and are spread northward via the wind from living hosts in tropical areas.
- Spores will infect corn and cause symptoms within 3-4 days. Within 7 to 10 days, more urediniospores are produced and new infections continue to occur as long as conditions remain favorable, which can rapidly lead to an epidemic.
- In the U.S., southern rust usually appears later in the growing season and is more prevalent in the southeastern states.
- In seasons with higher than average temperatures, southern rust can spread further up into the Corn Belt where it can impact corn yield.
- *P. polysora* is not known to have an alternate host.

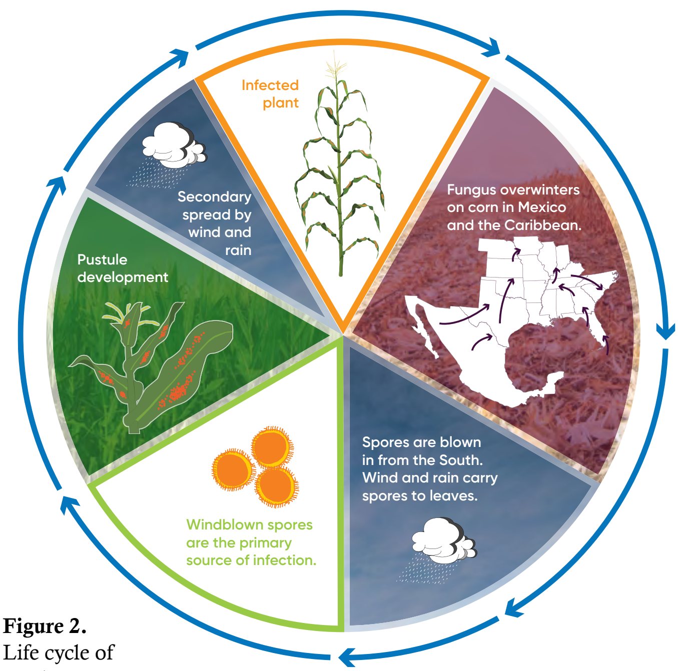


Figure 2. Life cycle of southern rust.

IDENTIFICATION

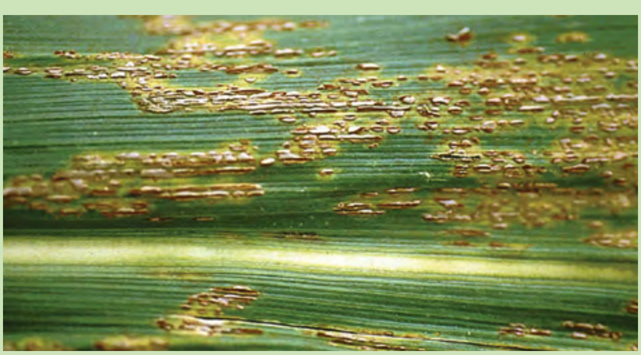
- Both rust diseases of corn can cause substantial yield losses under severe disease pressure; however, southern rust generally poses a greater risk to corn yield than common rust, making proper identification important.
- Southern rust looks very similar to common rust, but several characteristics distinguish the two, including the shape and color of pustules and their location on the plant.

SOUTHERN RUST

- Has small circular, pinhead-shaped pustules.
- Coloration of pustules/spores is reddish orange.
- Infects the upper leaf surface, as well as stalks and husks.
- Favored by higher temperatures (over 77 °F, 25 °C).

COMMON RUST

- Has larger pustules that are more elongate and blocky.
- Coloration of pustules/spores is brown to cinnamon-brown.
- Infects the upper and lower leaf surfaces.
- Favored by cooler temperatures (60-77 °F, 15-25 °C).



Southern Rust in Corn
- Forward-thinking Farming Webinar

DISTRIBUTION

- In recent growing seasons, southern rust has occurred further north in the Midwestern U.S. earlier in the season than has been historically typical for this disease.
- Southern rust is now routinely observed in Indiana, Illinois, Iowa, Nebraska, and Kansas and has been detected as far north as South Dakota, Minnesota, and Wisconsin.
- The increased prevalence of southern rust in the Corn Belt makes awareness and proper identification of this disease especially important.

Figure 3. Southern rust on corn; Johnston, IA; August 2024. Southern rust outbreaks often begin with isolated patches of disease in the middle or upper canopy along field edges.

Figure 4. Later in the season, *P. polysora* forms darker pustules called telia that contain teliospores.

Tar Spot of Corn

MARK JESCHKE, PH.D., AGRONOMY MANAGER

PATHOGEN FACTS

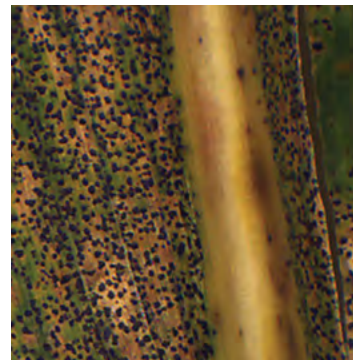
- Tar spot, caused by the fungal pathogen *Phyllachora maydis*, is a relatively new foliar disease of corn in the United States, first appearing in Illinois and Indiana in 2015 and subsequently spreading through much of the Corn Belt.
- Look for tar spot to develop during cool temperatures (60-70 °F, 16-20 °C), high relative humidity (>75%), frequent cloudy days, and 7+ hours of dew at night.
- Tar spot reduces yield by reducing the photosynthetic capacity of leaves and causing rapid premature leaf senescence.

IDENTIFICATION AND SYMPTOMS OF TAR SPOT

- Tar spot is the physical manifestation of circular-sharped, tar colored fungal fruiting bodies, called ascomata, developing on corn leaves.
- Initial symptoms are small brown lesions that darken with age.
- The texture of the leaf becomes bumpy and uneven when the fruiting bodies are present.
- Tar spot lesions cannot be rubbed away completely or dissolved in water.

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

- Under favorable conditions, tar spot spreads from the lowest leaves to the upper leaves, leaf sheathes, and eventually the husks of the developing ears.
- Severe infection can cause leaf necrosis.
- Affected ears can have reduced weight and loose kernels, and kernels at the ear tip may germinate prematurely.



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

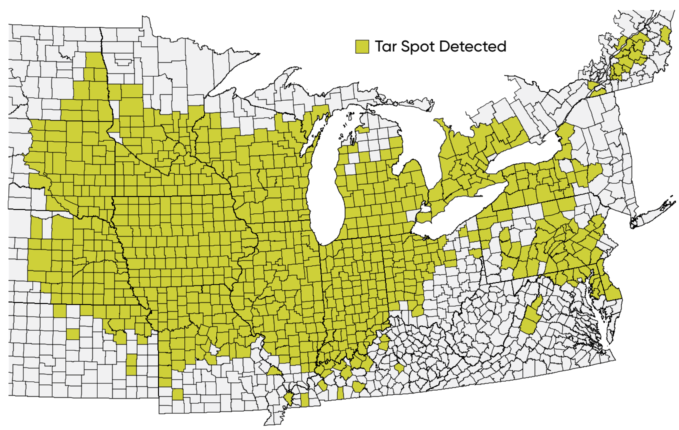


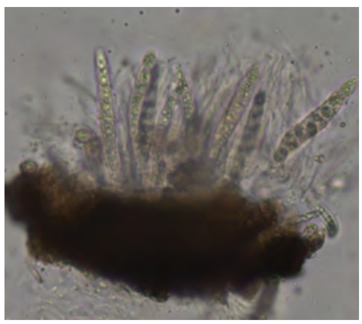
Figure 1. Counties in the Corn Belt with confirmed incidence of tar spot, as of October 2025. (Corn ipmPIPE, 2025; Corteva Plant Diagnostic Lab).

TAR SPOT OCCURRENCE IN THE U.S.

- Tar spot in corn was first observed over a century ago in high valleys in Mexico.
- The first confirmations of tar spot in the U.S. were in Illinois and Indiana in 2015 (Bissonnette, 2015; Ruhl et al., 2016).
- It has subsequently spread across much of the U.S. Corn Belt and into southern Ontario (Figure 1).
- Tar spot has also been found in several counties in southern Florida and southwestern Georgia.
- In 2018, tar spot established itself as an economic concern for corn production in the Midwest, with severe outbreaks reported in several states.
- A severe outbreak of tar spot impacted a large portion of the Corn Belt again in 2021.

TAR SPOT EPIDEMIOLOGY

- *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 more likely to develop during 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.



Microscopic view of fungal spores of P. maydis.

MANAGEMENT CONSIDERATIONS

YIELD IMPACT OF TAR SPOT

- 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).
- Severe tar spot infestations have been associated with reduced stalk quality. If foliar symptoms are present, monitor stalk quality carefully to determine harvest timing.
- There is no evidence that tar spot causes ear rot or produces harmful mycotoxins (Kleczewski, 2018).

DIFFERENCES IN HYBRID RESPONSE

- Observations in hybrid trials have shown that hybrids differ in susceptibility to tar spot (Kleczewski and Smith, 2018).
- 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).
- 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.

FOLIAR FUNGICIDES

- Several foliar fungicides are labeled for control of tar spot in corn (Wise, 2024).
- A multistate university study conducted in 2020 and 2021 showed that fungicide treatments with multiple modes of action were better at reducing tar spot severity and protecting corn yield than those with only a single mode of action (Telenko et al., 2022).
- Research suggests 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® and Aproach® Prima fungicides under moderate to high tar spot severity (Da Silva et al., 2019).
- 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 2).

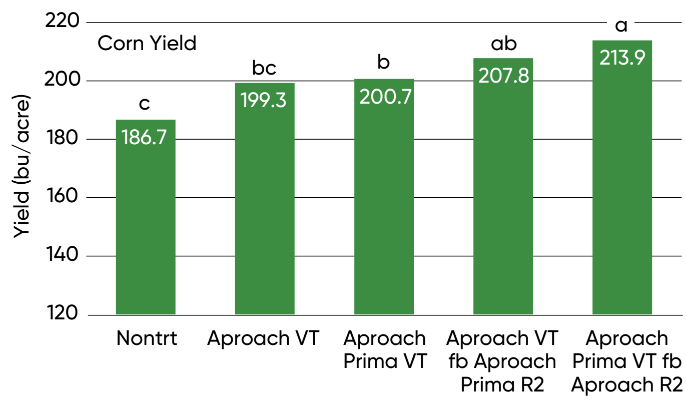


Figure 2. Fungicide treatment effects on corn yield under moderate to high tar spot severity in a 2019 Purdue University study.

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

AGRONOMIC PRACTICES TO MANAGE TAR SPOT

- The pathogen that causes tar spot overwinters in corn residue. How the amount of residue on a field's soil surface affects disease severity the following year is unknown.
- Observations so far suggest that rotation and tillage probably have little effect on tar spot severity.
- 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.

Gray Leaf Spot

MARK JESCHKE, PH.D., AGRONOMY MANAGER

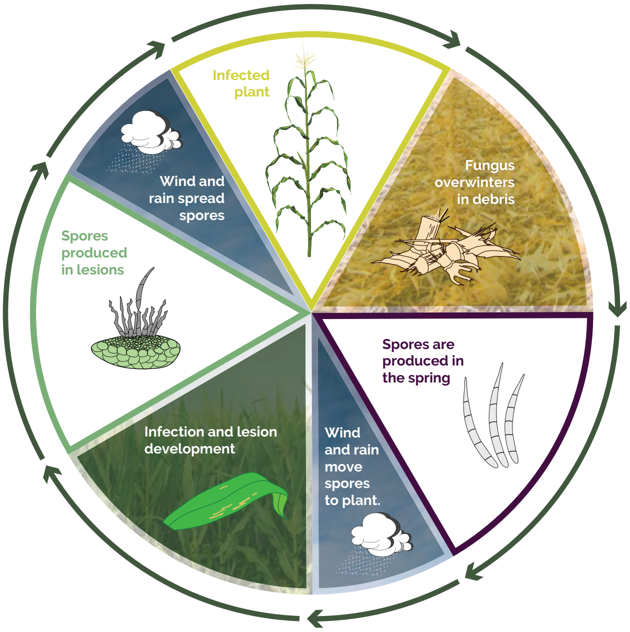
KEY POINTS

- Gray leaf spot (GLS) is a common fungal disease of corn that overwinters in corn residue.
- Cropping systems with reduced- or no-till and/or continuous corn are at higher risk for gray leaf spot outbreaks.
- Planting hybrids with genetic resistance to GLS can help reduce the risk of yield loss due to infection, and foliar fungicides can be used to manage gray leaf spot outbreaks.

CAUSAL PATHOGEN

- Gray leaf spot (GLS) is a common fungal disease in the United States caused by the pathogen *Cercospora zeae-maydis* in corn.
- Disease development is favored by warm temperatures, 80°F or 27°C; and high humidity, relative humidity of 90% or higher for 12 hours or more.
- *Cercospora zeae-maydis* overwinters in corn residue, allowing inoculum to build up from year to year in fields.
- Cropping systems with reduced- or no-till and/or continuous corn are at higher risk for gray leaf spot outbreaks.
- Conducive weather conditions encourage the rapid spread of disease near the end of summer and early fall, when corn plants allocate more resources to grainfill.

Gray Leaf Spot Disease Cycle
(Cercospora zeae-maydis)



IDENTIFICATION

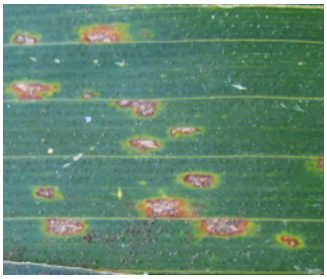
EARLY SYMPTOMS

- Gray leaf spot lesions begin as small necrotic pinpoints with chlorotic halos, these are more visible when leaves are backlit.
- Coloration of initial lesions can range from tan to brown before sporulation begins.
- Because early lesions are ambiguous, they are easily confused with other foliar diseases such as anthracnose leaf blight, eyespot, or common rust.

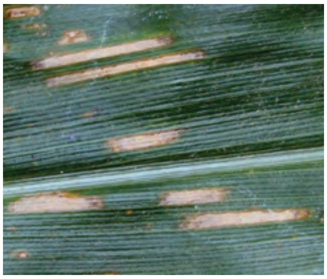
LATER SYMPTOMS

- As infection progresses, lesions begin to take on a more distinct shape.
- Lesion expansion is limited by parallel leaf veins, resulting in the blocky shaped “spots.”
- As sporulation commences, the lesions take on a more gray coloration.
- Entire leaves can be killed when weather conditions are favorable, and rapid disease progression causes lesions to merge.

Cercospora zeae-maydis spore.



GLS lesions begin as small necrotic spots with chlorotic halos.



As GLS develops, lesions become blockier and more gray in color.

As GLS progresses, lesions will coalesce and form larger necrotic areas.

CROP DAMAGE

- Gray leaf spot lesions on corn leaves hinder photosynthetic activity, reducing carbohydrates allocated towards grain fill.
- The extent to which gray leaf spot damages crop yields can be estimated based on the extent to which leaves are infected during grain fill (Table 1).
- Damage can be more severe when developing lesions progress above the ear leaf around pollination time.
- Because a decrease in functioning leaf area limits photosynthates dedicated towards grainfill, the plant might mobilize more carbohydrates from the stalk to fill kernels.
- This can result in a higher risk of stalk lodging and stalk rots due to a loss of structural integrity.

Table 1. Estimated yield loss based off of percent of tissue infected by gray leaf spot (Lipps, 1998).

Percent Leaf Area Affected at R5 (Early Dent Stage)	Approximate Yield Loss
5% or less	0 - 2%
6 - 25%	2 - 10%
25 - 75%	5 - 20%
75% - 100%	15 - 50%

MANAGEMENT CONSIDERATIONS

CULTURAL PRACTICES

- *Cercospora zeae-maydis* overwinters in corn debris, so production practices such as tillage and crop rotation that reduce the amount corn residue on the surface will decrease the amount of primary inoculum.
- Crop rotation away from corn can reduce disease pressure, but multiple years may be necessary in no-till scenarios.

HYBRID RESISTANCE

- Planting hybrids with a high level of genetic resistance can help reduce the risk of yield loss due to gray leaf spot infection.
- Pioneer® brand corn products and parent lines are improved through a screening process in areas with a high incidence of gray leaf spot and specialized "disease nurseries."
- Pioneer brand corn products are rated for their genetic resistance to gray leaf spot on a 1 to 9 scale, with most current products rated between 4 and 7.
- Susceptible hybrids are more likely to benefit from a foliar fungicide application, but resistant varieties may benefit as well under high gray leaf spot pressure (Figure 1).

FUNGICIDES

- During the growing season, foliar fungicides can be used to manage gray leaf spot outbreaks (Table 2).
- Farmers must consider the cost of the application and market value of their corn before determining if a fungicide is likely to be an economical solution to gray leaf spot.

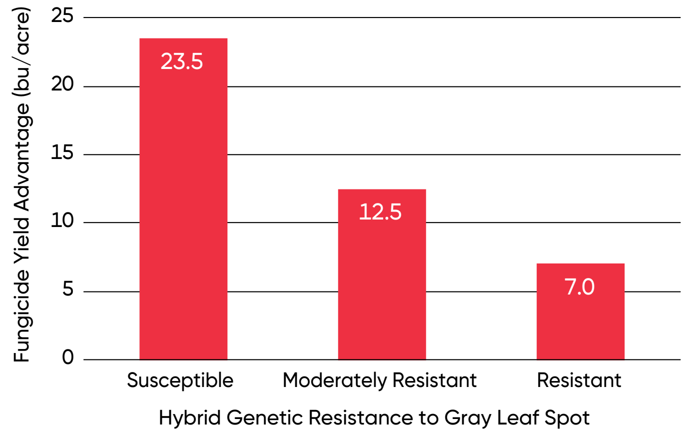


Figure 1. Average yield increase of hybrids with different levels of resistance to GLS due to a foliar fungicide application in a three-year research study with very high GLS pressure (Jeschke and Luce, 2009).

Table 2. Fungicide products rated very good to excellent for control of gray leaf spot. (Wise, 2025).

Trade Name	Active Ingredients	GLS Rating
Adastrio® 4.0 SC	Flutriafol + Azoxystrobin + Fluindapyr	VG-E
Aproach® Prima 2.34 SC	Cyproconazole + Picoxystrobin	E
Delaro® 325 SC	Prothioconazole + Trifloxystrobin	E
Delaro® Complete 3.83 SC	Prothioconazole + Fluopyram + Trifloxystrobin	E
Fortix® 3.22 SC Preemptor™ 3.22 SC	Flutriafol + Fluoxastrobin	E
Headline AMP® 1.68 SC	Pyraclostrobin + Metconazole	E
Lucento® 4.17 SC	Flutriafol + Bixafen	VG-E
Miravis® Neo 2.5 SE	Pydiflumetofen + Azoxystrobin + Propiconazole	E
Priaxor® 4.17 SC	Pyraclostrobin + Fluxapyroxad	VG
Revytek® 4.44 SC	Mefentrifluconazole + Fluxapyroxad + Pyraclostrobin	VG-E
Stratego® YLD 4.18 SC	Trifloxystrobin + Prothioconazole	E
Topguard® EQ 4.29 SC	Flutriafol + Azoxystrobin	VG
Trivapro® 2.21 SE	Benzovindiflupyr + Azoxystrobin + Propiconazole	E
Veltyma® 3.34 SC	Mefentrifluconazole + Pyraclostrobin	VG-E

Sugarcane Beetle

DEBORA MONTEZANO, PH.D., AGRONOMY RESEARCH MANAGER

KEY POINTS

- The sugarcane beetle (*Euetheola humilis*) is a sporadic pest of seedling corn, primarily in the southern United States.
- Adult sugarcane beetles cause the most significant damage to corn during the seedling stage by feeding on the roots and crown.
- Damage typically occurs in patches and can lead to substantial stand loss and yield reduction if infestations are severe.

DISTRIBUTION AND PEST STATUS

- *Euetheola humilis*, the sugarcane beetle, is a species of rhinoceros beetle in the family Scarabaeidae, native to North America and found throughout North, Central, and South America.
- Sugarcane beetle was historically considered a sporadic pest of corn, primarily in the Gulf Coast and southern United States.
- In recent years, the range of the sugarcane beetle has expanded northward into the Midwest. This expansion is likely driven by changes in crop management practices and shifting climate conditions.
- Populations are most frequently found in fields with abundant crop residue, sod, or grassy weeds, which provide ideal conditions for egg laying and larval development.
- Infestation risk is high when corn is planted following grass sod or pasture, as these rotations leave behind the habitat and food sources the beetles prefer.
- In addition to corn, the sugarcane beetle is a pest of several other crops, including rice, sugarcane, sweet potato, strawberry, and turfgrass.
- While sugarcane beetle outbreaks are rare, when they do occur, they can result in significant crop losses and economic impact for growers.

Figure 1. Sugarcane beetle

LIFECYCLE

- The sugarcane beetle undergoes complete metamorphosis — progressing through egg, larva, pupa, and adult stages — and typically completes one generation per year, though the timing of each stage can vary by region.
- Adults overwinter in the soil, usually in grassy areas or small grain fields, and become active in spring as temperatures rise. They begin feeding in seedling corn soon after emergence, primarily at night.
- Mating occurs shortly after adults become active in the spring, also often during the night. After mating, females lay eggs in the soil, usually in grassy areas or fields with abundant residue.
- Eggs hatch into white, C-shaped larvae in the soil. The larval stage consists of three instars. Larvae feed primarily on decaying plant material and grass roots; corn roots are a poor host for this species. Larval development takes about 57 days.
- After completing the third instar, larvae pupate in the soil, forming a creamy white pupa within a soil chamber.
- New adults emerge in the fall, feed briefly to build energy reserves, and then return to the soil to hibernate for the winter, typically in grassy or undisturbed areas.

IDENTIFICATION

- Adult sugarcane beetles are shiny, robust, oval-shaped, and dark brown to black, measuring about 12-16 mm (½ inch) in length, with clubbed antennae and strong legs for digging (Figure 2).
- Larvae are white, C-shaped grubs with dark brown heads, found in the soil near plant roots, while pupae are creamy white and develop in soil chambers.

Figure 2. Sugarcane beetle*

INJURY AND CROP IMPACT

- Adult sugarcane beetles cause the most significant damage to corn during the seedling stage by feeding on roots and the crown, sometimes boring into the stalk just below ground level and giving it a ragged appearance (Figure 3).

Figure 3. Sugarcane beetles feeding at the base of seedling corn plants.**

SIMILAR SPECIES

June Beetle

Phyllophaga spp; ¾ inch long; color often dark brown or reddish brown, rarely black; often hairy on ventral side between legs.

Masked Chafer

Cyclocephala spp; ½ inch long; color often yellowish brown, never black; area between eyes resembles a black "mask."

- Injury is most common within 45 days of planting, especially in fields with grassy weeds or heavy residue. Affected plants may show leaf streaking, deadheart (death of the growing point), stunting, abnormal side shoots, or die completely (Figure 4).
- Damage typically occurs in patches and can lead to substantial stand loss and yield reduction if infestations are severe (Figure 5). While grubs may be found near damaged plants, they do not contribute to corn injury.

Figure 4. Corn plants injured by sugarcane beetle feeding.

SCOUTING AND MONITORING

- Scouting should begin at planting and continue through early crop growth, focusing on symptoms such as wilting or stand loss.
- Digging around symptomatic plants can help confirm the presence of beetles or larvae. Light traps may be used to monitor adult activity at night and detect early infestation.

MANAGEMENT RECOMMENDATIONS

- Effective management of sugarcane beetle relies on an integrated approach.
- Culturally, it is important to control grassy weeds, minimize heavy residue before planting, avoid planting corn into sod or grassy fields, and improve field drainage.
- Early planting and proper fertilization help encourage vigorous seedling growth.
- Research indicates that neonicotinoid seed treatments can help control larval feeding in corn, but are not very effective against adult feeding, which is the most damaging stage.
- Using a high-rate (1250) insecticide seed treatment in at-risk fields will provide some degree of plant protection but should be paired with additional management practices.
- In fields with a history of sugarcane beetle problems, soil-applied insecticides at planting are recommended.

Figure 5. Corn stand loss from sugarcane beetle feeding.

PHOTO CREDITS:

*Figure 2: Sam Kieschnick, http://www.inaturalist.org/photos/97745967.

**Figure 3: (left) Clemson University - USDA Cooperative Extension Slide Series, Bugwood.org. (right) John C. French Sr., Retired, Universities: Auburn, GA, Clemson, and U of MO, Bugwood.org

Wheat Stem Maggot in Corn

DEBORA MONTEZANO, PH.D., AGRONOMY RESEARCH MANAGER

KEY POINTS

- The wheat stem maggot (*Meromyza americana* Fitch) is a sporadic pest of cover crops and corn native to North America.
- Damage typically occurs in patches and can lead to substantial stand loss and yield reduction if infestations are severe.
- Outbreaks in corn have been associated with late termination of rye cover crops and specific environmental conditions.

DISTRIBUTION AND PEST STATUS

- *Meromyza americana* Fitch, known as the wheat stem maggot (WSM), is a chloropid fly native to North America, distributed throughout the U.S. and southern Canada.
- Although considered a minor pest overall, WSM can cause regionally significant injury to cereal crops—particularly wheat, barley, oats, rye, and occasionally corn, resulting in localized yield losses in the Great Plains and Midwest.
- Outbreaks are relatively rare but can lead to severe stand loss and reduced yields when linked to specific agronomic practices.
- Major Nebraska outbreaks occurred in 2017 and 2025, with infestations reaching up to 50% in some fields. These were primarily associated with corn following green cover crops such as rye or with volunteer wheat present.
- Infestation risk is highest when corn is planted before cover crop termination, as living cover creates a "green bridge" that allows larvae to migrate from dying cover plants to young corn seedlings.

LIFECYCLE

- The wheat stem maggot typically completes two or three generations per year, depending on regional climate.
- In early spring, adults emerge from overwintering pupae. Females begin oviposition two to six days after emergence, laying eggs singly on leaves or at the stem base. Each female deposits one to four eggs per day for about two weeks.
- Larvae hatch and bore into plant stems, feeding internally on developing tissues. They pass through three instars, growing from 1 to 6-7 mm in length.
- The larval feeding period lasts about two weeks and produces the characteristic "dead heart" symptom.
- Pupation occurs inside the stem, in soil debris, or within volunteer grasses. Adults emerge to start the next generation, continuing the cycle (Figure 1).

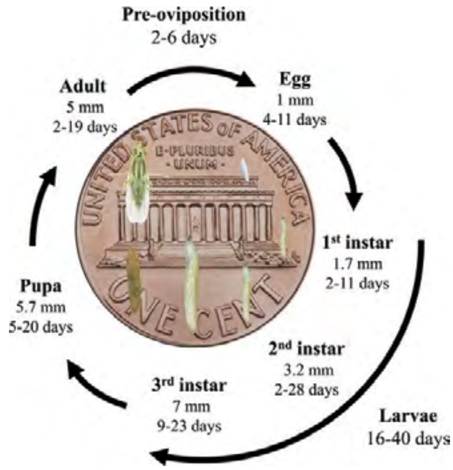


Figure 1. Wheat stem maggot lifecycle. Image courtesy of the University of Nebraska.

IDENTIFICATION

- Adult WSM flies are small (6 mm), slender, and greenish yellow with dark thoracic stripes and bright green eyes (Figure 2).
- Larvae are legless, smooth, and white to yellowish, reaching 5-8 mm in length.
- Pupae are reddish-brown and cylindrical, found within stems or soil residue.
- No external burrowing or root injury occurs, helping differentiate WSM from other corn pests.

Figure 2. Wheat stem maggot adult (left; image courtesy of the University of Nebraska) and larva (right).

INJURY AND CROP IMPACT

- Larvae feed internally, severing vascular tissues and destroying the growing point, disrupting nutrient flow and killing the central whorl leaf (Figure 3).
- Injury is typically patchy, with clusters of damaged plants among healthy ones, often linked to fields with grassy cover crops, cereal residue, or late-terminated rye (Figure 4).

Figure 3. Characteristic "dead heart" symptom caused by wheat stem maggot feeding in the central leaf whorl. Images courtesy of John Mick.

Figure 4. Patches of unevenly sized plants caused by wheat stem maggot feeding. Image courtesy of John Mick.

- The central (newest) leaf yellows and dies, forming the characteristic "dead heart." When pulled, the whorl detaches easily, revealing a hollow or water-soaked stem. (Figure 5).
- Upon dissection, small pale larvae or reddish-brown pupae are often visible inside the stem cavity.
- Severe infestations can cause stand loss and yield reductions up to 30 bu/acre.

Figure 5. Wheat stem maggot larvae visible inside the stem. Images courtesy of John Mick.

SCOUTING AND MONITORING

- Begin scouting in early spring and continue through the period before cover crop termination and corn emergence.
- Focus on fields with a history of WSM or grassy cover crops such as rye or wheat.
- Sticky traps and sweep nets can detect adult flies, though economic thresholds are not yet established.
- Pull symptomatic plants and split stems to confirm the presence of larvae or pupae.

MANAGEMENT RECOMMENDATIONS

- Scout cover crops for adult WSM activity prior to termination. If numbers are high, terminate cover crops at least 14 days before planting corn to prevent larvae from migrating from dying vegetation into emerging corn seedlings.
- Currently, no established economic threshold exists for wheat stem maggot in corn or other crops. Likewise, no rescue treatment is available once larvae have entered the corn whorl.
- In cases where early termination is not feasible, some researchers recommend a follow-up insecticide application after corn emerges. However, this approach is based on management principles for similar pests such as stalk borers and not specifically validated for wheat stem maggot.

OUTBREAKS AND CONTRIBUTING FACTORS

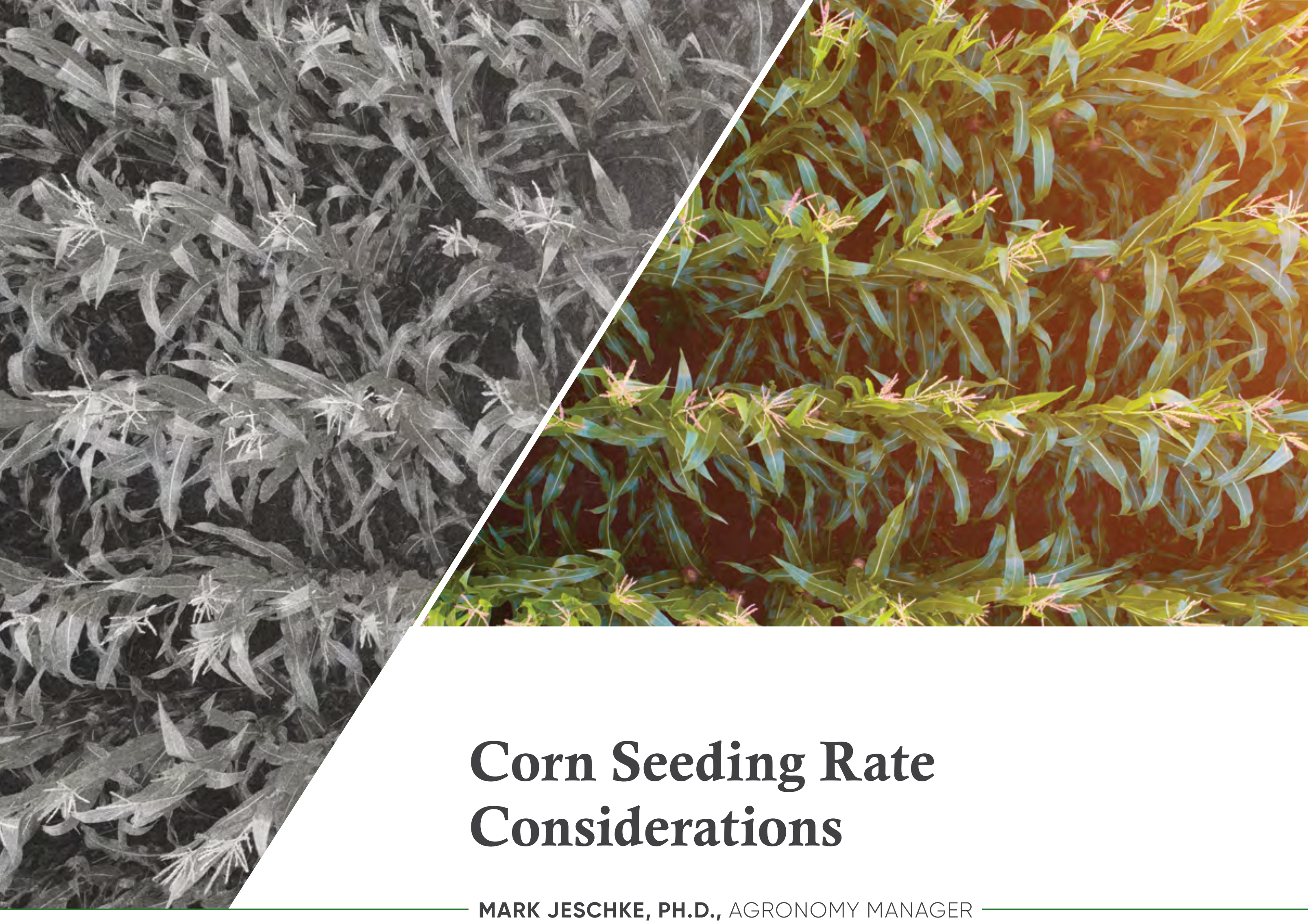
- Heavy infestations occur most often when corn follows grassy cover crops or volunteer wheat.
- The highest risk occurs when corn is planted "green" into living rye that is terminated after emergence, allowing maggots to move into seedlings.
- Drought stress can intensify visible symptoms.

2017 NEBRASKA OUTBREAK

- The 2017 WSM outbreak caused severe stand loss and economic damage across central, eastern, and southern Nebraska.
- Growers reported dead whorls and tillering in early corn planted after wheat or rye cover crops.
- A survey led by the University of Nebraska documented stand losses of 2–30%, with larvae confirmed inside corn stems, indicating movement from cover crops.

2025 NEBRASKA OUTBREAK

- Nebraska experienced another major wheat stem maggot outbreak in 2025. Infestations reported across 18 counties (Figure 6), ranged from 5% to 50% in severity.
- Infestation levels varied by county and management practices, confirming a strong link between WSM infestations and the use of rye cover crops, particularly when corn was planted "green" into living rye.



Corn Seeding Rate Considerations

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Improvement of corn hybrid genetics for superior stress tolerance has allowed hybrids to be planted at higher plant populations and produce greater yields.
- An analysis of Pioneer plant population data collected over a 30-year period showed that optimum plant populations increased from an average of 30,500 plants/acre in the late 1980s to 37,900 plants/acre in the mid-2010s.
- In general, corn response to plant population follows a quadratic response model in which yield increases with greater plant population up to an optimum point, beyond which yield declines.
- Optimum plant population can vary depending on field productivity level and can differ among hybrids.
- Corteva scientists evaluate the plant population response of Pioneer® brand corn products at numerous locations in the U.S. and Canada each year.
- The Pioneer Planting Rate Estimator, available on pioneer.com, allows users to generate estimated optimum seeding rates for Pioneer brand corn products based on data from Corteva research studies.

HIGHER DENSITY DRIVES HIGHER YIELDS

One of the most critical management factors in corn production is establishing a sufficient population density to allow a corn 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, which has driven higher yields.

Optimum plant density depends on the productivity level of the field – more productive environments generally maximize corn yield potential at higher plant densities. Optimum plant density can also vary by hybrid genetics – some hybrids will maximize yield potential at a higher or lower density than others.

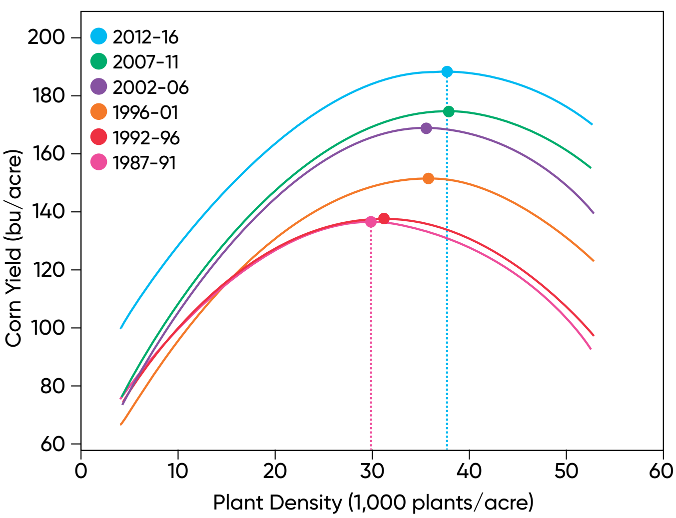


Figure 1. Agronomic optimum plant density averaged over all Pioneer® brand hybrids for six, 5-year time periods from 1987 to 2016 (Ciampitti, 2018a).

The goal for corn producers is to plant at the economically optimum seeding rate – the point at with the return on seed investment is maximized. In order to help corn producers achieve this goal, Corteva scientists conduct numerous research trials each year across North America to evaluate plant population response of Pioneer® brand corn products across a wide range of growing environments.

PLANT POPULATION TRENDS

The critical role that higher plant density has played in corn yield gains over time means that one of most important objectives of corn plant population research is simply to ensure that grower management practices are keeping pace with the genetic potential of modern corn hybrids. Planting corn at the same population as 20 or 30 years ago would result in lost yield potential and profitability.

The continual increase in optimum plant density throughout the hybrid corn era has been well-documented by research. An analysis of Pioneer plant population data collected over a 30-year period showed that the agronomically optimum plant population increased from an average of 30,500 plants/acre in the late 1980s to 37,900 plants/acre in the mid-2010s (Figure 1).

Farmers have taken advantage of the higher stress tolerance of modern hybrids by pushing plant populations higher. The most extensive USDA-NASS corn population dataset is for the state of Iowa, dating back to 1963. From 1963 to 2024, average plant population and average corn yield in Iowa both continuously increased (Figure 2). Trendline corn yield increased 170% over this period, from 74.5 bu/acre to 200.3 bu/acre (2.06 bu/acre/year). Trendline plant population increased 118%, from 15,200 plants/acre to 33,100 plants/acre (294 plants/acre/year). Greater yield per plant contributed to yield gains over this period as well, but not to the same extent as plant population, increasing only 18% from 1963 to 2024.

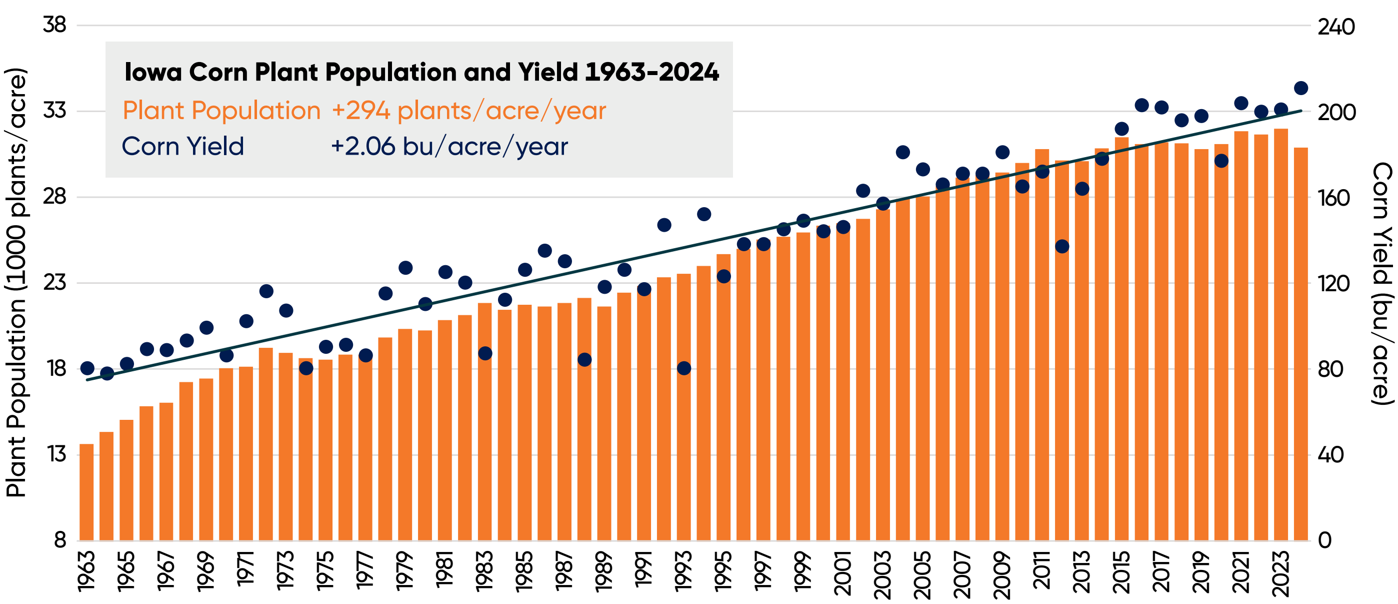


Figure 2. Average corn plant population and average corn yield in Iowa from 1963 to 2024 (USDA-NASS, 2025).

Plant population data for the ten largest corn-producing states shows a great deal of variation, both in current practices and trends over the past 20 years, illustrating the need to tailor corn population to the growing environment (Figure 3). Average population is highest in Illinois, at over 32,000 plants/acre, Indiana, Iowa, Minnesota, Ohio, and Wisconsin all above 30,000 plants/acre. In western states where corn yields are limited by water availability, plant populations are considerably lower. Nebraska and South Dakota have average populations around 26,000 plants/acre and Kansas only 23,000 plants/acre. In Nebraska, where populations are reported for both irrigated and dryland production, populations are around 6,000 plants/acre greater on the higher-yielding irrigated acres.

Average populations increased in all ten states over the past 20 years, but by varying degrees. Illinois, Missouri, and Ohio had the largest increases over this time period, at over 200 plants/acre/year, while Kansas had the smallest increase.

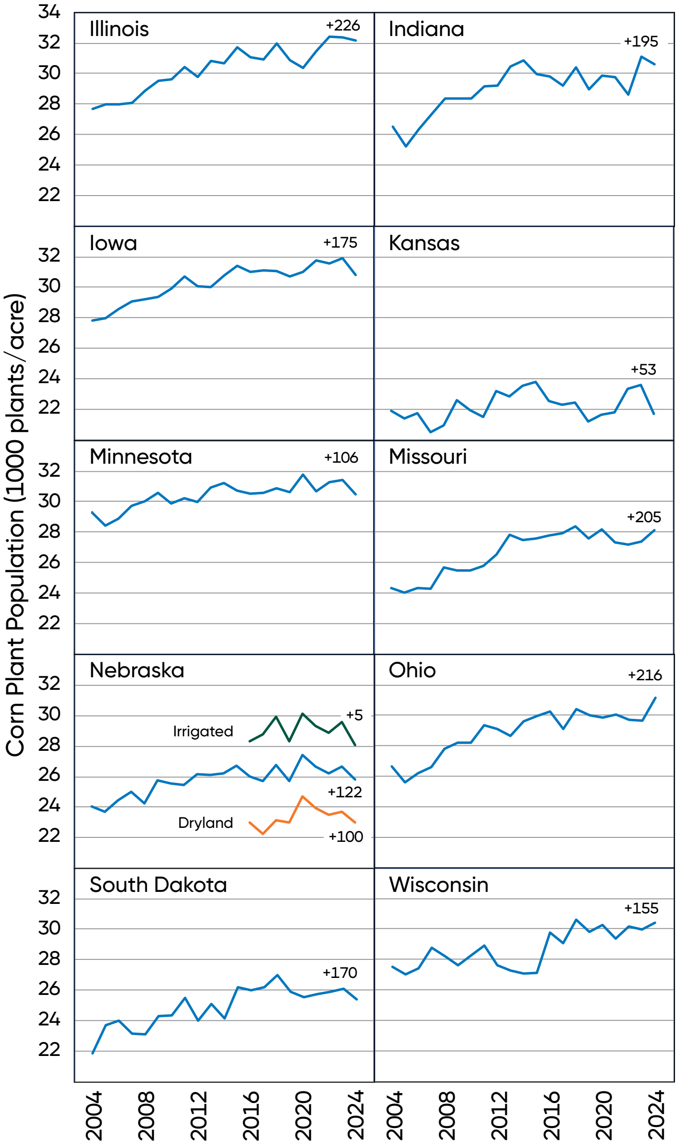


Figure 3. Average corn plant populations for major corn-producing states and rate of increase in plants/acre/year (USDA NASS, 2025).

CORTEVA CORN POPULATION RESEARCH

Pioneer has been conducting corn population studies for essentially its entire century-long history. Over the past few decades, corn population studies have been conducted in a comprehensive research program spanning corn production areas in the U.S. and Canada. These studies involve numerous hybrids covering a wide range of maturities, each tested at multiple locations representing a diverse range of growing conditions. Corteva scientists target representative environments based on maturity zone, expected yield (high or low), specific stresses, and other unique location characteristics. Hybrids are generally tested over multiple years, providing a robust characterization of plant population response. Over the past several years, a subset of plant population research studies has been focused on lower-yielding dryland environments, where water availability is significantly limited due to low rainfall, sandy soils, or both.

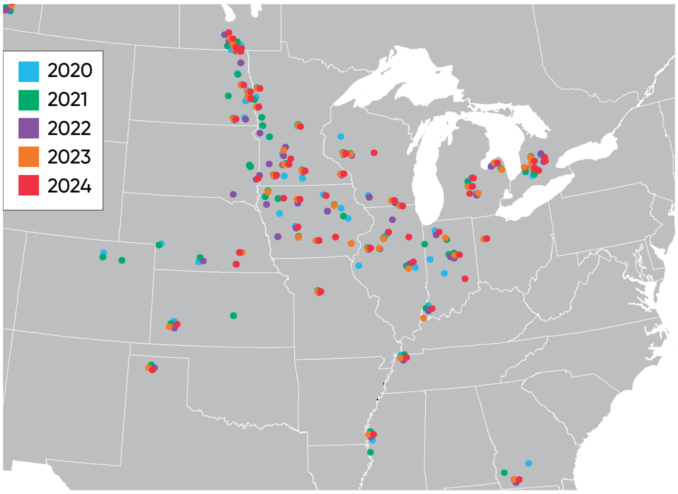


Figure 4. Corteva Agriscience plant population research locations in North America, 2020-2024.

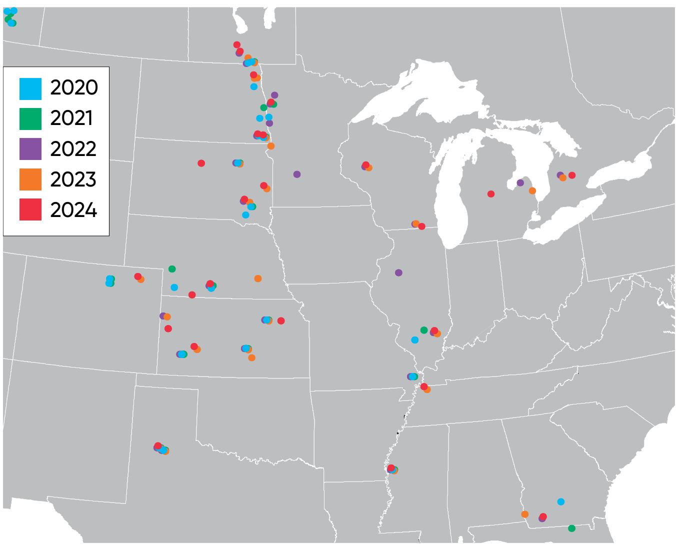


Figure 5. Corteva Agriscience water-limited plant population research locations in North America, 2020-2024.

An important feature of Corteva plant population research studies is the large population range over which hybrids are tested. At standard plant population research locations (not water-limited), all hybrids are tested at 18,000, 26,000, 34,000, 42,000, and 50,000 plants/acre, a range that extends well above and below the optimum plant population in most scenarios. This wide testing range is important for a couple of reasons. The high populations allow exploration of corn yield response to plant population at the highest yield levels, up to 300 bu/acre in some cases. At the other end of the range, the low populations provide a look at a hybrid's ear flex and ability to maintain yield in scenarios where stand establishment is below the targeted level. At water-limited research locations, hybrids are tested over a lower range of populations, spanning 12,000 to 32,000 plants/acre, to evaluate hybrid performance in dryland environments.

Figure 6. Pioneer Agronomy on-farm corn population trial in central Iowa prior to harvest.

In addition to the Corteva research studies, numerous Pioneer on-farm trials evaluating plant population response are conducted each year across the U.S. and Canada (Figure 6). These trials can be very valuable for getting a look at hybrid plant population response in local environments close to growers. On-farm trials generally focus on a narrower range of plant populations, often spanning around 10,000 to 12,000 plants/acre from the lowest to the highest population. Put together, the Corteva research studies and Pioneer on-farm trials provide wealth of data to help inform seeding rate decisions with Pioneer products. The Corteva research studies provide a robust characterization of plant population response and ear flex over multiple years and environments, while Pioneer on-farm trials provide additional local data points to help fine-tune seeding rate recommendations.

POPULATION VS. SEEDING RATE

Population and seeding rate are terms that are often used interchangably with corn, but have slightly different meanings. Population refers to the number of plants per unit area in the field; whereas, seeding rate (or planting rate) refers to the density of seeds per unit area that are planted. Because germination and emergence are never 100%, population will always be less than the seeding rate. For example a corn hybrid with 95% warm germination would require a seeding rate of 36,800 seeds/acre to achieve a population of 35,000 plants/acre.

AGRONOMIC VS. ECONOMIC OPTIMUM

In general, corn hybrid response to plant population follows a quadratic response model in which yield increases with greater plant population up to an optimum point, beyond which yield declines. The agronomic optimum population is the point at which yield is maximized, while the economic optimum is the point at which profitability is maximized. The economic optimum varies depending on the cost of seed and the price at which the grain will be sold, and is always less than the agronomic optimum. As yields increase with each increment of higher population, a point is reached where the yield benefit from the next addition of seed no longer exceeds the cost of the seed. Higher seed costs and lower grain sale prices will both push the economic optimum seeding rate lower, increasing the difference between the economic and agronomic optimum.

FIELD PRODUCTIVITY LEVEL

An important factor in optimizing corn population is the productivity level of a field, which is why Corteva scientists target a range of different enviroments when placing population research studies.

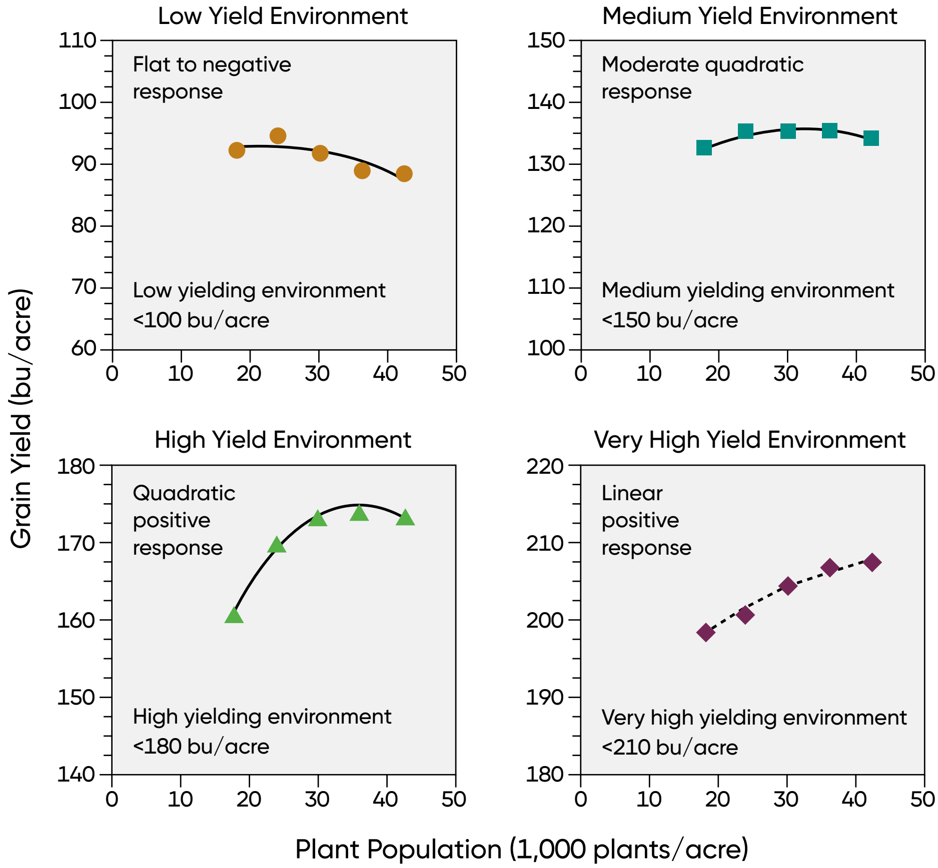


Figure 7. Corn hybrid response to plant population under four yield environments, a) low yielding <100 bu/acre; b) medium yielding 100-150 bu/acre; c) high yielding 150-180 bu/acre; and d) very high yielding 190-210 bu/acre (Ciampitti, 2018b).

Pioneer research has shown that yield response to plant population depends on the yield environment. An analysis of 15 years of plant population response data showed that in low yielding environments (below 100 bu/acre), maximum yield was attained at an average population of 24,000 plants/acre. In very high yield environments (above 200 bu/acre), yield response to plant population continued to increase even at 40,000 plants/acre (Figure 7).

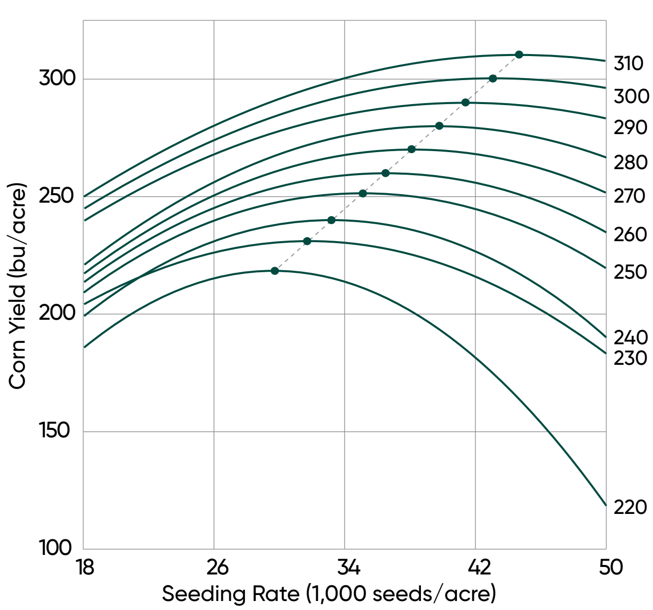


Figure 8. Corn yield response of a 111 CRM Pioneer® brand hybrid to seeding rate over a range of yield levels based on 4 years of testing across 36 locations.

Figure 8 shows plant population response curves for a current 111 CRM Pioneer® brand corn product tested in a wide range of yield environments. Agronomic optimum seeding rates range from around 30,000 seeds/acre at the low end of the yield level range to over 44,000 seeds/acre at the high end.

HYBRID DIFFERENCE IN POPULATION RESPONSE

Yield response to plant population can differ considerably among hybrids, making hybrid the second most important factor in seeding rate decisions behind field productivity level. Corteva scientists evaluate numerous hybrids each year in population research studies to better understand inherent differences in plant population response. Figure 9 shows an example of two hybrids of similar maturity with contrasting responses to plant population.

Data from Corteva plant population studies are used to assign ear flex ratings to Pioneer hybrids. Ear flex is the degree to which harvestable yield of the plant changes in response to environmental stress. There are many environmental factors that create stress on a plant, but one source of stress that is essentially always present is competition with other corn plants. All hybrids will produce

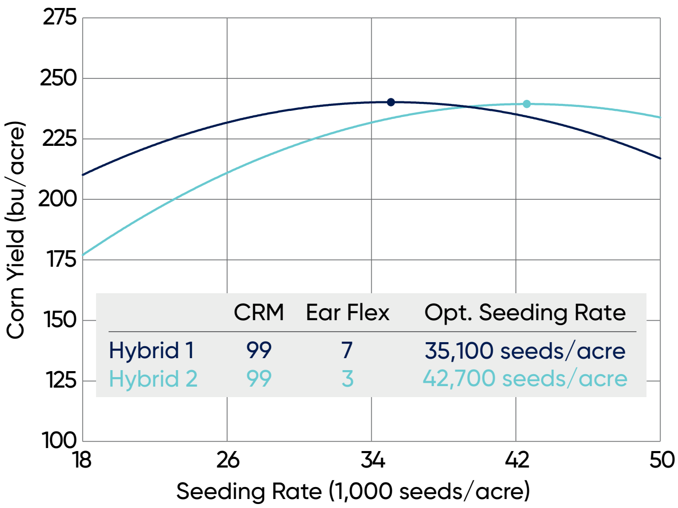


Figure 9. Corn yield response to seeding rate of two 99 CRM Pioneer® brand corn products with contrasting optimum seeding rates.

smaller ears as plant population increases, but the rate of change can differ among hybrids. The optimum plant population is the point at which the tradeoff between the number of plants per unit area and the yield per plant results in the greatest yield. Ear flex can be a product of changes in both the number of kernels per ear and kernel mass.

Ear flex ratings for Pioneer hybrids are based on the the difference in yield per plant at 18,000 plants/acre and 42,000 plants/acre. The larger this difference is, the more ear flex a hybrid is considered to have. Hybrids are indexed against an average and rated on a 1 to 9 scale, with most current commercial products scored between 4 and 7.

Figure 10 shows an example of yield per plant response to seeding rate of three different hybrids with low, medium, and high ear flex scores. Fixed-ear hybrids generally maximize yield at a higher population than flex-ear hybrids.

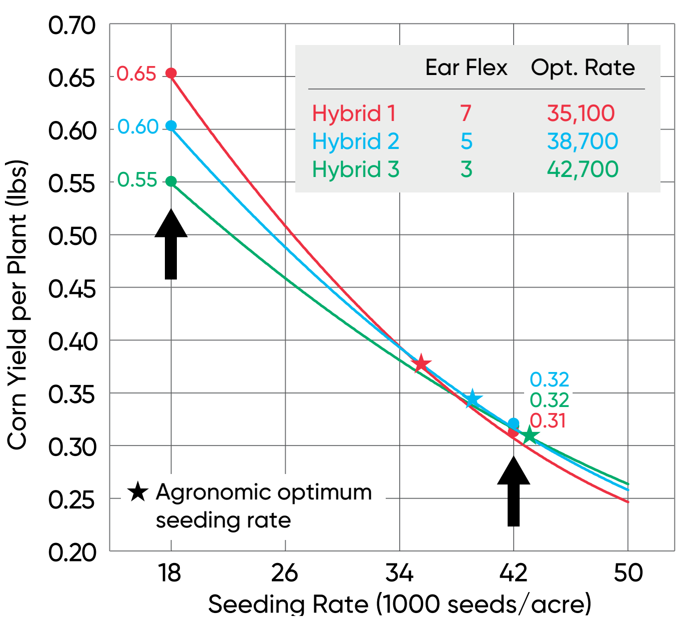


Figure 10. Corn yield per plant response to seeding rate for three 99 CRM hybrids with low, medium, and high ear flex scores.

PIONEER PLANTING RATE ESTIMATOR

The Pioneer Planting Rate Estimator, available on pioneer.com, allows users to generate estimated optimum seeding rates for Pioneer® brand corn products based on data from Corteva research studies (Appendix). The Planting Rate Estimator provides flexibility in customizing the graph display based on grain prices and seed costs.

The Pioneer Planting Rate Estimator has the ability to display population response curves for a wide range of yield levels, which can provide guidelines for creating variable rate seeding prescriptions. It is possible to display plant population response curves at 10 bu/acre increments for all yield levels where there was a statistically significant response based on the available research data. The yield levels available for display will vary among hybrids based on the available research data. Users also have the option of selecting a "Water-Limited Sites" version of the planting rate estimator, which includes data from studies conducted in drought environments. Farmers should use the Planting Rate Estimator as an initial guide and work with their Pioneer sales professional for refinements based on local observations and on-farm trials.

SEEDING RATE TIPS

Challenging growing environments may reduce corn plant populations below optimum levels. These conditions can occur when planting into no-till or high-residue seedbeds, or cloddy or compacted soils. Soil-borne diseases and soil insects can also diminish stands. All of these factors can interact to challenge stand establishment, and effects are magnified when planting early into cold, wet soils. Therefore, consider the following points when choosing your seeding rate:

- In general, plan to drop 5% more seeds than the target population to account for germination or seedling losses.
- Boost target seeding rates by an additional 5% for extreme or challenging environments such as those described in the paragraph above.
- In areas with perennial drought stress, seeding rate targets are lower. Base your seeding rate on the specific hybrid population response at the historical yield level of the field.
- Consult your Pioneer sales professional for optimum economic seeding rates of each Pioneer® brand corn product, as well as hybrid placement tips and other helpful management suggestions.

APPENDIX – PIONEER PLANTING RATE ESTIMATOR

- The Pioneer Planting Rate Estimator, available on pioneer.com, allows users to generate estimated optimum seeding rates for Pioneer® brand corn products based on data from Corteva Agriscience research trials.

PIONEER PLANTING RATE ESTIMATOR FEATURES

- The Planting Rate Estimator provides flexibility in customizing the graph display based on grain prices and seed costs.
- The Planting Rate Estimator has the ability to display population response curves for a wide range of yield levels, which can provide guidelines for creating variable rate seeding prescriptions.
- It is possible to display plant population response curves at 10 bu/acre increments for all yield levels where there was a statistically significant response based on the available research data.
- The yield levels available for display will vary among hybrids based on the available research data.
- Users also have the option of selecting a “Water-Limited Sites” version of the planting rate estimator, which includes data from studies conducted in drought environments.
- Growers should use the Planting Rate Estimator as an initial guide and work with their Pioneer sales professional for refinements based on local observations and on-farm trials.

View plant population responses from either standard or water-limited research sites.

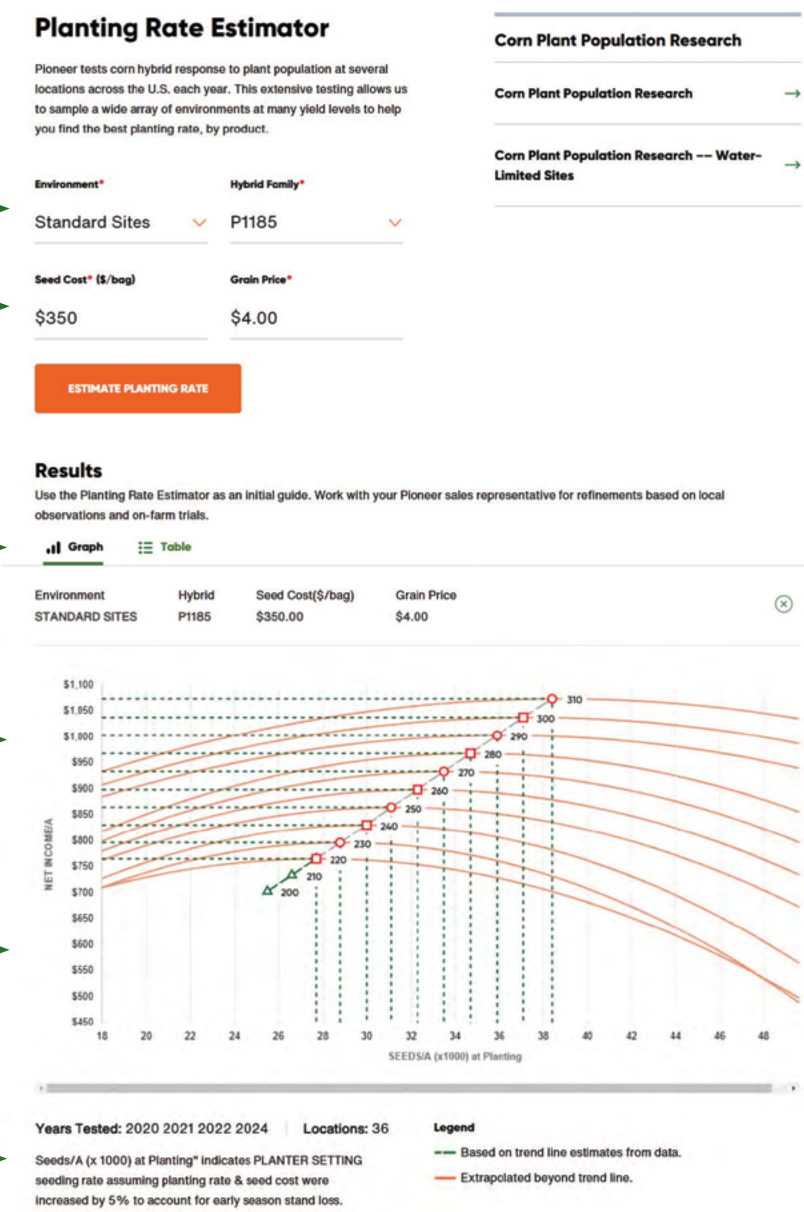
Select and compare plant population responses based on hybrid, corn grain price, and seed cost.

Net income/acre data can be displayed in graphical or tabular form.

Graph shows plant population response curves with economic optimum seeding rates based on the criteria selected above. Results are displayed as net income/acre.

To provide a wider range in yield levels for variable rate seeding (VRS), the seeding rate optimum response trend line is extrapolated to lower yield levels — that is, extended beyond the regression trend response based on data to yield levels as much as 40 bu/acre lower. This extrapolation is indicated with the change from gray to green in the trend line.

Years of testing and number of testing locations for the selected hybrid are shown.



Emergence Uniformity in Corn

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Uniform emergence is important in corn because of the highly competitive environment among plants for access to resources and the relatively low vegetative and reproductive plasticity of modern corn hybrids.
- Research on emergence uniformity of corn has shown that the impact of late emergence on individual plant yield can be substantial.
- Corn plants that emerge later than their neighbors are at a disadvantage in size and competitiveness and may produce smaller ears. If there are enough late-emerging plants, it can drag down the overall yield of the field.
- As corn yield levels continue to increase, driven in large part by greater plant densities, it raises the question of what degree of emergence uniformity is necessary in order to maximize corn yield potential.
- Recent research indicates that an emergence window of 3 or 4 days is sufficient to achieve full yield potential under most conditions and demonstrate that this is an attainable goal in a field environment.
- Results from greenhouse research suggest that an emergence window of less than 2 days is probably not achievable in a field environment.

SETTING THE CORN CROP UP FOR SUCCESS

The planting operation is one of the most critical factors in maximizing corn yield potential. The goal at planting is to achieve a "picket-fence" stand – equally spaced plants, all emerging at the same time, that will ultimately all produce uniformly sized ears.

Numerous research studies over the years have examined the effects of plant emergence and spacing uniformity on corn yield. Of the two, uniform emergence has generally been found to be the more important factor in affecting yield (Liu et al., 2004; Doerge et al. 2015). Plants that emerge later than their neighbors are at a disadvantage in size and competitiveness and may produce smaller ears. If there are enough late-emerging plants, it can drag down the overall yield of the field.

Figure 1. Corn plants emerging in a field in Northern Illinois.

The importance of uniform plant emergence has long been understood, and it has remained an area of focus for corn growers and agronomists seeking to optimize every aspect of the planting operation to maximize corn yield potential. As corn yield levels continue to increase, driven in large part by greater plant densities, it raises the question of what degree of emergence uniformity is necessary in order to maximize corn yield in high-productivity environments.

WHY IS UNIFORM EMERGENCE SO IMPORTANT IN CORN?

Uniform emergence is important in corn because of the highly competitive environment among plants in modern corn fields for access to resources, particularly sunlight (Satorre and Maddonni, 2018), and the relatively low vegetative and reproductive plasticity of modern corn hybrids (Rotili et al., 2021).

In contrast to other grass crops, where a single plant may produce multiple shoots and seed heads, selection for greater yield in corn has favored a compact, single-stalk phenotype that is tolerant to crowding stress and able to consistently produce a single well-sized ear in high-density environments. Corn plants may produce multiple tillers and more than one ear per plant in very low-density environments but have relatively limited capacity to convert a marginal advantage in resource availability into increased yield.

Limited vegetative and reproductive plasticity is why uniform emergence is so much more important in corn than it is in other crops such as soybeans (Andrade and Abbate, 2005). Compared to corn, soybean plants have considerable ability to adapt to their surroundings. Plants adjacent to gaps in the stand can respond by producing branches and leaves that will capture the available sunlight and result in additional pod formation and yield. Some degree of plant attrition is normal in a soybean field, and yield response of soybeans to plant density is relatively low. As long as the stand is able to attain full canopy coverage – capturing all available sunlight – the density, size, and spacing of individual plants comprising the stand is of lesser importance.

Corn has relatively limited vegetative and reproductive plasticity compared to other crops.

Corn, on the other hand, does not have the same degree of plasticity. Plants adjacent to a skip or a smaller plant in the row have some capacity to capitalize on their relative advantage in available resources through increased yield, but not enough to compensate for the lost yield from the missing or low-yielding plant (Liu et al., 2004; Doerge et al., 2015; Novak and Ransom, 2018). Unevenness in plant size is generally detrimental to the overall yield of a field (Figure 2) and emergence timing is an important determinant of relative plant size (Nafziger et al., 1991; Ford and Hicks, 1992; Carter et al., 2001; Liu et al., 2004; Novak and Ransom, 2018).

YIELD IMPACT OF UNEVEN EMERGENCE

Research on emergence uniformity of corn has shown that the impact of late emergence on individual plant yield can be substantial. A plant that emerges well after its neighbors faces a competitive disadvantage from which it will be unable to recover. Competition among corn plants for resources starts early in the season, at around the V4 stage, and intensifies during the rapid vegetative growth phase from V7 to V13 (Maddonni and Otegui, 2004). The difference in growth between advantaged and disadvantaged plants within the stand becomes larger as competition for resources increases. When the plants reach reproductive growth, smaller plants within the stand may produce a significantly smaller ear or no ear at all.

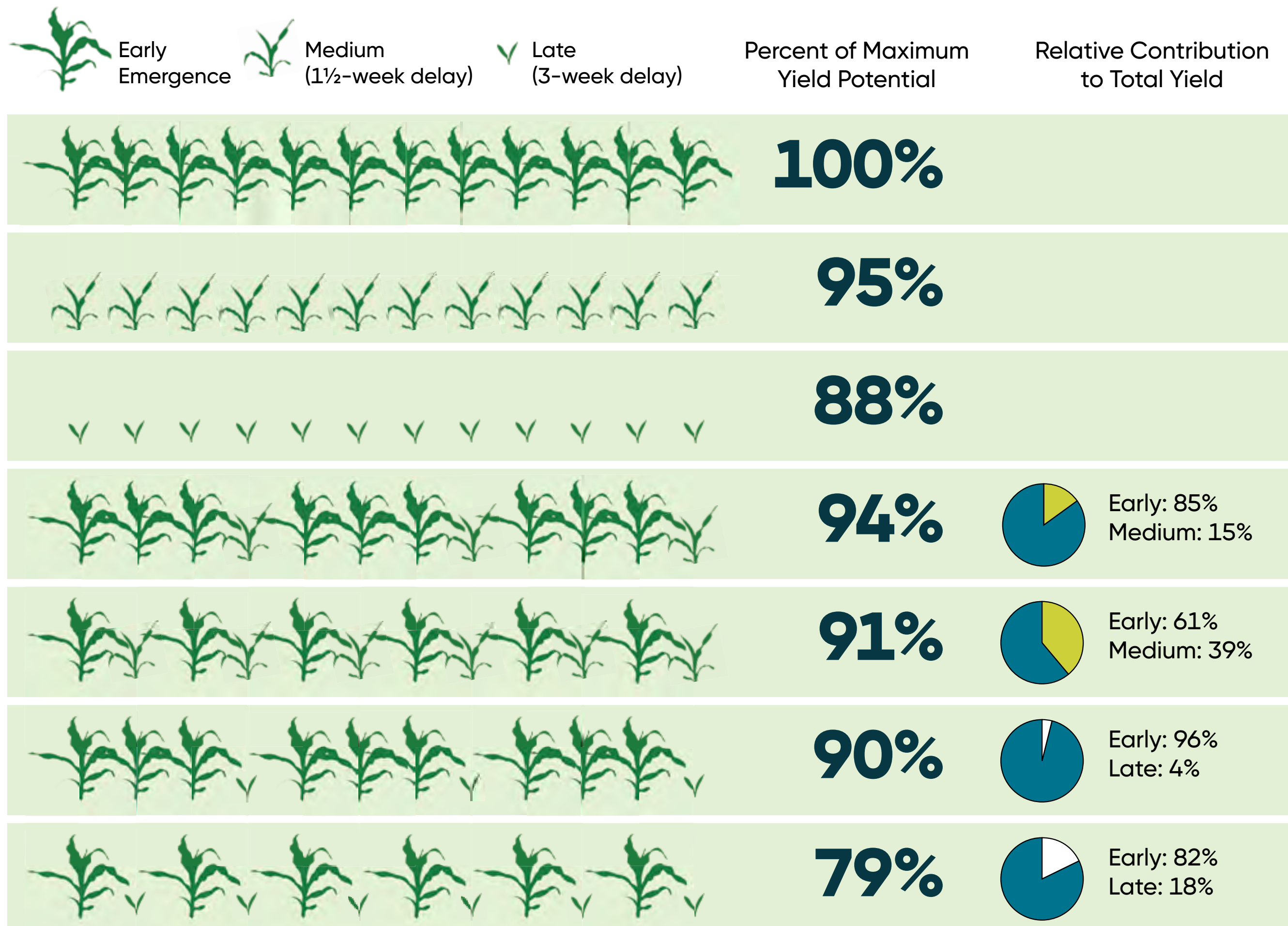


Figure 2. Yield potential of delayed and uneven corn stands. Based on data from Carter, P.R., E.D. Nafziger, and J.G. Lauer, Uneven emergence in corn, North Central Regional Extension Publication No. 344.

Several field studies have documented significant yield loss when the development of plants within the stand was delayed (Nafziger et al., 1991; Ford and Hicks, 1992; Liu et al., 2004). These studies typically used multiple planting dates achieve varying degrees of delayed plant growth, with additional seeds planted into the row a specific number of days after the initial planting. Liu et al. (2004) found that individual plant yield was reduced by an average of 35% for plants that emerged 12 days late and 72% for plants that emerged 21 days late.

The length of planting and emergence delays tested in studies in the 1980s and 1990s was often relatively large, ranging from 7 days to over 21 days, as the primary purpose of the studies was often to help inform replant decision making – determining at what point the predicted yield loss associated with uneven emergence was sufficient large to justify starting over and replanting the field.

Current interest in emergence uniformity in corn is primarily oriented around optimizing the planting operation to achieve the smallest emergence window possible and maximize yield potential. Corn growers are interested in the yield outcomes of plants emerging as little as 1 to 3 days after the first day of emergence, a much shorter window than was generally tested in older field studies.

Another factor to consider in revisiting this topic is the changes in corn production over the past few decades. Corn yield levels and plant densities have both increased (Figure 3). In 1984, the average corn population in Iowa was 21,400 plants/acre and the average yield 112 bu/acre. In 2024, those figures were 30,850 plants/acre and 211 bu/acre. Greater plant density increases interplant competition for resources and can exacerbate differences in competitive ability among individual plants within the stand (Carter et al., 2001; Maddonni and Otegui, 2004). Consequently, uneven emergence could have a greater impact on yield than it did 40 or even 20 years ago. Planter technology has also improved considerably, creating more opportunities to fine-tune settings for optimal planting performance than was previously possible.

Figure 3. Overhead view of corn planted at density of 27,000 plants/acre and 36,000 plants/acre. Greater plant density increases interplant competition for resources and can exacerbate differences in competitive ability among individual plants within the stand.

HOW UNIFORM DOES EMERGENCE NEED TO BE?

As corn growers strive to optimize every part of their corn production system for greater productivity, it is important to understand what level of emergence uniformity is necessary for maximum yield potential or even attainable under modern corn production systems. Working to optimize the planting operation for uniform plant emergence is generally going to be favorable for maximizing yield potential but it must be considered within the context of other management factors that can also affect yield, as there may be tradeoffs involved. For example, the most straightforward way to get the shortest emergence window possible would be to plant relatively late in the spring into a clean-tilled field. This would offer the greatest opportunity to plant seeds into a warm, uniform seedbed; however, the negative effects of later planting and intensive tillage may outweigh any benefit gained from more uniform emergence. The tradeoff between planting timing and fieldwork suitable days vs. optimal seedbed conditions will vary depending on climate and geography.

Efforts to optimize corn emergence uniformity must be considered within the context of other management factors that can affect yield.

One of the challenges in evaluating the effect of uniform emergence in corn is the fact that field studies have used different methods to measure and express emergence uniformity. On-farm emergence studies conducted by farmers and agronomists commonly measure emergence by time, counting the number of plants that emerge every 24 hours or every 12 hours during the emergence window.

A more accurate assessment of emergence uniformity can be achieved by using temperature data to express emergence timing as a function of growing degree units (GDU). Corn phenology is driven by heat unit accumulation not elapsed time, so difference in GDUs provides a more accurate measure of how far apart two plants are developmentally. Measuring emergence differences by GDUs also helps account for differences in planting timing – for example, a 3-day difference in emergence with mid-April planting would likely represent a smaller difference in GDUs and corn development than a 3-day difference with mid-May planting when temperatures are warmer and GDU accumulation per day is greater.

The best measure of emergence timing is using soil GDUs (sGDU), measured at planting depth, since it most closely measures temperatures that the developing seedlings actually experience in the furrow. However, accurately tracking soil GDUs requires specialized equipment that may not be available or practical in all cases.

RECENT STUDIES ON CORN EMERGENCE TIMING

Older corn emergence uniformity studies generally did not focus on relatively fine-scale differences in emergence timing within the first few days after the start of emergence, but a pair of recent studies did. The first was a 3-year field study at Ohio State University (partially supported by the Pioneer Crop Management Research Awards program) that assessed effects of soil temperature and moisture flux on emergence timing and uniformity of corn (Lindsey and Thomison, 2020; Nemergut et al., 2021). The second was a 2-year field study conducted by Iowa State University that tested the effects of seed size uniformity and planting depth on corn emergence and yield in conventional and perennial groundcover systems.

The Ohio State study (Nemergut et al., 2021) found that plants emerging within 3 days of the first emerged plants had no per plant yield loss. Plants that emerged more than 3 days after the start of emergence had a 5% decrease in yield per day (Table 1). Adequate planting depth was important for uniform emergence in this study – shallow-planted seeds experienced lower and more variable soil moisture closer to the soil surface, which led to less-uniform emergence.

The Iowa State study (Kimmelshue et al., 2022) produced contrasting results in the two years of the study. The first year of the study (2019) had cold and wet conditions immediately after planting, which delayed the start of emergence, but warmer temperatures once emergence began. Under these conditions, individual plant yield in the conventional cropping system remained stable for the first 5-6 days of the emergence window and then declined linearly after that. In the second year of the study (2020), yield loss was observed with each additional day of delayed emergence after the first day. Yield declined linearly by 7.8 g of yield per plant per day. The researchers attributed this outcome to drought stress that occurred later in the season in 2020. Total growing season precipitation at the Central Iowa study location in 2020 was half of that of 2019. Previous research showed that stress associated with higher plant density increased interplant competition for resources and exacerbated differences in competitive ability among plants (Carter et al., 2001; Maddonni and Otegui, 2004); it's likely that increased stress due to drought could have a similar impact.

Environmental stress can increase competition among plants and magnify the effects of uneven emergence.

Findings from these two studies show how environmental conditions after emergence can influence the impact of uneven emergence and provide insight into the range of potential outcomes with delayed emergence under different conditions. In the Ohio State study and the first year of the Iowa State study, which experienced relatively normal growing conditions, there was little or no difference in yield for plants emerging within the first few days after the start of emergence. In contrast, the second year of the Iowa State study experienced significant growing season stress, which likely increased competition among plants and magnified the effects of uneven emergence. Under these conditions, individual plant yield began to drop off almost immediately, with plants emerging on the second day of the emergence window already losing yield potential (Table 1).

Table 1. Individual plant yield potential by day of emergence under normal and high stress environments based on results from studies by Ohio State University (Nemergut et al., 2021) and Iowa State University (Kimmelshue et al., 2022).

Day of Emergence	Yield Potential by Day of Emergence		
	Normal Stress		High Stress
	OSU	ISU (2019)	ISU (2020)
	%		
1	100	100	100
2	100	100	95
3	100	100	90
4	95	100	84
5	90	100	78
6	85	90	70
7	80	72	62

AT WHAT POINT DO LATE-EMERGING PLANTS BECOME "WEEDS?"

Corn plants that emerge too late to contribute meaningfully to yield are commonly derided as "weeds," but is this characterization justified? The designation of a plant as a weed implies that its presence is detrimental to overall yield. A plant that fails to produce an ear while reducing the yield potential of its neighbors in the row by pulling resources away from them would certainly seem to meet the definition of a weed. The key question here is what the impact of the late-emerging plant is on its neighbors.

Figure 4. Ear formation of plants in a Pioneer uneven corn emergence study. In both photos, emergence of the center plant was delayed relative to the plants on either side of it – by 8 days (top) and 18 days (above). Photos taken September 19, 2012.

Plant spacing studies have shown that plants adjacent to a skip in the row can have increased yield due to greater availability of resources. Doerge et al. (2015) reported that plants next to a skip increased their yield by about 10%. Novak and Ransom (2018) found similar results, with an 11% increase in yield for plants next to a skip. For plants adjacent to a late-emerging plant (11-17 days after normal emergence) Novak and Ransom found that there were compensatory increases in yield, but not as much as with a skip – only around 5%. In this scenario, the late-emerging plant would need to produce at least 12% of normal yield to compensate for the yield potential that it is taking away from its neighbors – anything less than this and the late-emerger would be accurately characterized as a weed. Results from emergence timing studies indicate that emergence of a plant would need to be severely delayed relative to its neighbors – likely by 2 weeks or more – before it would cross the threshold of becoming a "weed."

WHAT IS A TYPICAL EMERGENCE WINDOW FOR CORN?

Recent field studies provide insight into the degree of emergence uniformity necessary to maximize yield potential in modern corn production systems, but how does this compare to emergence uniformity that is currently being achieved?

A Pioneer field study conducted at Johnston, Iowa compared corn emergence timing in continuous corn and a corn-soybean rotation (Figure 5). Emerged plants were flagged and counted each day. In both cropping sequences, nearly all plants emerged within the first two days and emergence reached 100% on day 3 in the corn-soybean rotation and day 4 in continuous corn (Figure 6). This study had multiple factors that favored uniformity of emergence – it was planted in a well-managed research field using a research planter travelling at relatively low ground speed. It was also very warm during the emergence window, with 90 GDUs accumulating over 4 days.

Figure 5. Newly emerged corn plants in a Pioneer field study comparing emergence timing in a corn-soybean rotation to continuous corn (May 11, 2012).

In the Iowa State emergence study, the time from the start of emergence (T_0) until 95% emergence (T_{95}) was 5.28 days in 2019 and 4.25 days in 2020. With some additional time added to account for the last 5% of emergence, the total emergence window in this study was likely around 5-6 days. Nemergut et al. reported time from 10% to 90% emergence ($T_{10\text{-}90}$) for the Ohio State study which averaged 3.5-3.8 days (58-62 GDUs). The total emergence window was likely a day or two more than that, which would put it very much in line with the emergence window in the Iowa State study. Across all three studies, emergence windows ranged from approximately 3 to 6 days.

Corn emergence windows across three field studies ranged from 3 to 6 days.

Applying the emergence timing yield outcomes from the two university studies to the emergence data from the Pioneer study provides a look at potential field-level yield outcomes. In two of the three scenarios, there is no yield loss associated with uneven emergence. Under the high stress scenario however, some yield loss would be predicted – 2% yield loss in corn-soybean rotation and 2.7% in continuous corn.

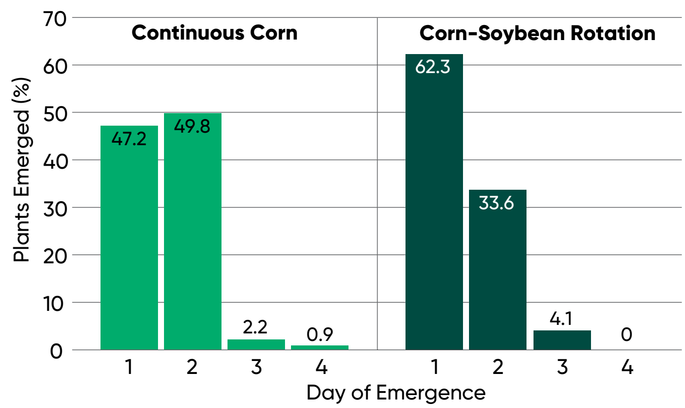


Figure 6. Percent of plants emerged by day in a Pioneer field study comparing emergence timing in a corn-soybean rotation to continuous corn.

WHAT POTENTIAL EXISTS FOR IMPROVEMENT?

The field studies reviewed here provide insight into corn emergence uniformity currently being achieved with well-managed systems under relatively favorable conditions, but what would be the maximum uniformity possible if every part of the planting operation and growing conditions were perfectly optimized? – 2 days? 1 day? Given the widespread interest among corn growers in achieving the shortest emergence window possible, it is important to consider what "success" in this area actually looks like. After all, corn plants are not machines, they are biological organisms that exist in variable, dynamic, and often unpredictable environments. It's reasonable to conclude that some degree of variability in emergence timing will simply be impossible to eliminate.

Greenhouse or growth chamber studies would seem to offer a potential answer to this question, given their highly controlled and uniform growth environments. A paper published in 2012 (Egli and Rucker, 2012) included results from multiple greenhouse and growth chamber experiments testing the effects of seed lot vigor on corn emergence uniformity. Emergence uniformity in this study was reported based on the time from 10% to 90% emergence ($T_{10\text{-}90}$).

The shortest T_{10-90} times reported from experiments included in this study were 20.4 hours and 24.5 hours. The full emergence windows (T_{0-100}) were not reported but, based on the data presented in the paper, can be estimated to be around 40-45 hours. This would be equivalent to around 40 accumulated GDUs based on the reported soil temperatures. Given that even the most uniform and favorable field environment would be unlikely to match or exceed a greenhouse environment for emergence uniformity, these results suggest that an emergence window of around two days or 40 GDUs is probably the best that could reasonably be achieved in a field environment.

An emergence window of around 2 days or 40 GDUs is probably the best that can be achieved in a field environment.

EMERGENCE UNIFORMITY IN PERSPECTIVE

Uniform emergence is important for maximizing corn yield; numerous research studies over the past few decades have clearly demonstrated this fact. However, it is one factor among many with the potential to influence yield, so it must be kept in perspective when prioritizing the allocation of attention and resources in pursuit of greater corn yields. One consistent finding among emergence studies has been that relative emergence timing is often not strongly predictive of individual plant yield (Kovács and Vyn, 2014; Nemergut et al., 2021), demonstrating that emergence uniformity matters, but it is not the only thing that matters. Once the plant is out of the ground, it is subject to numerous other factors, such as moisture, nutrient availability, soil compaction and disease and insect injury that can vary spatially in the field and differentially impact individual plant yield.

Studies have found that relative emergence timing is often not strongly predictive of individual plant yield

CONCLUSIONS

Research indicates that an emergence window of 3 or 4 days is sufficient to achieve full yield potential under most conditions and demonstrates that this is an attainable goal in a field environment. Results from greenhouse research suggest that an emergence window of less than 2 days is likely not achievable in a field environment. Much shorter emergence window targets of 12 hours, or 8 hours, or 10 GDUs are commonly touted by corn yield contest growers as essential for maximizing yield potential, but there is no evidence that this degree of uniformity is necessary or even possible; consequently, these targets should not be considered realistic management goals.

Optimizing Corn Water Use Efficiency in Irrigated Fields

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KEY POINTS

- Field research was conducted in 2023 and 2024 to explore the potential to increase water use efficiency of corn in irrigated production.
- Water use efficiency in irrigated fields in Colorado and Nebraska averaged 7.8 and 10.6 bu acre^{-1} inch^{-1}, respectively.
- Differences in water use efficiency across fields were partly explained by over-irrigation during grain filling.
- Within a field, the plant density that maximized grain yield also generally maximized water use efficiency.
- At the yield levels of the study locations, some hybrids required 34,000 plants acre^{-1} to maximize yield, while others required up to 40,000 plants acre^{-1}.
- The water use efficiency of hybrids across sites ranged from 8.5 to 10 bu acre^{-1} inch^{-1}.

INCREASING WATER USE EFFICIENCY

Agricultural irrigation consumes 42% of all freshwater withdrawals in the U.S. (Dieter et al., 2018). In parts of the U.S. Midwest, where potential evapotranspiration significantly exceeds rainfall, crops are irrigated. However, the thickness of the aquifers from which this water is pumped has been declining, raising concerns about future crop production in this region (Whittemore et al., 2023; McGuire and Strauch, 2024; Jasechko et al., 2024).

To achieve stable aquifer water levels and extend its usable life, it is essential to increase the efficiency of water use. Additionally, crop production is threatened by rising temperatures and heat stress, which are exacerbated by limited water availability (Cohen et al., 2020; Kusmec and Schnable, 2024). In this context, there is an urgent need to develop alternative strategies to address the challenge of increasing crop production while conserving fresh water. One key metric for comparing fields or management practices is water use efficiency, or water productivity, which measures bushels of corn produced per inch of water, including both irrigation and precipitation.

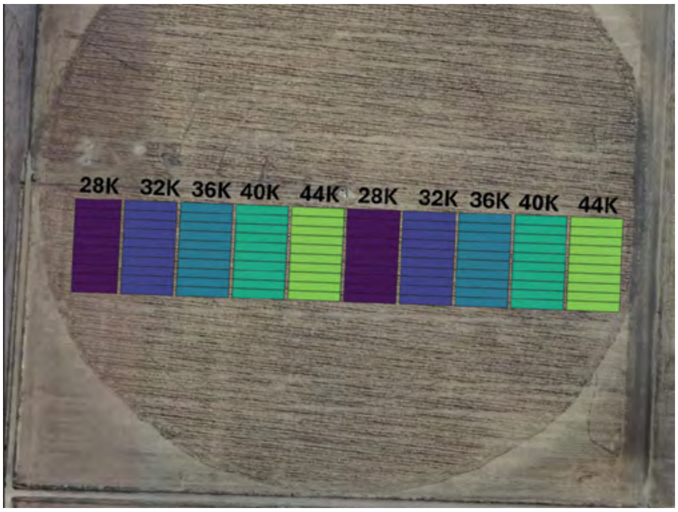


Figure 1. Example plot layout for water use efficiency trials conducted in 2023 and 2024.

Newer high-yielding hybrids are significantly more efficient at using water than older ones, especially under limited water availability.

Crop and irrigation management can significantly affect how efficiently water is used. Nitrogen fertilizer rate, plant density, row spacing, and soil cover all affect water-related processes, which influence corn water use efficiency (Echarte et al., 2023). In addition, hybrid selection can also affect water use efficiency. Newer high-yielding hybrids are significantly more efficient at using water than older ones, especially under limited water availability (Rotundo et al., 2025). Although higher water availability is generally associated with greater yields, similar yields can be obtained with very contrasting water availabilities, resulting in distinct water use efficiencies.

Corteva Agriscience started an agronomy research program in 2023 to measure the water use efficiency of farmers in their irrigated fields and identify opportunities for optimizing this efficiency. This initiative started in Colorado and Nebraska, and in 2025 was expanded to include locations in Kansas, Oklahoma, and Texas. Objectives of this research program were (i) to describe the current water use efficiency farmers have for irrigated fields in Colorado and Nebraska, and (ii) to determine the effect of management options (in this case, hybrid selection and plant density) on water use efficiency.

FIELD TRIALS

A total of 36 experiments were conducted in 2023 and 2024 in growers' irrigated fields in Colorado and Nebraska (Figure 2A). Each experiment tested between 4 to 19 commercial hybrids across 4 to 10 different plant densities, which ranged from 22,000 to 44,000 plants acre^{-1} (Figure 1). All locations were irrigated, had pivot telemetry, and were enrolled in Water Reporter from Granular Insights. Water Reporter is a digital twin based on a mechanistic model developed by Corteva Agriscience. It considers weather variables, irrigation schedules and quantities, crop information, and satellite images to provide various outputs, including daily evapotranspiration and soil water content.

WATER USE EFFICIENCY

Grain yield across experiments ranged from 160 to 300 bu acre^{-1} (Figure 2C). The average grain yield was similar between Colorado and Nebraska (255 bu acre^{-1}), although some experiments in Colorado had average yields below 220 bu acre^{-1} (Figures 2B and 2C). Total water availability, which includes both precipitation during the season and irrigation, ranged from 21.0 to 40.9 inches (Figure 2D). On average, Colorado had higher water availability than Nebraska (32.3 vs. 26.7 inches, respectively), due to different irrigation amounts (21.6 inches in Colorado vs. 13.2 inches in Nebraska (Table 1).

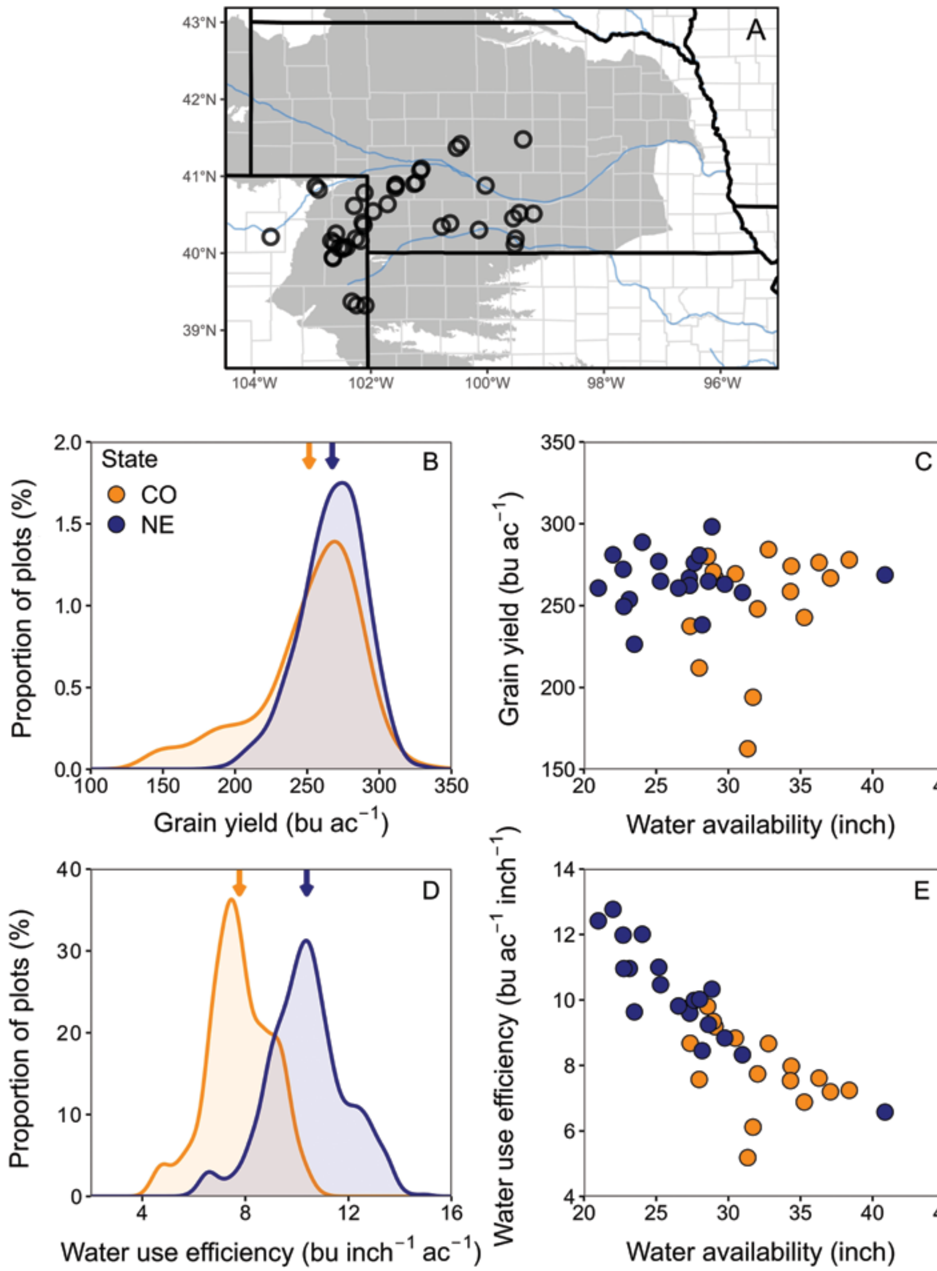


Figure 2. (A) Location of the 36 field experiments conducted on growers' fields in Colorado and Nebraska in 2023 and 2024. The shaded grey area in the map shows the Ogallala aquifer. (B and D) Grain yield and water use efficiency data distribution. Arrows indicate the mean grain yield and water use efficiency in Colorado and Nebraska. (C and E) Association between grain yield and water use efficiency with water availability across locations.

Table 1. Ranges explored for different variables across locations and average values for Colorado and Nebraska.

Trait	Minimum	Average	Maximum	Colorado	Nebraska
Irrigation (inch)	7.0	16.8	30.7	21.6	13.2
Rainfall (inch)	5.9	12.4	19.6	10.6	13.8
Water Availability (inch)	21.0	29.2	40.9	32.3	26.7
Evapotranspiration (inch)	21.3	25.5	29.5	26.0	25.1
Yield (bu acre^{-1})	163	255	298	245	266
Water Use Efficiency (bu acre^{-1} inch^{-1})	5.2	9.1	12.8	7.8	10.6
Optimum Plant Density (plants acre^{-1})	28,100	35,700	40,000	37,200	35,600

The differences in grain yield and water availability across locations resulted in contrasting water use efficiencies, which ranged from 5.2 to 12.8 bu acre^{-1} inch^{-1} (Figure 2E). On average, locations in Nebraska showed a water use efficiency of 10.6 bu acre^{-1} inch^{-1}, higher than the Colorado average, which was 7.8 bu acre^{-1} inch^{-1} (Figure 2D). Despite differences between the states, irrigation practices and crop management significantly impacted water use efficiency for grain production.

IRRIGATION MANAGEMENT

Differences in water use efficiency were driven and explained by changes in water availability rather than by achieved grain yield (Figure 2E). For the analyzed sites there was no correlation between grain yield and water availability (Figure 2C). This lack of association could be related to the lack of severe water-limited growing conditions (less than 15 inches of available water). Fields with higher water availability showed lower water use efficiencies. This is consistent with previous observations in years with varying water availability in the U.S. Midwest (Rotundo et al., 2025).

When analyzing the water balance – the difference between incoming and outgoing water in the crop root zone – fields with significantly greater water availability than the crop's evapotranspiration exhibited lower water use efficiencies (Figure 3A). Water balance ranged from neutral to highly positive, with some fields having up to 18 inches of water applied that was not evapotranspired by the crop. Additionally, experiments located in Colorado tended to show a more positive water balance than those in Nebraska.

We further analyzed the water balance across crop stages (Figure 3B). During the pre-flowering stage, the crop maintained an average positive water balance of 3 inches, which was consistent across both states. However, there were marked differences between the states during the post-flowering stages. In Nebraska, the post-flowering water balance was mostly neutral or slightly negative, while Colorado locations generally had a positive water balance. Based on these findings, there is an opportunity to increase water use efficiency in several locations in Colorado by adjusting irrigation amounts during the grain filling period.

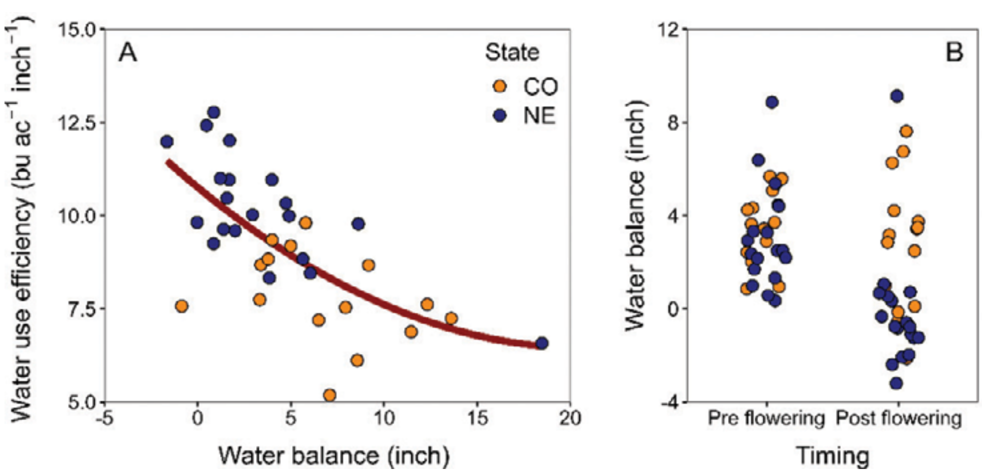


Figure 3. Irigation management effect on water use efficiency. (A) Relationship between water balance and water use efficiency across locations. (B) Water balance before and after flowering across locations. Water balance is the difference between water inputs via rainfall and irrigation and water loss through evapotranspiration.

HYBRID SELECTION AND PLANT POPULATION

Grain yield response to plant density typically follows a curvilinear pattern, with an optimum plant density that maximizes yield. At low plant densities (below the optimum), yield is limited because not all available resources are captured by the crop, particularly light. With an increase in plant density, the total evapotranspiration remains similar because more water is transpired through the crop and less water is lost by evaporation from the soil surface. Conversely, yield is limited at very high plant densities (above the optimum) due to increased competition among plants. This competition can result in a higher number of barren plants, a reduced harvest index (proportion of biomass allocated into the grain), and an increased risk of lodging.

On average, across all hybrids and locations, the optimum plant density for maximizing yield was 37,000 plants acre^{-1}, which achieved an average yield of 259 bu acre^{-1} (Figure 4A). The optimum plant density varied based on the yield target. For a yield target of 210 bu acre^{-1} the optimum density was 34,000 plants acre^{-1}, for a target of 250 bu acre^{-1} it was 36,000 plants acre^{-1}, and for a

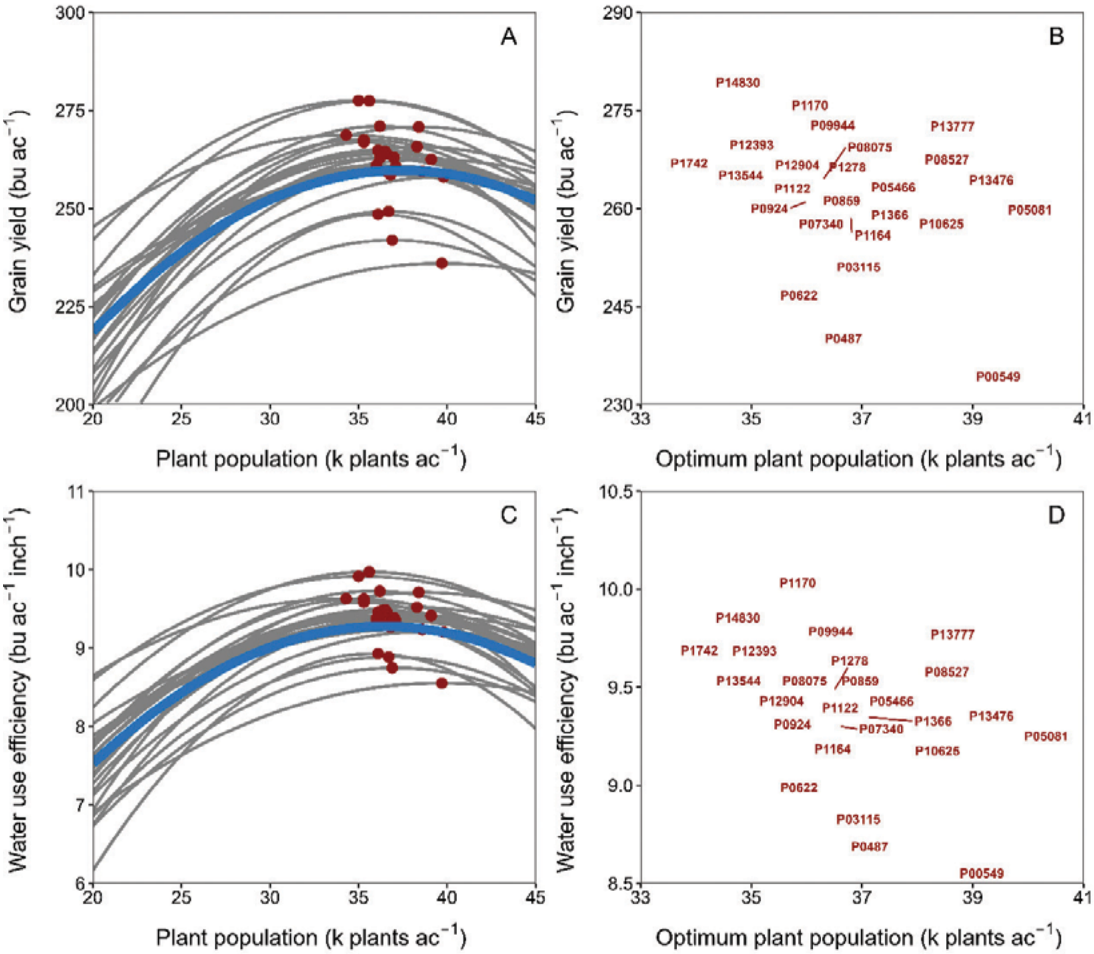


Figure 4. Hybrid and plant density effects on grain yield and water use efficiency. Plant density effect on grain yield (A) and water use efficiency (C). The blue line represents the average response across hybrids, while grey lines represent the individual responses of each hybrid. The red dots indicate the optimum plant density for each hybrid. Plant density that maximized grain yield (B) and water use efficiency (D) for each specific hybrid.

target of 290 bu acre^{-1} it was 38,000 plants acre^{-1}. Additionally, there were slight variations in the optimum plant density between states, with locations in Colorado requiring slightly more plants than those in Nebraska to achieve the same yield target.

The response of grain yield to plant density differed among hybrids (Figure 4A). Each hybrid reached its maximum yield at a distinct plant density. Some hybrids required 34,000 plants acre^{-1} to maximize their yield, while others needed up to 40,000 plants acre^{-1} (Figure 4B). Interestingly, hybrids that required a higher number of plants for maximizing yield were not always the ones that produced the highest overall yields. For example, some high-yielding hybrids, such as Pioneer® P14830 and P1742, reached their maximum yield at around 34,500 plants acre^{-1}, which was notably lower than the average optimum plant density (37,000 plants acre^{-1}).

The plant density that maximized grain yield generally was very similar to the plant density that maximized water use efficiency. On average, across all hybrids and locations, the optimum plant density for maximizing water use efficiency was 36,600 plants acre^{-1}. Additionally, there were variations in the maximum water use efficiency attained by different hybrids, as well as in the plant densities that resulted in this maximum efficiency. The optimum plant density ranged from 34,000 to 40,000 plants acre^{-1}, while the maximum water use efficiency for hybrids varied from 8.5 to 10 bu acre^{-1} inch^{-1} of water. This implies that with 25 inches of available water, a farmer could get a yield from 212 to 250 bu acre^{-1}, depending on the chosen hybrid.

CONCLUSIONS

In the irrigated U.S. Midwest, the thickness of the aquifer from which water is pumped has been declining, posing a risk to crop production. In response, Corteva Agriscience started an agronomy research program to describe the water use efficiency that farmers are getting in their irrigated fields and identify management practices to optimize that efficiency. Between 2023 and 2024, 36 experiments were conducted in growers' irrigated fields from Colorado and Nebraska, testing commercial hybrids across a range of plant densities. This initiative is ongoing, and in 2025 it was expanded to include 60 more locations, some of which are in Kansas, Oklahoma, and Texas.

Water use efficiency in irrigated fields in Colorado and Nebraska averaged 7.8 and 10.6 bu acre^{-1} inch^{-1}, respectively. Differences in water use efficiency across fields were explained by irrigation management, with fields that over-irrigated during grain filling showing the lowest efficiencies. Within individual fields, the combination of hybrid and plant density that maximized grain yield also showed the highest water use efficiency. Hybrids differed in the plant density required to maximize yield. Interestingly, hybrids that required a higher number of plants to maximize yield were not always the ones that produced the highest overall yields.

ACKNOWLEDGEMENTS

Authors wish to thank all growers and agronomists for executing the experiments and collecting the data.

Field Evaluation of Sidedress Nitrogen Applications in Corn

BILL LONG, FIELD AGRONOMIST — **MARK JESCHKE, PH.D.,** AGRONOMY MANAGER

KEY FINDINGS

- Yield was significantly affected by N management, with the 100 lbs N/acre program yielding less than the 150 lbs N/acre and 180 lbs N/acre rates.
- The four corn hybrids in the study responded similarly to nitrogen management.
- Grain harvest moisture and test weight both differed among hybrids, but neither were affected by nitrogen management.

STUDY OBJECTIVES

- A field experiment was conducted in northeast Iowa in 2024 by Heritage Ag Research to evaluate nitrogen management program effects on corn growth and yield.
- The experiment was conducted at two different seeding rates and with four different Pioneer® brand corn products to determine if either hybrid or plant population influenced yield outcomes of different nitrogen management programs.
- Crop canopy biomass and chlorophyll levels were assessed via UAV-based remote sensing at multiple dates during the growing season to evaluate the utility of remote sensing in monitoring crop health and nitrogen status.

STUDY DESCRIPTION

- **Location:** Field research site near Readlyn in northeast Iowa
- **Previous Crop:** Soybean
- **Plot Layout:** Four row x 30-ft plots in a split-plot arrangement within a randomized complete block design; 5 replications.
- **Seeding Rates:** 32,000 and 36,000 seeds/acre

EXPERIMENTAL FACTORS

- **Nitrogen Treatment Program**
  - 100 lbs N/acre (50 lbs fb 50 lbs)
  - 150 lbs N/acre (50 lbs fb 100 lbs)
  - 180 lbs N/acre (50 lbs fb 130 lbs)
- **Hybrid/Brand**[1]
  - P00549PCE (PW, ENL, RIB) - 100 CRM
  - P05737PCE (PW, ENL, RIB) - 105 CRM
  - P1027AM (AM, LL ,RR2) - 110 CRM
  - P13050AM (AM, LL ,RR2) - 113 CRM
- Corn was planted on May 19, which was later than normal for the location due to above-average rainfall during the spring planting window (Table 1).

Figure 1. Lower canopy showing symptoms of nitrogen deficiency.

- The field study was comprised of two parallel experiments – one planted at 32,000 seeds/acre and the other at 36,000 seeds/acre. This design allowed comparisons of hybrid and nitrogen management programs at lower and higher seeding rates, but not direct comparisons between seeding rates.
- All nitrogen treatments were applied as sidedress injection of 32% UAN. Initial treatments of 50 lbs N/acre were applied on June 14 and follow-up applications of 50, 100, or 130 lbs N/acre were applied on June 26.
- Crop canopy data were collected by UAV flights conducted on August 19, September 2, September 20, and October 7.
- Canopy reflectance data from the center two rows of each plot were used to calculate three vegetation indices: normalized difference vegetation index (NDVI), leaf chlorophyll index (LCI), and modified chlorophyll absorption in reflective index (MCARI).
- The study was harvested on October 13 and the center two rows of each four-row plot used to determine yield, grain moisture, and test weight.

Table 1. Cumulative monthly precipitation at the research location near Readlyn, Iowa in 2024 compared to monthly averages.

Month	2024	Average
	—— inches ——	
April	4.0	3.9
May	10.1	4.7
June	7.2	4.9
July	4.7	4.5
August	2.0	4.1
September	0.4	3.0

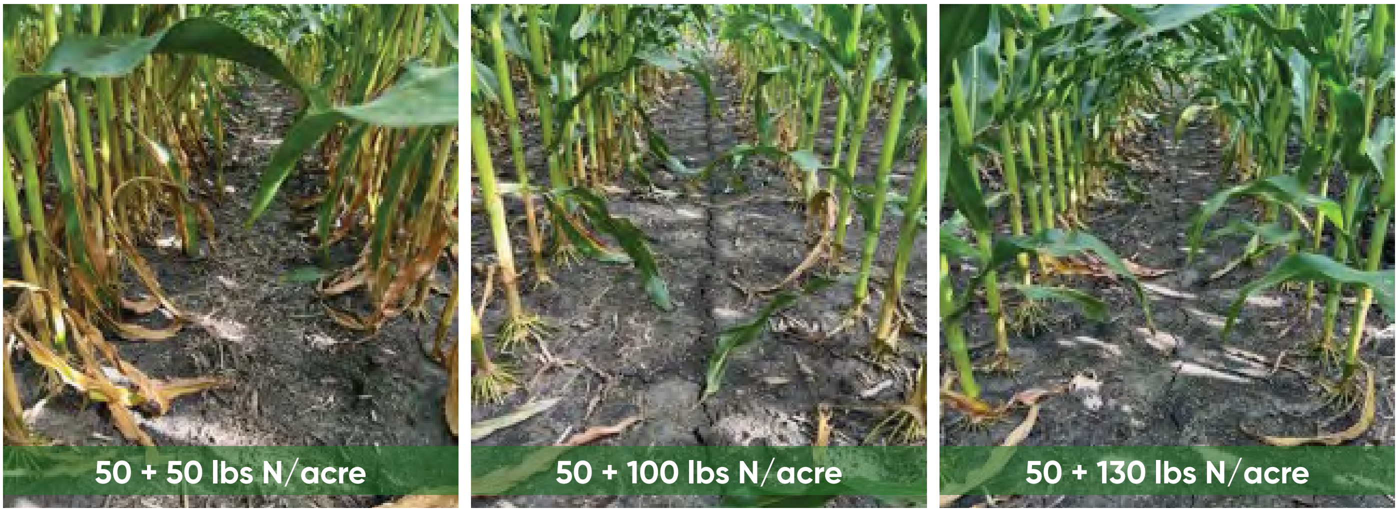


Figure 2. Lower canopy of 100, 150, and 180 lbs N/acre nitrogen treatment plots on September 9, 2024.

RESULTS AND DISCUSSION

CORN YIELD

- Corn yield significantly differed among hybrids at both seeding rates (Figure 3).
- At 32,000 seeds/acre, yield of Pioneer® P00549PCE brand corn was significantly lower than yield of the other three corn products, an outcome likely at least partly attributable to its shorter relative maturity.
- Yield differences among hybrids were similar at the 36,000 seeds/acre rate except for Pioneer P13050AM, which yielded significantly lower than P05737PCE and P1027AM at the higher seeding rate.
- Yield was significantly affected by nitrogen management at both seeding rates, with the 100 lbs N/acre program yielding less than the 150 lbs N/acre and 180 lbs N/acre rates (Figure 3).
- The 180 lbs N/acre program did not provide a significant yield advantage over the 150 lbs N/acre program and results did not suggest the need for more nitrogen at the higher seeding rate.
- Weather conditions during the 2024 growing season may have factored into the yield results – rainfall was above average early in the season before N was applied but below average following the two application timings.
- A nitrogen experiment using the same total N rates but applied prior to planting may have produced different results, as N applied in April or May would have been at greater risk of loss through leaching and denitrification.
- The lack of a significant interaction between hybrid and nitrogen management at either seeding rate indicates that the hybrids responded similarly to nitrogen management.
- Numerous Pioneer research studies over the years have compared nitrogen rate response of different hybrids (Jeschke and DeBruin, 2016). Differences in hybrid response to N in these studies have generally been relatively minor and inconsistent, which suggests that attempting to tailor nitrogen management programs to individual hybrids is unlikely to improve yield or efficiency.

HARVEST MOISTURE

- Grain moisture at harvest significantly differed among hybrids and was positively correlated with hybrid maturity, an outcome that was to be expected given the relatively wide range hybrid maturities in the study (Figure 4).
- Grain moisture of hybrids was very similar between seeding rates, except for P13050AM, which was 2.5 points wetter at the higher seeding rate. The experimental design of this study does not allow any conclusions to be drawn as to whether this was a meaningful difference attributable to seeding rate or not.
- Nitrogen management did not significantly affect grain moisture, nor were there significant hybrid by nitrogen interactions, at either seeding rate.

TEST WEIGHT

- Grain test weight significantly differed among hybrids and was inversely correlated with hybrid maturity (Figure 5).
- Nitrogen management did not significantly affect test weight, nor were there significant hybrid by nitrogen interactions, at either seeding rate.
- Test weight was slightly lower across the board at the 36,000 seeds/acre seeding rate but, again, it's unclear given the experimental design if this was a meaningful difference attributable to seeding rate.
- Test weight in this study was likely influenced by the onset of drought stress during the grain filling period, caused by below-average rainfall in August and September.

VEGETATION INDICES

- There were significant differences among hybrids for all three vegetation indices at all imagery timings (Table 2).
- Leaf chlorophyll index (LCI) was the vegetation index most affected by nitrogen management, with significant differences among nitrogen programs in every instance except in the 32,000 seeds/acre seeding rate at the final imagery timing.
- NDVI significantly differed among nitrogen programs at the first two imagery timings, only in the higher seeding rate at the third timing, and in neither seeding rate at the final timing.
- MCARI was not affected by nitrogen management.

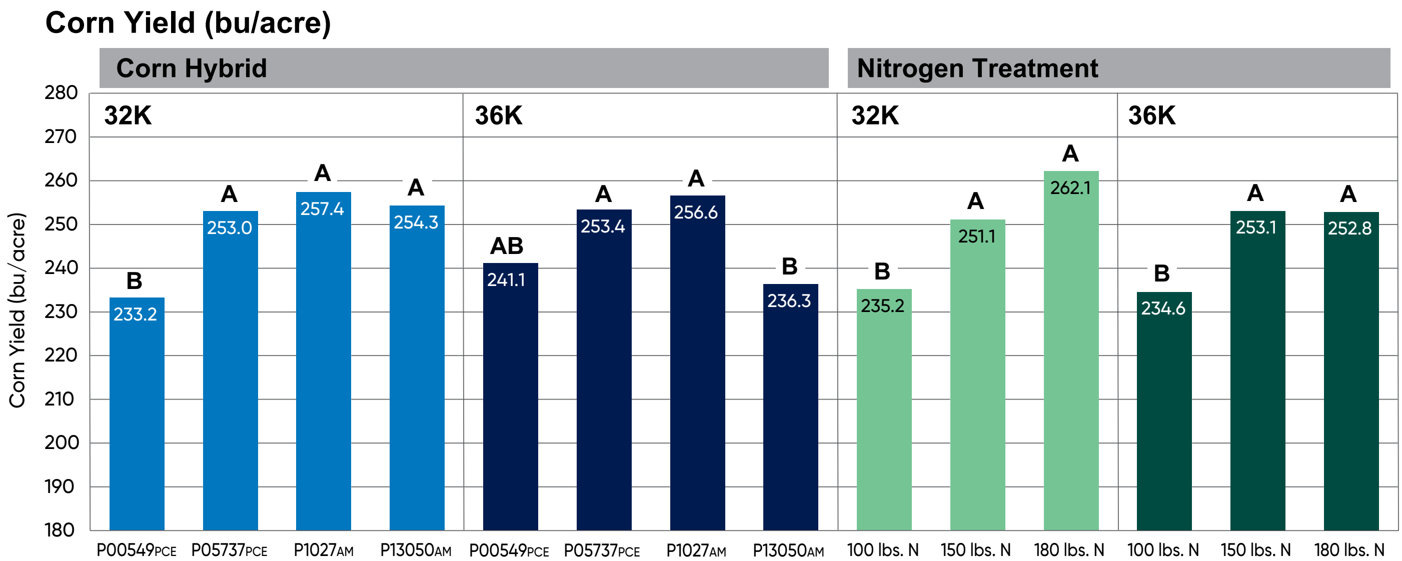


Figure 3. Corn yield by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05.

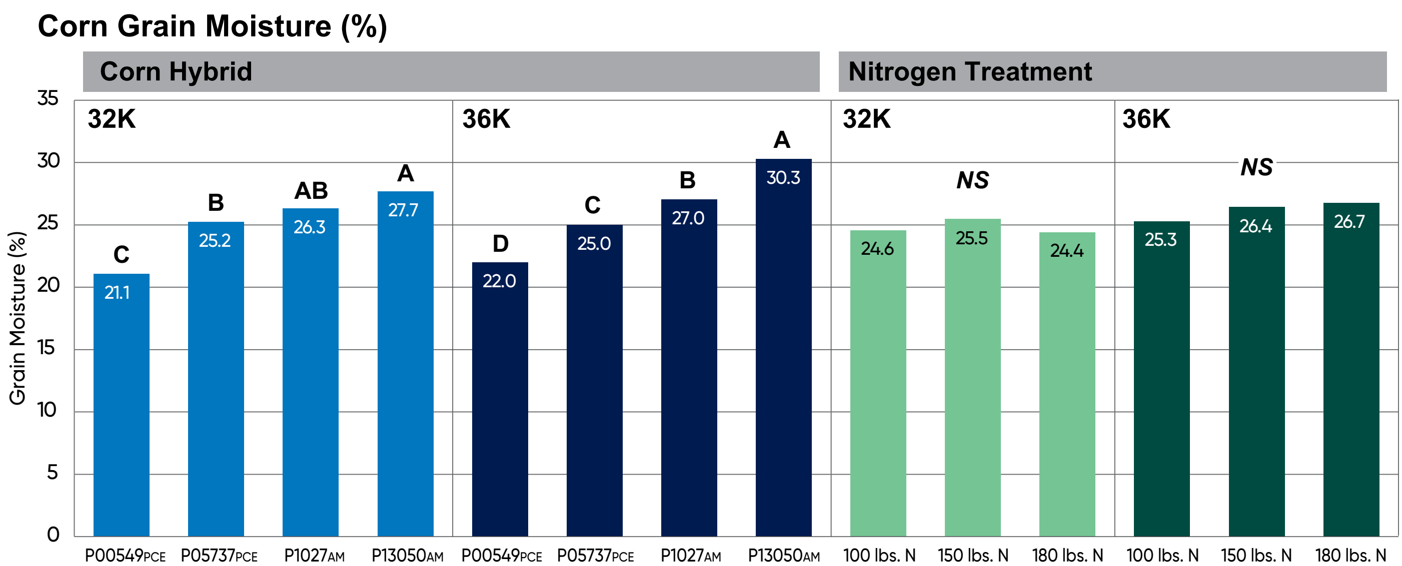


Figure 4. Corn grain moisture at harvest by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05. NS = no significant difference.

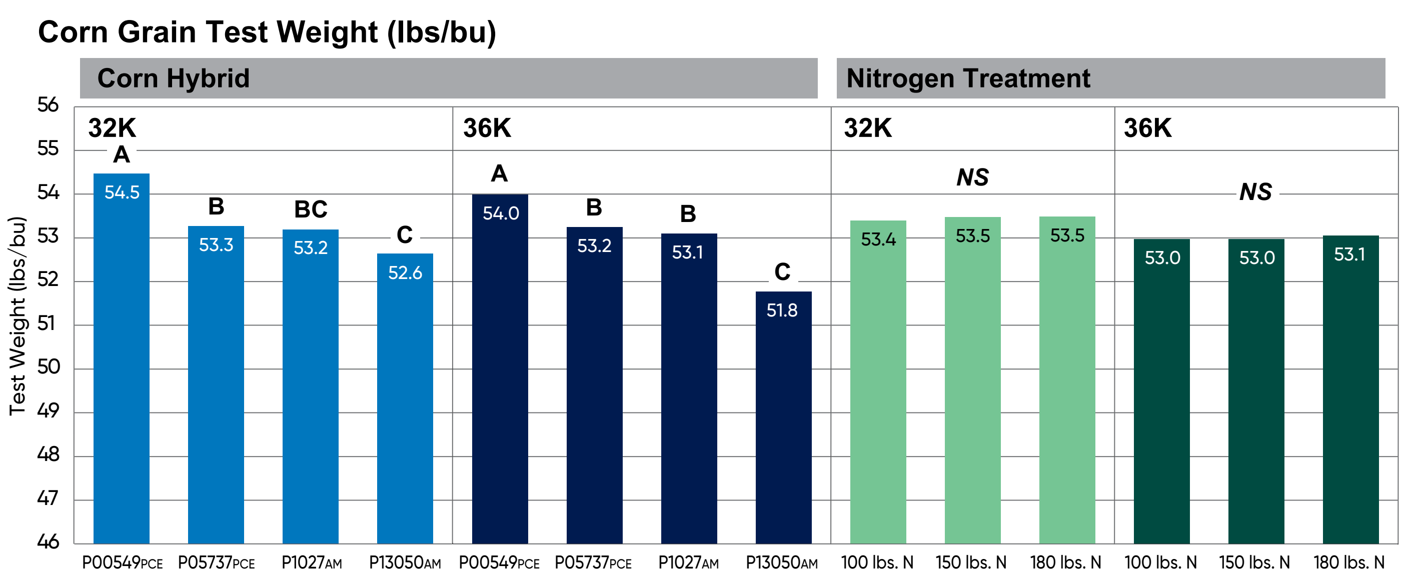


Figure 5. Corn grain test weight by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05. NS = no significant difference.

NDVI

- The normalized difference vegetation index (NDVI) is a widely-used metric for quantifying the **health and density of vegetation**. It is calculated based on reflectance in the red and NIR bands (Figure 6).
- Values near zero indicate bare soil, while higher positive values of NDVI range from sparse vegetation (0.1 - 0.5) to dense green vegetation (0.6 and above).
- NDVI is generally effective at characterizing spatial variability in plant health but it is not as good for tracking changes in crop condition over time.

LCI

- Leaf chlorophyll index (LCI) is a measure of **chlorophyll content** in plant leaves in areas of complete leaf coverage. LCI is calculated using reflectance values in the red-edge and near-infrared (NIR) regions.
- The red-edge band is highly sensitive to the light reflected off of the cellular structure of a plant. The NIR region is sensitive to the internal structure of the leaf and its moisture content, which can be used in conjunction with the red-edge band for LCI calculations.

MCARI

- Modified chlorophyll absorption in reflectance index (MCARI) is a vegetation index used to estimate **chlorophyll concentration** that is sensitive to variations in chlorophyll content and leaf area index (LAI). It's calculated using reflectance values in the red, green, and near-infrared (NIR) spectral bands.
- MCARI is useful when there are high levels of background reflectance from soil and other objects in the imagery. To achieve the highest accuracy of plant health analysis, MCARI should be used together with NDVI or LAI.

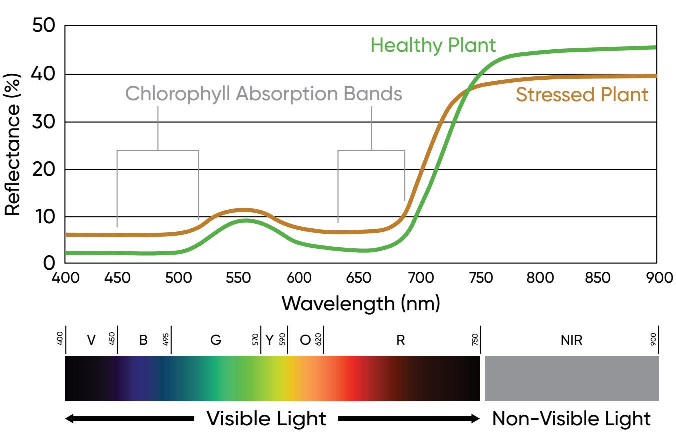


Figure 6. Generalized electromagnetic radiation reflectance profiles of healthy and stressed plants.

Table 2. Effects of hybrid and nitrogen management on vegetation indices (NDVI, LCI, and MCARI). An 'x' indicates that the main effect was significant at α=0.05.

NDVI		8-19	9-2	9-20	10-7
32K	Hybrid	x	x	x	x
	Nitrogen	x	x		
36K	Hybrid	x	x	x	x
	Nitrogen	x	x	x	
LCI		**8-19**	**9-2**	**9-20**	**10-7**
32K	Hybrid	x	x	x	x
	Nitrogen	x	x	x	
36K	Hybrid	x	x	x	x
	Nitrogen	x	x	x	x
MCARI		**8-19**	**9-2**	**9-20**	**10-7**
32K	Hybrid	x	x	x	x
	Nitrogen				
36K	Hybrid	x	x	x	x
	Nitrogen				

- Vegetation index means by hybrid and nitrogen treatment from the August 19 imagery timing are shown in Figures 7-9.
- All three vegetation indices showed significant differences among hybrids. NDVI had the greatest degree of statistical separation, with all hybrids differing significantly from each other at both seeding rates (Figure 7).
- LCI showed less statistical separation among hybrids compared to NDVI, but generally similar patterns (Figure 8).
- MCARI differed from the other two indices – at 32,000 seeds/acre, P1027AM was significantly greater than the other three hybrids, while at 36,000 seeds/acre P13050AM dropped off compared to the other hybrids (Figure 9).
- When comparing vegetation indices to yield, hybrid means often ranked in similar order, but significant differences in vegetation indices often occurred where there were no corresponding differences in yield.
- For nitrogen treatments, both NDVI and LCI corresponded with yield results, with values for the 100 lbs N/acre treatment significantly lower than the other two rates.
- MCARI did not differ among nitrogen treatments at either seeding rate.
- Figures 10-12 show how vegetation indices changed at later imagery timings. All three declined toward the end of the season, with the greatest decline in late-September to early October as the canopy senesced.

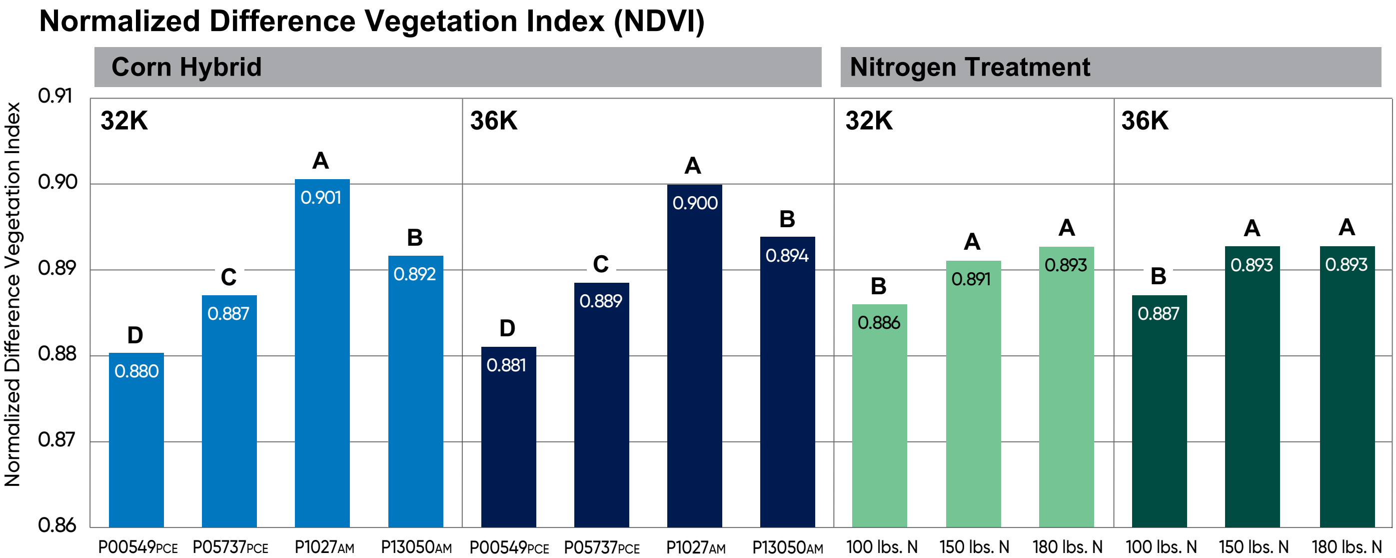


Figure 7. Normalized difference vegetation index (NDVI) by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates on August 19, 2024. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05.

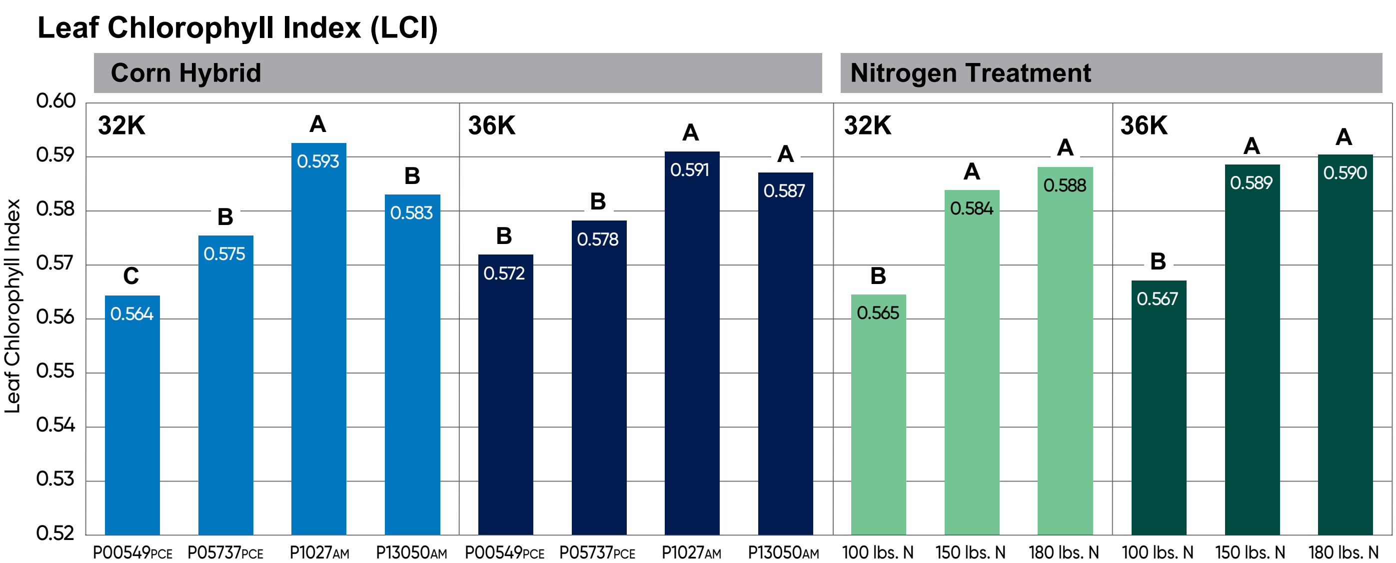


Figure 8. Leaf chlorophyll index (LCI) by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates on August 19, 2024. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05.

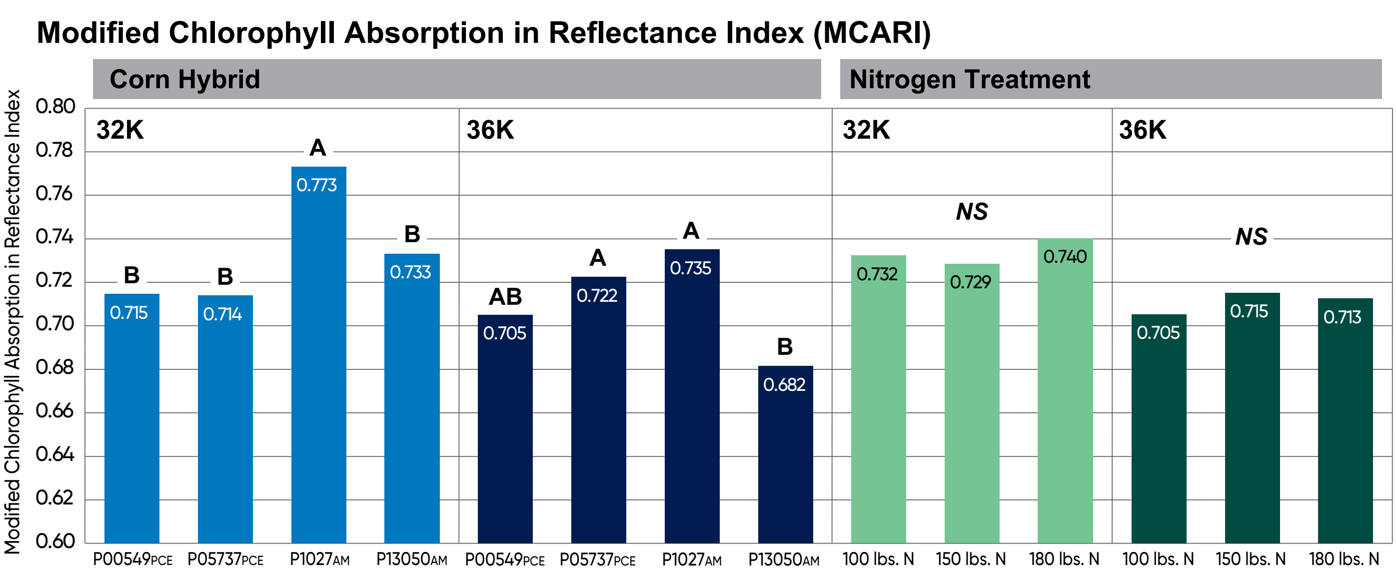


Figure 9. Modified chlorophyll absorption in reflectance index by hybrid and nitrogen treatment at 32,000 and 36,000 seeds/acre seeding rates on August 19, 2024. Means with the same letter within each group are not significantly different based on Student's t test at α=0.05. NS = no significant difference.

- NDVI remained relatively unchanged until the final imagery timing on October 7 (Figure 10), while both LCI and MCARI had noticeable declines by September 20 (Figure 11 and 12).
- The primary interest in vegetation indices in this study was in their utility for assessing nitrogen status and predicting associated yield outcomes.
- Results suggest that NDVI and LCI could be useful for this purpose, but differences in these indices among hybrids were equal to or greater than those among nitrogen treatments, suggesting the need to calibrate predictions to individual hybrids.

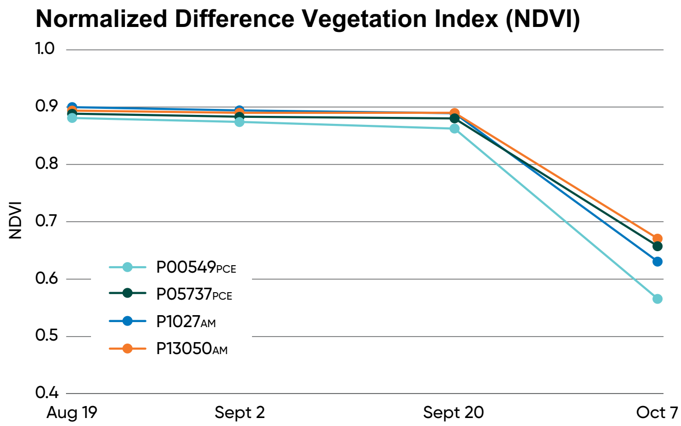


Figure 10. Normalized difference vegetation index (NDVI) by hybrid at 36,000 seeds/acre seeding rate.

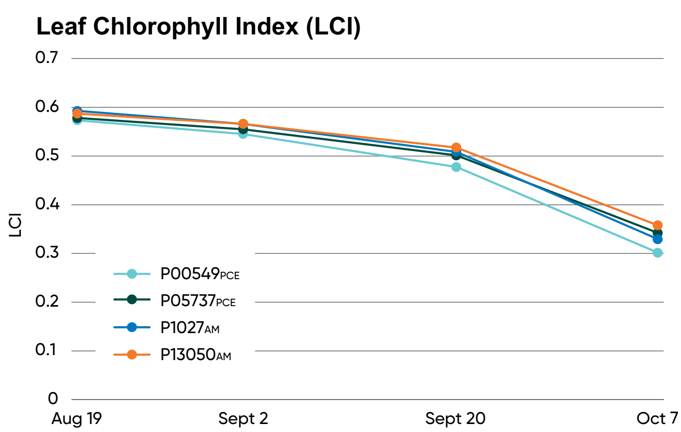


Figure 11. Leaf chlorophyll index (LCI) by hybrid at 36,000 seeds/acre seeding rate.

- The effect of hybrid differences in NDVI on nitrogen status assessment is illustrated in Figure 13.
- This example shows NDVI values by nitrogen treatment for P05737PCE and P1027AM, two hybrids that had a signficant difference in NDVI values despite no significant difference in yield.
- The NDVI value for P1027AM at the lowest nitrogen treatment rate - which was yield-limiting - is greater than the NDVI values for P05737PCE at the upper two nitrogen treatment rates where nitrogen was not yield limiting.

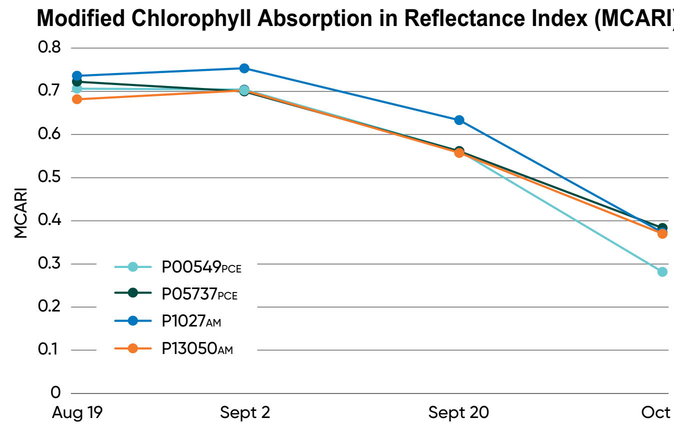


Figure 12. Modified chlorophyll absorption in reflectance index (MCARI) by hybrid at 36,000 seeds/acre seeding rate.

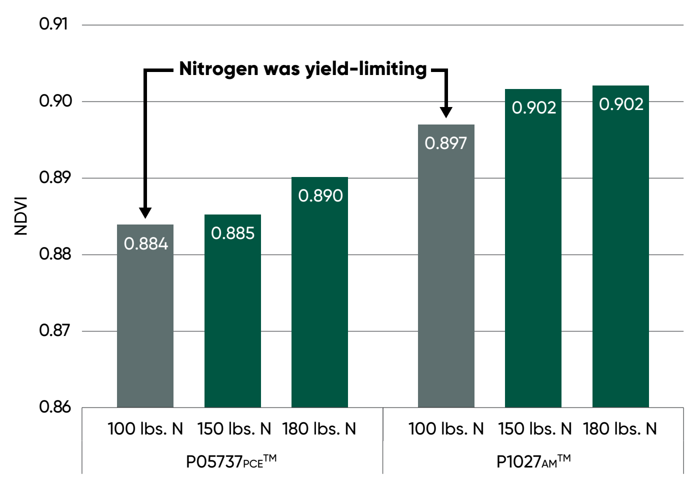


Figure 13. Normalized difference vegetation index (NDVI) by nitrogen treatment for P05737PCE and P1027AM at 32,000 seeds/acre.

Foliar Fungicides For Use in Corn

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- As foliar fungicide use in corn has become more common, the number of products in the marketplace with multiple active ingredients has increased.
- Mode of action is the primary criterion by which fungicides are categorized and target site is the basis for FRAC groups, which are group numbers assigned by the Fungicide Resistance Action Committee that are shown on fungicide product labels.
- Three different groups of fungicides are commonly used in corn: demethylation inhibitors (Group 3), succinate dehydrogenase inhibitors (Group 7), and quinone outside inhibitors (Group 11).
- Fungicides are sometimes referred to as having “preventative” or “curative” activity but both types need to be applied early in the infection process to be effective.
- Fungicides can differ in their mobility both in and on plant tissues.
- Using fungicides with multiple modes of action can help slow the development of resistance in pathogens and provide more effective disease control.

CORN FUNGICIDES

Over the past couple decades, foliar fungicides have gone from a mostly new and untested practice to a trusted component of many growers' management systems. This has occurred as research results and grower experience have demonstrated that fungicides can be very effective tools for managing foliar diseases and protecting yield in corn.

As foliar fungicide use in corn has become more common, the number of products in the marketplace has increased. Older fungicides typically only had one active ingredient, but many newer ones have two, or even three, active ingredients with different modes of action. With the increasing complexity of fungicide options available to corn growers, it is important to understand different fungicide modes of action, how they work, and good stewardship practices.

FUNGICIDE MODE OF ACTION

Fungicides inhibit fungal growth by disrupting critical processes in fungal cells. Fungicide **mode of action** (MOA) refers to the cellular process inhibited by a fungicide. Fungicide **target site** (or site of action) refers to the specific enzyme involved in a cellular process to which a fungicide binds. It is possible for two fungicides to have the same mode of action but different target sites, meaning that they disrupt the same cellular process but target different enzymes involved in the process to do so.

Target site is the basis for FRAC codes, which are group numbers assigned by the Fungicide Resistance Action Committee that are shown on fungicide product labels (Figure 1). A pathogen that develops resistance to a specific fungicide will generally also be resistant to other fungicides that share the same target site, a phenomenon known as cross resistance. Consequently, from a resistance management standpoint, target site is the most important distinguishing factor for categorizing fungicides.

Fungicides within a target site grouping are also sometimes further subdivided into **chemical groups**, which are based on structural characteristics of the fungicide molecules.

FRAC currently recognizes 12 different known fungicide modes of action. Of these, two are currently utilized in foliar fungicide products used in corn: inhibition of cellular respiration or inhibition of sterol biosynthesis in cell membranes. This includes three different FRAC groups (target sites), two of which share the same mode of action:

- **Group 3: Demethylation Inhibitors** (DMI) - sterol biosynthesis
- **Group 7: Succinate Dehydrogenase Inhibitors** (SDHI) - cellular respiration
- **Group 11: Quinone Outside Inhibitors** (QoI) - cellular respiration

In practice, the term "mode of action" is often used in place of target site or FRAC group, despite not being technically accurate. For example, SDHI and QoI fungicides have the same mode of action, as they both work by inhibiting cellular respiration. In common usage though, they are generally referred to as different "modes of action" because they have different target sites, do not exhibit cross resistance, and are in different FRAC groups.

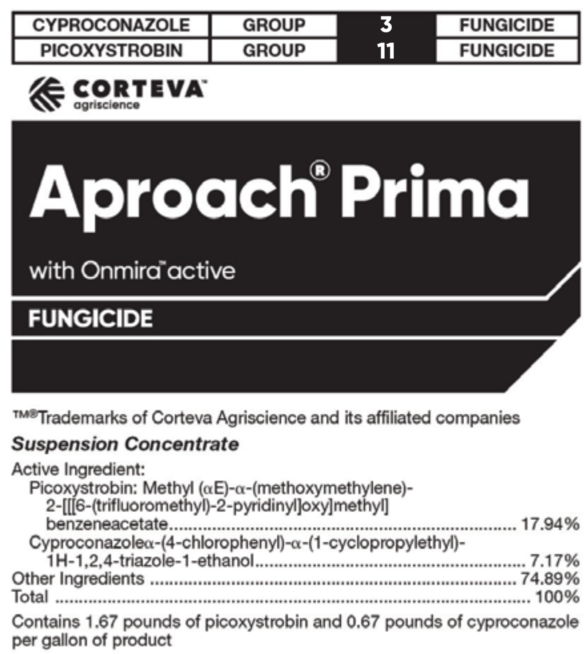


Figure 1. Example of a fungicide product label showing the names and FRAC groups of the active ingredients.

PREVENTATIVE VS. CURATIVE FUNGICIDES

Fungicides are sometimes referred to as having "preventative" or "curative" activity (Mueller and Robertson, 2008). This distinction is based on the stage of fungal infection that is disrupted by a particular fungicide mode of action. These terms can be somewhat misleading however, as no fungicides are truly curative – once plant tissue has been damaged by fungal infection, it cannot be recovered. Both types of fungicides need to be present early in the infection process to be effective.

QoI and SDHI fungicides are considered preventative fungicides. The mode of action for both types of fungicides is inhibition of cellular respiration, which means that they kill the fungus by stopping energy production in the mitochondria of the fungal cells. QoI fungicides usually accumulate in the waxy cuticle on the leaf surface, and do not prevent growth of fungal mycelium inside leaf tissue. If fungal spores are exposed to QoI or SDHI fungicides before they germinate, the germination process is stopped, and infection is prevented. QoI and SDHI fungicides both need to be applied prior to infection or in the very early stages of infection to be effective (Figure 2).

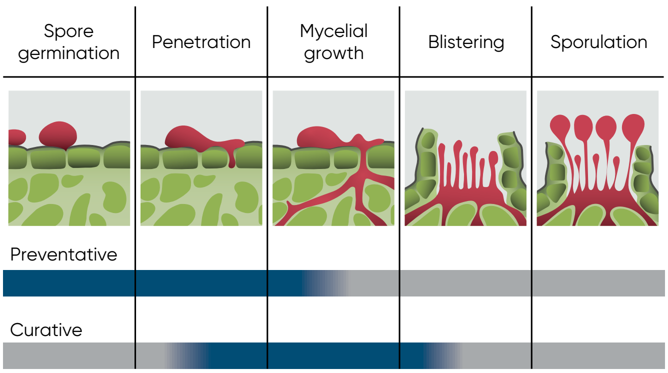


Figure 2. Stages of fungal infection and efficacy windows of "preventative" and "curative" fungicides.

Most DMI active ingredients are considered curative fungicides. DMI fungicides are absorbed into the leaf tissue and disrupt fungal development early in the infection process. The mode of action for these fungicides is inhibition of sterol production, which is a type of lipid molecule required to form cell membranes. A fungal spore exposed to a DMI fungicide can still germinate but once the supply of sterols in the spores is depleted, fungal growth stops. Despite being characterized as "curative," DMI fungicides still need to be applied prior to infection or in the very early stages of infection to be effective.

It is important to remember that infection can begin well before visual symptoms of foliar diseases become apparent. The period from the start of infection until visual symptoms develop is known as the latent period. The length of this period differs among foliar diseases – from as little as 3 days for southern rust to 3 weeks or more for gray leaf spot (Table 1). The major fungal foliar diseases of corn are all polycyclic, which means that many disease cycles can occur in a single season and new infections will continue to occur as long as conditions are favorable and susceptible plant tissue is available.

Table 1. Approximate latent periods of common corn diseases.

Corn Disease	Latent Period
Southern rust (*Puccinia polysora*)	3-4 days
Common rust (*Puccinia sorghi*)	6-7 days
Northern leaf blight (*Exserohilum turcicum*)	7-14 days
Tar spot (*Phyllachora maydis*)	14-20 days
Gray leaf spot (*Cercospora zeae-maydis*)	14-28 days

FUNGICIDE MOBILITY

Fungicides can differ in their mobility both in and on plant tissues. Fungicides are broadly classified as either contact or penetrant (Oliver and Beckerman, 2022):

Contact fungicides, also known as protectants, are adsorbed to plant surfaces where they form a thin protective layer that prevents spore germination. Contact fungicides must be applied before spores land on the leaves to be effective, as they have no protective effect once infection has already begun. Many older fungicides are protectants.

Penetrant fungicides penetrate the waxy cuticle on the leaves and are absorbed into plant tissues, where they can have varying degrees of mobility within the plant (Figure 3):

- **Translaminar** – The fungicide is absorbed into the leaf tissue and can penetrate through the leaf to the opposite surface but does not move throughout the plant.
- **Locally systemic** – The fungicide undergoes very limited translocation in plant tissues, not moving far from the site of penetration.
- **Xylem mobile** – The fungicide is translocated via the xylem tissue, which allows it to move upward in the plant from the site of penetration but not downward.

Very few fungicides (and none currently used in corn) are fully systemic within plants, which would require translocation via both the xylem and phloem tissues allowing both upward and downward movement in the plant.

Fungicides can also move outside the plant. Surface redistribution occurs when rewetting of leaf tissue after application allows the fungicide to spread locally on the leaf's surface from the point

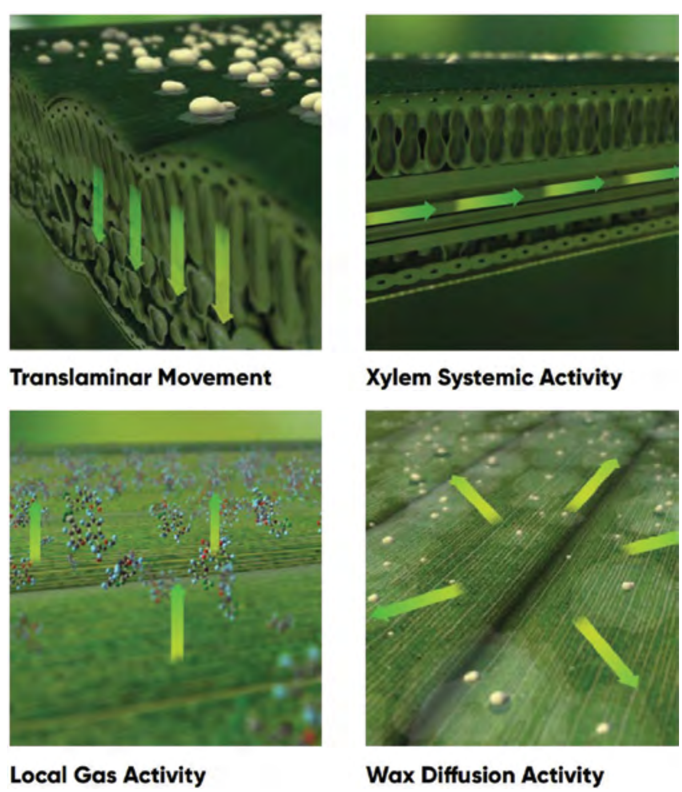


Figure 3. Different types of fungicide mobility.

of application. Some fungicides also have vapor phase mobility, which means that they can redistribute within the crop canopy via vapor movement following application, allowing them to move from leaf to leaf and have activity in plant tissues that were not directly exposed to the initial application (Figure 3).

All three classes of fungicides currently used in corn are classified as penetrants, as they all are absorbed into plant tissues and have some degree of mobility within plants (Oliver and Beckerman, 2022). SDHI fungicides (Group 7) are the least mobile, only having locally systemic distribution within plant tissues. QoI fungicides (Group 11) vary in their mobility. Most have only locally systemic and translaminar mobility in plants; however, azoxystrobin and picoxystrobin are both translaminar and xylem mobile, and picoxystrobin further exhibits vapor movement within the canopy. DMI fungicides (Group 3) are the most mobile, with all members of this group able to translocate upward in plants via the xylem tissue.

GROUP 3: DEMETHYLATION INHIBITORS (DMI)

Mode of Action: Sterol biosynthesis in membranes

Target Site: C14-demethylase in sterol biosynthesis

Mobility: Xylem-mobile

Resistance Risk: Medium

Group 3 fungicides are commonly referred to as the triazoles, as most of the active ingredients used in corn come from this chemical group (Table 2). These fungicides were first introduced in the mid-1970s and are effective against many fungal diseases, especially rusts and leaf spots. Corn fungicide products containing only a DMI active ingredient are available, although many current fungicides combine a DMI with a Group 11 fungicide (strobilurin), as well as three-way products that also include a Group 7 fungicide.

DMI fungicides work by inhibiting C14-demethylase, an enzyme that plays a role in sterol production. Although all DMI fungicides target this enzyme, different active ingredients may act in slightly different parts of the biochemical pathway, resulting in differing spectra of activity for these fungicides (Mueller et al., 2013).

DMI fungicides are locally systemic and xylem-mobile, which means they can spread in the leaf tissue from the site of application and move upward in the plant via the xylem tissue. These fungicides typically have around 14 days of residual activity after application.

Table 2. Group 3 DMI fungicide active ingredients used in fungicide products labelled for control of foliar diseases in corn.

Common Name	Chemical Group
cyproconazole	triazoles
flutriafol	triazoles
mefentrifluconazole	triazoles
metconazole	triazoles
propiconazole	triazoles
tebuconazole	triazoles
tetraconazole	triazoles
prothioconazole	triazolinthiones

DMI fungicides are considered medium risk for resistance development. Resistance has been documented in multiple fungal species, with multiple known mechanisms of resistance (FRAC, 2024). Reduced sensitivity to certain DMI fungicides has been reported in several U.S. states for *Fusarium graminearum* (fusarium head blight) in wheat. Recent research suggests that there may be isolates of *Exserohilum turcicum* – the causal pathogen of northern corn leaf blight – that are resistant to the DMI fungicide flutriafol (Anderson et al., 2024).

GROUP 7 SUCCINATE DEHYDROGENASE INHIBITORS (SDHI)

Mode of Action: Cellular respiration

Target Site: Complex II: succinate-dehydrogenase

Mobility: Locally systemic

Resistance Risk: Medium-high

SDHI fungicides have been on the market since the late 1960s. The first generation of these fungicides had relatively limited disease and application spectra. SDHI fungicides with increased spectrum and potency were commercialized beginning in the early 2000s and new ones continue to be launched today. Corn fungicide products that include a SDHI typically also include a Group 3 or Group 11 fungicide, or both.

SDHI fungicides inhibit complex II of the fungal mitochondrial respiration pathway by binding and blocking SDH-mediated electron transfer from succinate to ubiquinone. SDHI fungicides are locally systemic, capable of moving a short distance from the site of application. SDHIs have longer residual activity than other groups.

Resistance to SDHI fungicides has been documented in several fungal pathogens. Field isolates with target site mutations conferring reduced sensitivity have been found in *Pyrenophora teres* (net blotch) in barley, *Zymoseptoria tritici* (septoria leaf blotch) in wheat and *Sclerotinia sclerotiorum* (sclerotinia stem rot) in canola (FRAC, 2015).

Table 3. Group 7 SDHI fungicide active ingredients used in fungicide products labelled for control of foliar diseases in corn.

Common Name	Chemical Group
fluopyram	pyridinyl-ethyl-benzamides
benzovindiflupyr	pyrazole-4-carboxamides
bixafen	pyrazole-4-carboxamides
fluindapyr	pyrazole-4-carboxamides
fluxapyroxad	pyrazole-4-carboxamides
pydiflumetofen	N-methoxy-(phenyl-ethyl)-pyrazole-carboxamides

GROUP 11 QUINONE OUTSIDE INHIBITORS (QOI)

Mode of Action: Cellular respiration

Target Site: Complex III: cytochrome bc1

Mobility: Locally systemic / translaminar, some are xylem-mobile

Resistance Risk: High

The QoI fungicides, commonly known as strobilurins, are a relatively new group of fungicides, with the first fungicide in this group (azoxystrobin) released in 1996. Stobilurins are modeled after a naturally occurring fungicidal compound (strobilurin A) produced by *Strobilurus tenacellus*, a species of wood-rotting mushrooms. These mushrooms grow on pinecones and produce a fungicidal compound to suppress other fungi that compete for the same food source.

The target site of the QoI fungicides is the mitochondrial respiratory complex III, which is an integral membrane protein complex that couples electron transfer. The QoI fungicides bind to the quinone outside site of complex III and block electron transfer between cytochrome b and cytochrome c1 across the membrane. QoI fungicides are active against a broad range of plant pathogens. Most have locally systemic and translaminar mobility in plants, and some are also xylem mobile. These fungicides can have 7-21 days of residual activity.

QoI fungicides are considered high-risk for the development of resistance in pathogens. Currently there are more than 20 plant pathogens with some level of resistance to QoI fungicides, including *Cercospora sojina* (frogeye leaf spot) and *Cercospora kikuchii* (cercospora leaf blight) in soybeans (Zhang et al., 2012; Price et al., 2015).

Table 4. Group 11 QoI fungicide active ingredients (strobilurins) used in fungicides labelled for control of foliar diseases in corn.

Common Name	Chemical Group
azoxystrobin	methoxy-acrylates
picoxystrobin	methoxy-acrylates
pyraclostrobin	methoxy-carbamates
trifloxystrobin	oximino-acetates
fluoxastrobin	dihydro-dioxazines

MULTIPLE MODE OF ACTION FUNGICIDES

In the early 2000s, when foliar fungicides started to come into common usage in field corn, most fungicide products available to growers only included one active ingredient. Today, many fungicide products have multiple active ingredients. Numerous strobilurin + triazole products are available and strobilurin + triazole + SDHI products have become more common in recent years (Table 5).

One of the most important benefits of fungicide products with multiple modes of action is resistance management. Pathologists commonly recommend mixing or rotating fungicide modes of action to slow the development of resistance in pathogens. By using fungicides with different modes of action, growers can reduce the selection pressure on fungal populations, slowing down the development of resistance to specific fungicide types. This is important for preserving the effectiveness of fungicides, especially products such as the strobilurins, which are considered high risk for resistance development.

Fungicides with multiple modes of action can also provide more effective disease control by targeting a broader range of fungal diseases and pathogens and providing more comprehensive protection for the corn crop. Tar spot of corn (*Phyllachorra maydis*) has shown improved control when using multiple modes of action. Fungicide products with two or three modes of action provided greater suppression of tar spot than single mode of action fungicides in a multi-state study (Goodnight et al., 2024).

Table 5. Active ingredients (%) by FRAC group of foliar fungicides labelled for use in corn (Wise, 2025).

	Group 11					Group 3								Group 7					
Trade Name	**azoxystrobin**	**picoxystrobin**	**pyraclostrobin**	**trifloxystrobin**	**fluoxastrobin**	**cyproconazole**	**flutriafol**	**mefentrifluconazole**	**metconazole**	**propiconazole**	**tebuconazole**	**tetraconazole**	**prothioconazole**	**fluopyram**	**benzovindiflupyr**	**bixafen**	**fluindapyr**	**fluxapyroxad**	**pydiflumetofen**
Quadris® 2.08 SC, generics	22.9																		
Aproach® 2.08 SC		22.5																	
Headline® 2.09 EC/SC			23.6																
Tilt® 3.6 EC, generics										41.8									
Folicur® 3.6 F, generics											38.7								
Domark® 230 ME												20.5							
Proline® 480 SC													41						
Quilt Xcel® 2.2 SE, generics	13.5									11.7									
Topguard® EQ 4.29 SC	25.3						18.63												
Affiance® 1.5 SC	9.35											7.48							
Aproach® Prima 2.34 SC		17.94				7.17													
Veltyma® 3.34 SC			17.56					17.56											
Priaxor® 4.17 SC			28.58															14.33	
Headline AMP® 1.68 SC			13.64						5.14										
Delaro® 325 SC				13.7									16.0						
Stratego® YLD 4.18 SC				32.3									10.8						
Fortix® 3.22 SC					14.84		19.3												
Preemptor™ 3.22 SC					14.84		19.3												
Lucento® 4.17 SC							26.74									15.55			
Adastrio® 4.0 SC	15.7						15.7										10.5		
Miravis® Neo 2.5 SE	9.3									11.6									7.0
Trivapro® 2.21 SE	10.5									11.9					2.9				
Revytek® 4.44 SC			15.49					11.61										7.74	
Delaro® Complete 3.83 SC				13.1									14.9	10.9					

Maximizing the Value of Foliar Fungicides in Corn

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- There are several factors that can influence the likelihood of a corn yield benefit from a foliar fungicide application.
- Continuous corn and minimum tillage fields can be at higher risk of foliar disease and more likely to benefit from a fungicide application due to greater amounts of surface residue harboring pathogens from the previous corn crop.
- Hybrids that have lower levels of genetic resistance to a given foliar disease are more likely to benefit from a fungicide application if that disease becomes prevalent.
- The severity of foliar diseases in a given year is largely driven by environmental conditions.
- Wet conditions are generally favorable for foliar diseases in corn; specifically, conditions that enable prolonged periods of wetness on the surfaces of leaves.
- Research has generally shown that the VT/R1 growth stage is the most effective application timing for disease control and yield protection in corn.
- Fungicides with multiple modes of action can provide more effective disease control and help reduce the selection for resistance in plant pathogens.

PROTECTING CORN YIELD

Over the past 20 years, foliar fungicide treatments in corn have gone from a new and mostly untested practice to a trusted component of many growers' management systems. This has occurred as research results and grower experience have demonstrated that fungicides can be very effective tools for managing foliar diseases and protecting yield in corn.

Over 2,000 Pioneer on-farm trials conducted over 14 years found an average corn yield response to foliar fungicide treatment of 7.4 bu/acre (Jeschke, 2021). Yield responses exceeding 20 bu/acre are not uncommon when disease pressure is very high, while fungicides may have little or no yield benefit under low disease pressure. Determining where in that range of responses a given field is likely to be is important in maximizing the value of a fungicide treatment.

Deciding if/when to apply a foliar fungicide in corn can be difficult. There are several factors that can influence corn yield response to fungicide application. Complicating the decision is the fact that treatments must be made ahead of the onset of foliar diseases to be effective. Diseased leaf tissue cannot be recovered after infection, so applications must be made before it is obvious that a fungicide treatment is needed.

*Over 2,000 Pioneer on-farm trials conducted over 14 years found an average corn yield response to foliar fungicide treatment of **7.4 bu/acre.***

Bringing as much advanced knowledge to the table as possible is important for making the best decisions. Fortunately, there has been no shortage of foliar fungicide research over the past 20 years, so there is plenty of knowledge available on when fungicides are or are not likely to be economically beneficial in corn.

Anyone who has taken an introductory plant pathology class is likely to be familiar with the disease triangle concept – the three factors that must be present at the same time for plant disease to occur: a disease-causing pathogen, a susceptible host, and favorable environmental conditions (Figure 1). The disease triangle concept can provide a useful framework for evaluating the potential benefit of a foliar fungicide treatment in corn.

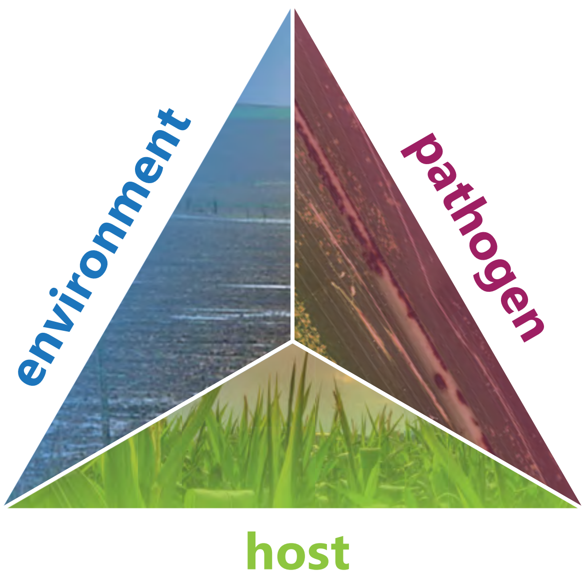


Figure 1. The disease triangle is a conceptual model used to illustrate how diseases arise and spread. All three factors represented by the triangle must be present for disease to occur.

DISEASE-CAUSING PATHOGENS

In order for plant disease to occur, a disease-causing pathogen must be present in the field. All corn fields are likely to have multiple pathogens present that are capable of infecting corn; however, which pathogens and in what quantities can vary based on a number of factors.

PATHOGEN LIFECYCLES

There are two basic types of disease cycles among the fungal diseases that infect corn leaves. Many pathogens, such as gray leaf spot and northern corn leaf blight, overwinter in diseased corn leaves, husks, and other plant parts. Spores are produced on crop residue when environmental conditions become favorable in the spring and early summer. These spores are spread by rain splash and air currents to the leaves of new crop plants, where primary infections are produced. Secondary spread then occurs from plant to plant and even from field to field as spores are carried long distances by the wind. As the plants die, the fungi remain in the dead plant tissue.

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

Pathogens for diseases such as gray leaf spot and northern corn leaf blight overwinter in diseased corn leaves, husks, and other plant parts.

CROP ROTATION AND TILLAGE

For foliar diseases that overwinter in corn residue, the amount of residue remaining on the soil surface from the previous corn crop affects the amount of disease inoculum available to infect the current crop. Crop rotation and tillage can both influence surface residue levels and, consequently, foliar disease risk. Continuous corn and minimum tillage fields can be at higher risk of foliar disease and more likely to benefit from a fungicide application due to greater amounts of surface residue harboring pathogens from the previous corn crop. Survival of diseases in corn residue can lead to earlier infection and higher disease incidence and severity in the subsequent corn crop.

Many common diseases, including gray leaf spot, northern corn leaf blight, southern leaf blight, eyespot, tar spot, and northern leaf spot overwinter in corn residue, providing a source of inoculum to infect corn planted the following season. However, the extent to which disease pressure is affected by surface residue levels can vary by disease.

Surface residue appears to have a larger effect on gray leaf spot pressure. The increase in prevalence and severity of gray leaf spot beginning in the 1990s has been attributed, at least in part, to the widespread shift to reduced tillage systems in the 1980s and 1990s (Lipps, 1998). Severity of tar spot, on the other hand, does not appear to be strongly influenced by crop rotation or tillage (Ross et al., 2023).

Figure 2. High levels of surface residue can increase the amount of inoculum for overwintering diseases, increasing the risk of foliar disease in the subsequent crop. Gray leaf spot in particular seems to be more prevalent in high residue systems.

SUSCEPTIBLE HOST

Susceptible host is, to some extent, the most straightforward of the three factors influencing corn disease – if there is corn planted in a field then a susceptible host for corn pathogens is present. However, corn hybrids can differ considerably in their susceptibility to foliar diseases, which can have a significant impact on the likelihood of needing a foliar fungicide application to protect yield.

GENETIC DISEASE RESISTANCE

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

Scenarios in which the severity of a specific foliar disease is extremely high can be useful in illustrating how much the genetic resistance of a corn hybrid to that disease can matter. Pioneer scientists, agronomists, and university collaborators have conducted several corn fungicide studies in which a single foliar disease was predominant at the research location or locations. In some cases, research locations were chosen specifically due to their history of a specific disease; in others, environmental conditions happened to be favorable for a given disease when the study was conducted.

One such research project was conducted over three years at the University of Tennessee Research and Education Center at Milan at a research site specifically chosen due to a history of high gray leaf spot pressure. Three Pioneer brand corn hybrids with differing levels of resistance to gray leaf spot were included in the study. Results showed that genetic resistance to gray leaf spot had a large effect on yield response to foliar fungicide – ranging from 7 bu/acre with a resistant hybrid to over 23 bu/acre with a susceptible hybrid (Figure 3).

Pioneer scientists conducted fungicide research trials at several Midwestern sites in 2009, a growing season that experienced unusually high levels of common rust in parts of the Midwest.

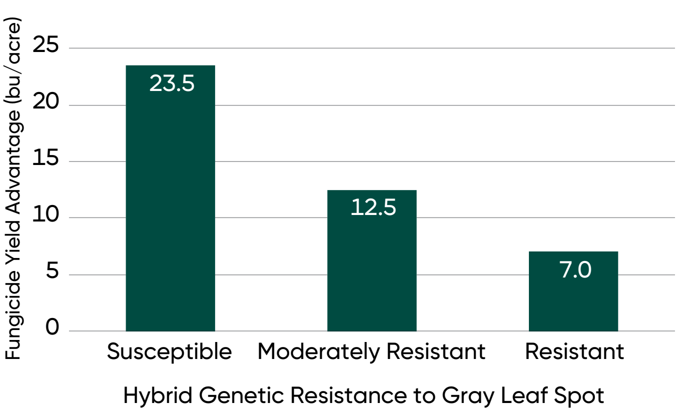


Figure 3. Average yield response of hybrids susceptible, moderately resistant, and resistant to gray leaf spot to foliar fungicide application in a 3-year University of Tennessee/Pioneer research study.

Corn yield response to fungicide application varied widely among research locations, largely due to differences in common rust pressure. Genetic resistance of hybrids to common rust made a big difference in fungicide yield response at sites with severe common rust (Figure 4). At low pressure locations, genetic resistance still made a difference, but yield response of both susceptible and moderately resistant hybrids was below the level likely to provide economic benefit.

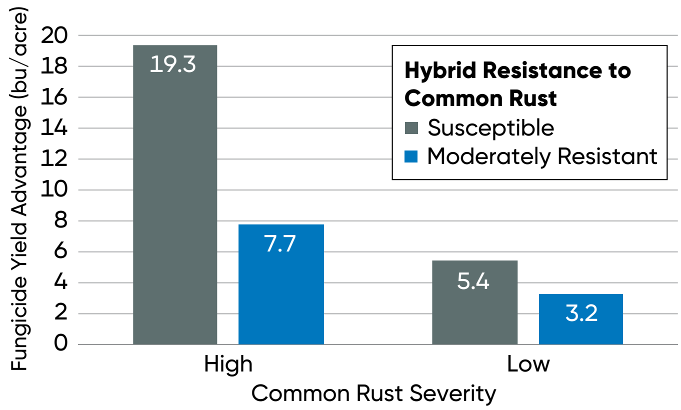


Figure 4. Average fungicide yield response of hybrids with low resistance (3 on a 1-9 scale) and moderate resistance (4-6) to common rust in Pioneer small-plot trials.

HYBRID MATURITY AND PLANTING DATE

Hybrid maturity and planting date have also been found to influence susceptibility to yield loss from foliar diseases. These factors are important because of their impact on the growth stage of corn relative to the timing of disease development. Later planted fields and/or later maturing hybrids can be more vulnerable to yield loss because they are not as far along in the grain filling process when disease development peaks in late summer compared to shorter maturity or earlier planted corn. These later-developing fields are often more likely to benefit from a fungicide application.

FAVORABLE ENVIRONMENT

The severity of foliar diseases in a given year often comes down to environmental conditions (Figure 5). Farmers that have been growing corn for many years are likely able to recall past years in which a specific foliar disease was especially severe, as well as years in which foliar diseases were largely absent. On a broad scale, host susceptibility and pathogen presence do not change a lot from year to year – environmental conditions are generally the operative factor driving disease pressure. Optimal conditions for disease development are similar, but not identical, across common foliar pathogens in corn, so conditions in a growing season may favor multiple foliar diseases, or one specific disease.

LEAF WETNESS DURATION

Wet conditions are generally favorable for foliar diseases in corn; specifically, conditions that enable prolonged periods of leaf wetness (Rowlandson et al., 2015). Fungal spores require liquid water on leaves to initiate germination and infect the leaf tissue. This water can come from rainfall, as well as dew or irrigation. Conditions that allow the water to persist on the leaves – such

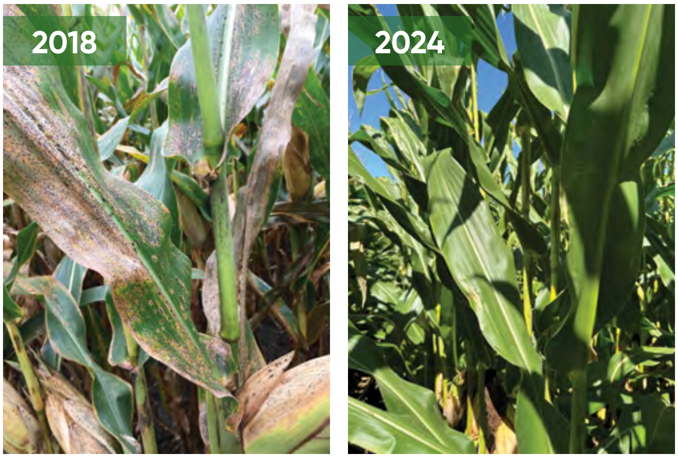


Figure 5. Left: A northern Illinois corn field on September 1, 2018, a year characterized by widespread severe tar spot infestation. **Right:** The same field on the same date in 2024, a year when hot and dry conditions late in the season suppressed foliar diseases.

as high humidity, persistent cloud cover, low winds, and mild temperatures – will tend to favor disease development.

Conversely, dry conditions will tend to suppress disease development. This has been evident in the results of foliar fungicide trials during drought years. Pioneer on-farm research trials conducted across multiple locations in Iowa from 2007 to 2014 demonstrated the extent to which corn yield response to foliar fungicides can vary year to year due to weather conditions. 2011 and 2012 were both abnormally dry years in Iowa. The average yield response to foliar fungicides in on-farm trials conducted during the two drought years of 2011 and 2012 was well below the average response observed in years with greater precipitation (Figure 6).

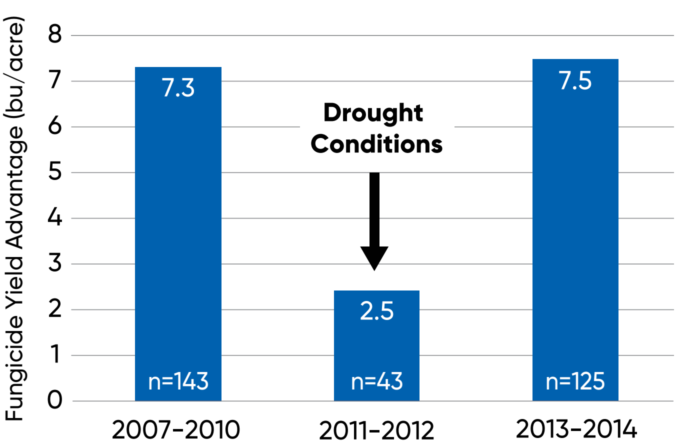


Figure 6. Average corn yield response to foliar fungicides in Iowa on-farm trials in drought years (2011-2012) compared to years with normal or above-normal precipitation (2007-2010 and 2013-2014).

Similar results were observed in a multistate study conducted in 2020, in which nearly all field locations experienced some degree of drought stress in the latter part of the growing season. The average yield response to foliar fungicide treatment in this study was only 1-2 bu/acre (Berning, 2020).

TEMPERATURE

Temperature is an important factor in foliar disease pressure, both in its direct effect on disease development and through its effect on leaf wetness. Warm, but not excessively high temperatures are generally favorable for disease development but within that range, individual pathogens differ in their optimal temperature ranges (Figure 7). Common rust and tar spot are both favored by relatively low temperatures, gray leaf spot and northern corn leaf blight by moderate temperatures, and southern rust by relatively high temperatures.

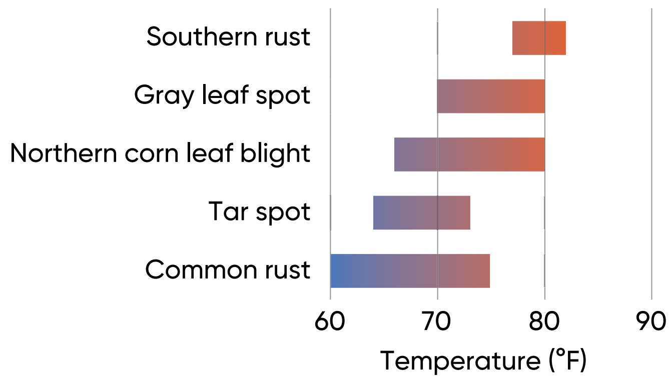


Figure 7. Optimal temperature ranges for development of foliar diseases (Jardine, 2019; Peltier et al., 2011; Webster et al., 2023).

YIELD RESPONSE AND ECONOMIC RETURN

The first thing to consider when deciding whether or not to use a foliar fungicide in corn is the potential impact on yield. The numerous field studies that have evaluated corn fungicides over the past 20 years provide a look at the range of potential outcomes. Over 2,000 Pioneer on-farm trials conducted over 14 years found an average corn yield response to foliar fungicide treatment of 7.4 bu/acre (Jeschke, 2021). In cases where foliar disease pressure was low, often due to drought conditions, yield response could be less than 2 bu/acre. In cases with very high disease pressure, yields responses could exceed 20 bu/acre (Figure 8).

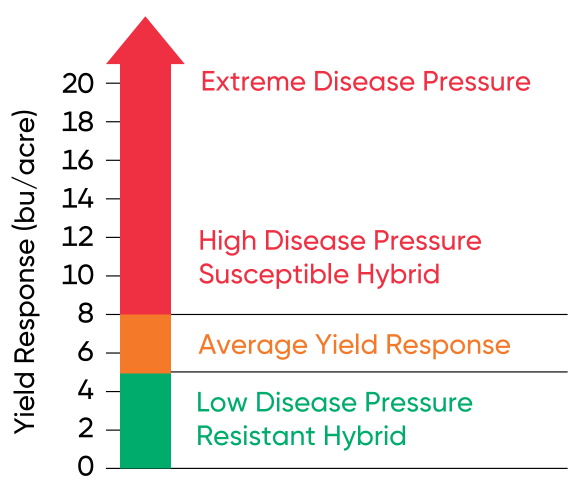


Figure 8. General range of expected yield response to foliar fungicide treatment in corn.

A meta-analysis of university studies conducted over eight years found an average yield response of 3.7 to 6.2 bu/acre, depending on the fungicide product used (Paul et al., 2011). A more recent meta-analysis found similar results, with yield response ranging from 3.5 to 6.9 bu/acre depending on the fungicide product used (Wise et al., 2019). The economic viability of a fungicide application can vary greatly according to the price of corn and cost of the fungicide and application. Higher corn prices and lower treatment costs reduce the break-even yield response, while lower corn prices and higher costs increase it (Table 1).

Table 1. Yield response necessary to cover the cost of fungicide and application over a range of costs and corn prices.

Fungicide + Application Cost/Acre	Corn Price ($/bu)				
	3	4	5	6	7
	bu/acre				
20	6.7	5.0	4.0	3.3	2.9
22	7.3	5.5	4.4	3.7	3.1
24	8.0	6.0	4.8	4.0	3.4
26	8.7	6.5	5.2	4.3	3.7
28	9.3	7.0	5.6	4.7	4.0
30	10.0	7.5	6.0	5.0	4.3
32	10.7	8.0	6.4	5.3	4.6
34	11.3	8.5	6.8	5.7	4.9
36	12.0	9.0	7.2	6.0	5.1

TIMING OF FUNGICIDE APPLICATION

Foliar fungicides are typically only applied once during a growing season to corn so optimal application timing is important for maximizing yield and economic benefit. Apply too late, and yield may already be lost due to foliar disease. Apply too early, and diseases may be able to develop after the fungicide has broken down and lost its efficacy.

There are three main factors that influence optimal fungicide application timing in corn:

- Duration of fungicide activity.
- Timing of disease onset and progression.
- Critical period for protecting corn yield.

DURATION OF FUNGICIDE ACTIVITY

If one fungicide application could provide season-long disease protection, application timing would be far less important, but – like all crop protection products – fungicides have a limited window of efficacy. Foliar fungicides generally have around 21 days of activity, with some newer products extending that to as long as 35 days. The total duration of the reproductive growth period in corn, from silking to black layer, is typically around 65 days for a central Corn Belt hybrid (Abendroth et al., 2011), so a single fungicide application would – at best – only provide disease protection for around half of that period (Figure 9).

A fungicide needs to be present on the plant prior to infection or in the very early stages of infection to be effective.

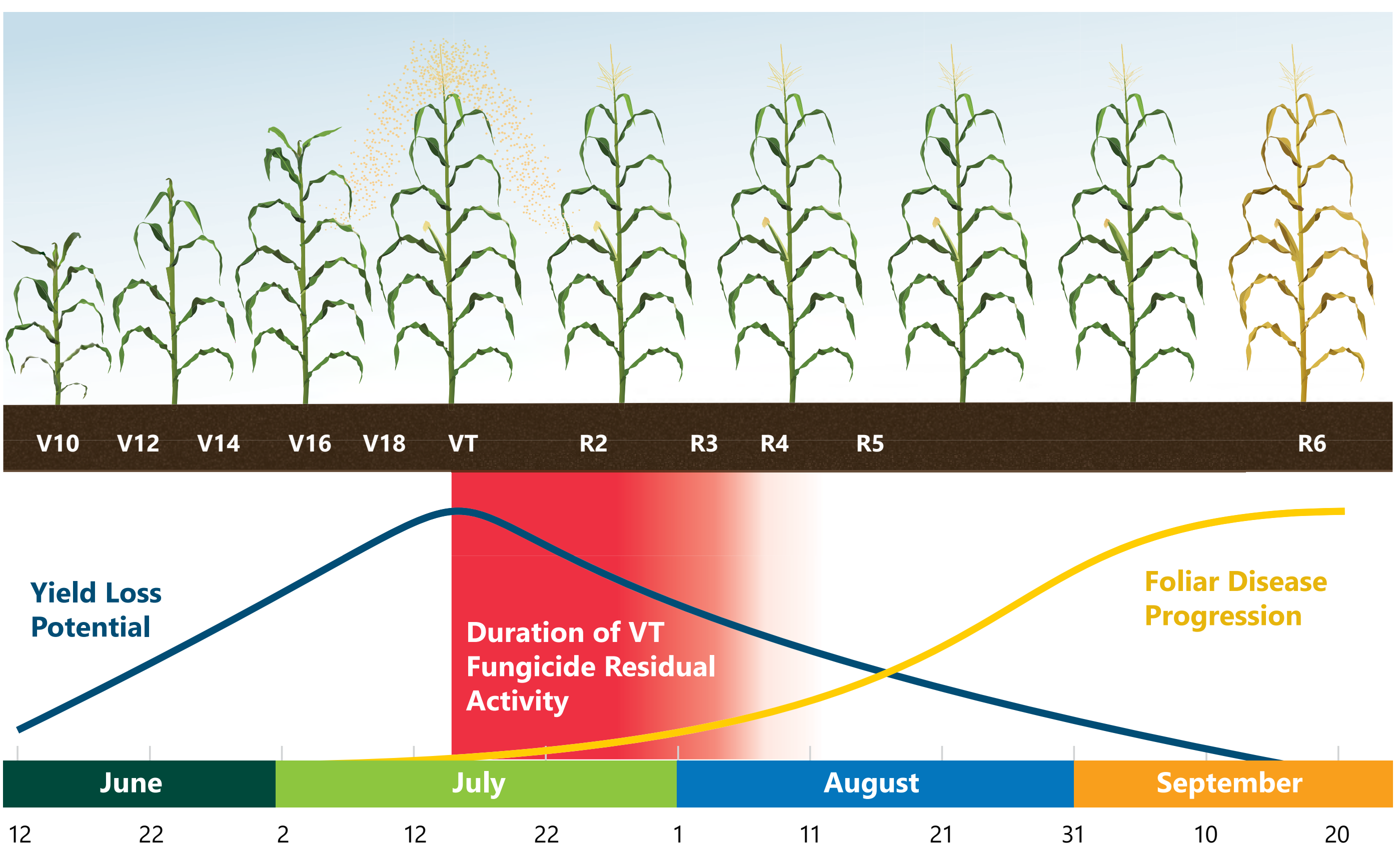


Figure 9. Generalized model of corn foliar disease progression and yield loss potential by growth stage.

TIMING OF DISEASE ONSET AND PROGRESSION

A fungicide needs to be present on the plant prior to infection or in the very early stages of infection to be effective (Mueller and Robertson, 2008). Ideally, the best time to apply a fungicide would be right when foliar disease is beginning to proliferate withing the crop canopy – aligning the window of maximum fungicide activity with the phase of disease progression when it would have the greatest impact. In practice, this is challenging to do because the onset and progression of foliar disease is heavily dependent on environmental conditions.

As plants begin shifting resources toward the developing ear, the leaves have less capacity to defend against fungal infection.

Foliar diseases are generally most active during the latter part of the season when corn is in the reproductive growth stages. There are some diseases that can show up during early vegetative growth, most notably anthracnose leaf blight, but the diseases most likely to impact yield tend to spread most rapidly during the late vegetative stages and reproductive stages. Environmental conditions tend to be more favorable for foliar disease development during this time – temperatures are more conducive for disease development and the shading of the crop canopy helps preserve moisture on the lower leaves. Additionally, as the plants begin shifting resources toward the developing ear, the leaves have less capacity to defend against fungal infection.

CRITICAL PERIOD FOR CORN YIELD

The reproductive stages are also the period that is the most critical for protecting corn yield. Foliar diseases impact yield by reducing the amount of functional photosynthetic leaf area during grain fill. The yield impact associated with lost leaf area peaks at the VT/R1 stage and then gradually declines as the plant gets closer to physiological maturity (Figure 9).

The leaves in the upper part of the canopy – from the ear leaf up – account for the majority of photosynthate feeding into the ear during grain fill, so these leaves are the most important to protect from foliar disease (Nielsen, 2021). Fungicides have limited mobility in plant tissue, so only leaves that receive a fungicide treatment are protected. If a fungicide is applied before the uppermost leaves have emerged, those leaves will not be directly protected by the fungicide.

FUNGICIDE TIMING RESEARCH

The VT/R1 growth stage (between tasseling and brown silk) is the most commonly recommended stage for fungicide application because this is point at which the three factors for optimal timing intersect to offer the greatest likelihood of economic benefit. Research has generally shown that VT/R1 is the most effective application timing for disease control and yield protection (Paul et al. 2011; Wise and Mueller 2011; Wise et al. 2019).

Optimal fungicide application timing can vary depending on the timing and rate of disease progression.

Figure 10. Early vegetative stage applications put the fungicide on the crop well ahead of the onset of most foliar diseases.

Optimal fungicide application timing can vary depending on the timing and rate of disease progression. A University of Nebraska study that compared multiple fungicide timings found that VT or R3 applications provided the best results (Jackson-Ziems et al., 2016), with yield response declining with later application timings. Applications as late as R5 (dent) still significantly improved yield in some cases, but not as much as the earlier applications. A University of Arkansas study comparing VT, R3, and R5 fungicide applications for southern rust control found that the R3 application provided better disease control in one year when southern rust came on later but did not improve yield over the VT timing, and that the VT timing was generally best for yield protection (Faske and Emerson, 2021). Diseases such as southern rust or tar spot, which can come on late and spread quickly, may justify a later R stage application but, in general, the closer the crop is to physiological maturity, the less impact a fungicide treatment is likely to have on yield.

VEGETATIVE STAGE APPLICATIONS

Earlier applications during vegetative growth stages have been explored as a way to simplify field logistics. Application around the V5-V6 stage would allow a fungicide to be tank mixed with a post-emergence herbicide application, reducing the number of trips across the field. Standalone fungicide applications around the V10-V14 timing have also been evaluated, as they could more easily be performed using a ground sprayer rather than aerial application, which is often necessary for VT/R1 treatment.

Applying fungicide at the V5-V6 stage puts it on the crop well ahead of the onset of most foliar diseases, and residual activity would be gone by the time the crop reached grain fill. A V10-V14 application would put the window of fungicide efficacy closer to peak foliar disease activity but would leave the upper-most leaves on the plant unprotected and leave the door open for a late flush of disease. An application at V12 would be about 3 weeks ahead of tasseling, which means residual control would be running out right as the crop is entering reproductive growth.

Early vegetative stage fungicide applications have not proven to be consistently economically beneficial. A University of Illinois survey of fungicide research trials found an average yield response of 1.5 bu/acre with V6 applications compared to 8.0 bu/acre for VT/R1 applications (Bradley, 2010). A meta-analysis of research studies conducted over two years in the U.S. and Canada found an average yield increase of 2.0 bu/acre with V6 applications.

Late vegetative stage (V10-V14) applications have not been as thoroughly researched. The limited studies that have been done have shown that a V12 application can provide similar disease suppression to a VT/R1 application in some cases, particularly when disease pressure is low. An Iowa State University study actually found better suppression of gray leaf spot with a V12 application in one year when conditions were conducive to earlier disease development (Robertson and Shriver, 2018). A 3-year Purdue University study found that V12 and VT applications provided similar levels of gray leaf spot protection when pressure was low, but VT applications had a significant advantage under higher disease pressure (Telenko et al., 2020).

FUNGICIDE MODES OF ACTION

In the early 2000s, when foliar fungicides started to come into common usage in field corn, most fungicide products available to growers only included one active ingredient. Today, many fungicide products have multiple active ingredients. There are three classes of fungicide currently used in foliar products labelled for use in corn:

- **Group 3**: Demethylation Inhibitors (DMI) (triazoles)
- **Group 7**: Succinate Dehydrogenase Inhibitors (SDHI)
- **Group 11**: Quinone Outside Inhibitors (QoI) (strobilurins)

Numerous strobilurin + triazole products are available and strobilurin + triazole + SDHI products have become more common in recent years.

Table 2. Average corn yield response to single and double mode of action VT/R1 foliar fungicide applciations in two meta-analyses of university fungicide studies.

Paul et al., 2011	Yield Response
	bu/acre
Trifloxystrobin + propiconazole	6.2
Azoxystrobin + propiconazole	5.3
Pyraclostrobin	4.1
Azoxystrobin	3.7
Wise et al., 2019	**Yield Response**
	bu/acre
Strobilurin + triazole+SDHI	9.2
Strobilurin + triazole	6.9
Strobilurin	3.5

Fungicides with multiple modes of action can provide more effective disease control by targeting a broader range of fungal diseases and pathogens and providing more comprehensive protection for the corn crop. Two meta-analyses of university fungicide studies showed better yield protection, on average, with multiple mode of action products compared to single mode of action products (Paul et al., 2011; Wise et al., 2019) (Table 2).

Fungicide products with multiple modes of action are also important for resistance management. Pathologists recommend mixing or rotating fungicide modes of action to slow the development of resistance in pathogens. By using fungicides with different modes of action, growers can reduce the selection pressure on fungal populations, slowing down the development of resistance to specific fungicide types. This is important for preserving the effectiveness of fungicides, especially products such as strobilurins, which are considered high risk for resistance development.

SCOUTING FOR FOLIAR DISEASES

Scouting the fields for disease pressure can be helpful for informing fungicide treatment decisions. Many foliar diseases start on the bottom leaves of the corn plant and gradually move up the plant depending on environmental conditions. Diseases that blow in from outside the field, such as southern rust, will often show up first along the field edges. The best time to start scouting is during the late vegetative growth stages prior to tasseling. If disease is not present on the leaves below the ear leaf, a fungicide application may not be needed at that time. Continue scouting on a weekly basis, especially when environmental conditions are conducive to disease development and in fields with susceptible corn hybrids.

Plant Health and Rumen Starch Digestion of Corn Silage

DANN BOLINGER, M.S., DAIRY SPECIALIST

SUMMARY

- Healthy corn plants permit the harvesting of more mature kernels for corn silage, enhancing yield and starch content while maintaining fiber digestibility.
- Although more physilogically mature plants have lower rumen starch digestibility, healthier corn plants have greater rumen starch digestibility, at harvest and after 28 days of ensiling.

INTRODUCTION

Improvements in corn plant health have been associated with hybrid genetics, fungicide utilization, plant nutrient uptake, and other stress reducing practices. Healthy plants faciliate harvesting corn for silage in a more mature state without sacrificing fiber digestibility (Figure 1). Allowing plants to advance in maturity notably enhances yield and starch content. A frequently raised quality concern of advancing maturity of a healthy plant is the decline of rumen starch digestibility. Is the decline in pre-ensiled rumen starch digestibility impactful enough to discourage harvesting at an advanced maturity?

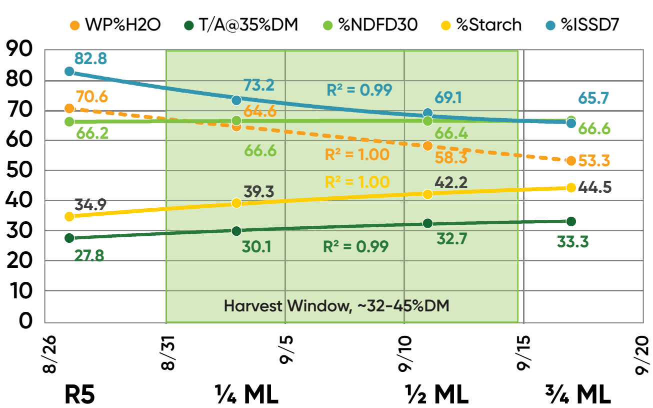


Figure 1. Changes in corn silage yield and at-harvest quality as plants mature from R5 (dent) to ¾ milk line (n=9; Bolinger, 2024).

STUDY DESIGN

A fungicide trial is an excellent method for comparing differences in plant health alone. The same hybrid, same field, same planting and harvest dates eliminates all known variables not associated with simple plant health. Two 2021 fungicide trials in Michigan were harvested at multiple kernel maturities with rumen starch digestibility (%ISSD7) measured at harvest (pre-ensiled) and 28 days ensiled. Visual assessments demonstrated obvious differences in plant health (Figure 2), while maintaining comparable plant physiological maturity.

PLANT HEALTH IMPACT ON STARCH DIGESTION

In both trials (different fields, hybrids, and intensity of disease pressure) and regardless of kernel maturity, the healthier plants have greater rumen starch digestibility (Figure 3). Plant health appeared to be more reliable than whole plant dry matter as a predictor of change in rumen starch digestibility during ensiling.

Figure 2. Visual appraisal of plant health differences within same hybrid with and without fungicide. (Left: Field B at ¼ ML, Right: Field B at ½ ML)

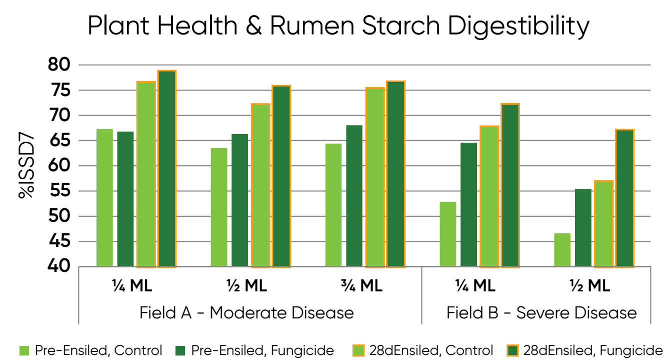


Figure 3. Rumen starch digestibility of two fields, two fields with and without fungicide, at harvest and ensiled 28 days at different plant maturities. (Bolinger, 2021)

Water moving from healthy stover to the grain while in the silo is likely a contributing factor to healthier plants having greater post-ensiled rumen starch digestibility. The concept of reconstituting dry corn kernels with water has been demonstrated as an effective means to regain lost rumen starch availability (Benton, et.al., 2003). Healthy plant moisture migration in storage is also a probable contributing cause for the observed convergence and ranking changes in relative pre- vs. post-ensiling hybrid rumen starch digestibility (Figure 4).

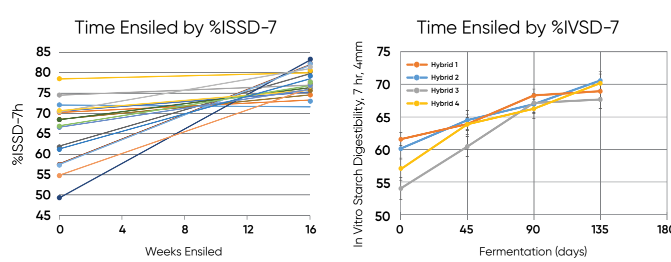


Figure 4. Individual sample rumen starch digestibility changes during ensiling. LEFT: %ISSD7 0 to 16 weeks ensiled, n=17 (Bolinger, 2018). RIGHT: %IVSD7 0 to 135 day ensiled, n=4 (Lawrence, et.al., 2020).

Understanding Silage Plot Nutritional Parameters

BILL MAHANNA, PH.D., PIONEER GLOBAL NUTRITIONAL SCIENCES MANAGER

KEY POINTS

- Agronomic traits and dry matter yield should be the first criterion when selecting a silage hybrid.
- Starch content contributes upwards of 50% of yield and 65% of the energy in corn silage.
- Only minimal genetic differences exist for other nutritional traits for hybrids grown in the same environment and harvested at the same maturity.

% DRY MATTER (DM)

% DM is the resulting feedstuff after 100% of the water has been removed by drying (100% - moisture). Feed analysis for ruminants report nutrients on a DM basis given dairy and beef nutritional requirements are based on DM due to the large variation in moisture among ruminant feedstuffs.

Differences in hybrid entry DM can give an indication if the maturities of plot entries were similar. Increases in starch, in healthy plants, is highly correlated with increases in whole plant DM.

% SUGAR

Sugar is found in both the milky portion of the kernel (pre-blacklayer) and in the stover. It is sometimes called water soluble carbohydrates (WSC). Fermentation organisms primarily use sugar (not starch) to produce acids responsible for lowering silage pH.

There will typically be more sugar in less mature plants at harvest. Comparison between hybrid entries to estimate differences in maturity can be evaluated by DM content (lower DM with less mature kernels), lower starch levels and higher sugar levels.

% STARCH

Starch accumulation is determined by genetics and the growing environment the plant receives. It should be the primary nutrition parameter when selecting a silage hybrid being the most energy dense nutrient and contributing upwards of 50% of DM yield and 65% of the energy in corn silage.

Kernels continue to accumulate starch until reaching physiological maturity at blacklayer. Healthy plants should be allowed to mature to at least ¾ milkline to optimize starch yield.

Healthy corn silage plants harvested at the recommended ¾ milkline (to capture more starch) will be higher in DM (e.g. 36-38% DM) compared to plants harvested at only ¼ milkline (30-32%). Taller plants with more biomass will not be as impacted by starch accumulation as shorter plants.

% NEUTRAL DETERGENT FIBER (NDF)

NDF is the total cell wall comprised of the ADF fraction (lignin + cellulose) plus hemicellulose. It is the residue left after boiling sample in neutral detergent solution. If amylase and sodium sulfite are used during the extraction (recommended procedure), the fiber fraction should be called amylase treated NDF (aNDF) to distinguish from original method. If reported on an ash free basis it is termed aNDFom.

A certain quantity of fiber is necessary in the diet, and of the proper chop length (effective fiber) being controlled by ration design and chop length of all the forages found in the diet. Quantity of fiber in corn silage is not as important to nutritionists as digestibility of the fiber (NDFD) or the level of undigestible fiber (uNDF) that contributes to lowered intakes

NDF levels will be diluted (reduced) in samples containing more sugar/starch and should not be a hybrid selection criterion.

% NEUTRAL DETERGENT FIBER DIGESTIBILITY

A measurement of the NDF (neutral detergent fiber, or total cell wall) digestibility typically measured by in vitro (test tube) incubations with rumen fluid at varying incubation times and reported as % NDFD (as a % of total NDF). The most popular single timepoints used by nutritionists to compare samples is either 24 or 30-hour NDFD. Multiple time points are often generated to create a digestion curve from which digestion rates (Kd) can be calculated.

While of great interest to nutritionist when balancing diets, NDFD should not be a primary hybrid selection criterion as it is influenced three-times more by growing environment than genetics. There is minimal NDFD differences between hybrids grown in the same environment, chopped at the same height and harvested at a similar maturity stage. The small 2-3 point difference in NDFD among hybrids is within the error of the lab method and not typically biologically significant to the cow by the time the corn silage is included in the TMR with other feedstuffs.

While not a primary hybrid selection criterion, it is very important for nutritionists to know the NDFD when balancing diets to account for the effects of the growing environment (primarily moisture, nitrogen fertility and late-season diseases) experienced by the hybrid. Unlike starch digestibility, fiber digestibility remains essentially unchanged over time in fermented storage.

UNDIGESTED NEUTRAL DETERGENT FIBER, %DM (UNDF240)

uNDF240 is the neutral detergent fiber (cell wall or lignin + cellulose + hemicellulose) that is not digested after a certain number of hours incubated with rumen bacteria. uNDF is reported as a % of DM (not as a % of the NDF) with typical rumen retention times of either 24, 30, 120 or 240 hours.

Nutritionists use uNDFom30 or uNDFom240 to estimate when the level of undigested fiber gets so high in the total diet that animals begin to decline in dry matter intake.

uNDF can be thought of as the opposite of NDFD, and like NDFD, should not be a primary hybrid selection criterion given that it is also controlled three-times more by growing environment and harvest maturity than by hybrid genetics.

% CRUDE PROTEIN (CP)

Calculated by multiplying the total nitrogen in the feed by 6.25, based on the assumption that 100% protein contains 6.25% nitrogen.

Protein should not be a silage hybrid selection criterion because hybrids do not differ significantly in protein content. Nitrogen fertility is a key driver of silage protein content, and the amino acid composition of corn protein is of poor quality (low in lysine and methionine). This is why nutritionists utilize soybean or canola as sources of these limiting amino acids.

POUNDS OF MILK (OR BEEF) PER TON/ ACRE

A corn silage index that estimates the pounds of milk (or converted to beef gain) produced per DM ton of forage based on University of Wisconsin (MILK2006 or MILK2024) calculations.

There are several assumptions built into these kinds of indexes regarding fiber and starch digestibility which may not appropriately rank hybrid genetic potential before introduced to the influence of varying growing environments and harvest timing.

% STARCH DIGESTIBILITY, 7-HOUR

This is an in vitro (test tube) rumen fluid (or enzymatic) starch digestibility analysis. Sample grind size (1-4mm) and incubation time (2-10 hours) vary by laboratory, but commonly presented as 7-hour starch digestibility.

This is not reported on Pioneer reports, nor in any University silage trial reports because research has shown minimal differences exist between similar maturity hybrids grown in the same environment. It also only represents ruminal digestion and does not account for intestinal digestion.

It is also well documented that ruminal starch digestion increases over time in fermented storage due to microbial action solubilizing the protein (zein) which surrounds kernel starch granules.

Starch digestibility is an important parameter for nutritionist to balance diets after a hybrid is exposed to growing environment and harvest management, but similar to NDFD, it should not be a selection criterion to rank hybrid genetic potential.

SUMMARY

When selecting or ranking a silage hybrids' genetic potential, prior to the influences of non-genetic factors such as growing environment or harvest management, it is best to consider agronomic strength/ weaknesses, DM yield and starch content before considering other nutritional traits or indexes.

Importance of Late-Season Plant Health in Silage Production

DANN BOLINGER, M.S., DAIRY SPECIALIST

SUMMARY

- Healthier corn plants exhibited a wider harvest window (32%- 42%DM) compared to less healthy plants.
- Healthier corn plants provided opportunity to capture more starch, digestible starch, and total yield by allowing harvest of a more mature plant without sacrificing fiber digestiblity.
- Genetic differences appeared to be significant enough to utilize plant health as a primary corn brand and hybrid selection criteria.
- Pioneer® brand corn hybrids showed an advantage over Dekalb® and Enogen™ brand corn products in all of these considerations.

INTRODUCTION

Drought, plant diseases, fungicide utilization, and other circumstances influencing plant stress have demonstrated that greater plant health is advantageous in corn silage production. While genetic variation in plant health among commercially available corn hybrids is broadly recognized, there has been little exploration into the implications of those differences on whole plant corn silage yield and quality. Anecdotal observations suggest potentially impactful differences in corn silage production between commercially available genetic sources. A 2024 field trial observed and quantified these differences in plant health between leading silage corn seed brands and their influence on yield, quality, and harvestability.

TRIAL DESIGN

Three corn hybrid products from each of Pioneer, Dekalb, and Enogen brands of 107±3 corn relative maturity (CRM) were planted in alternating strips in uniform highly productive loam soils (Table 1). Average weekly milk line progressions by brand were equal across brands demonstrating comparable physiological maturity.

Table 1. Brand representation of 107±3 CRM hybrid products.

Pioneer (P)	Dekalb (D)	Enogen (E)
1. P04511V	DKC105-25RIB	E105Z5-D1
2. P0732Q	DKC106-98RIB	E107C1-D1
3. P0720Q	DKC107-33RIB	E110F4-D1

The growing season was very favorable for high yields and high plant health from preplant through R5 (dent). The trial received a fungicide application via a ground applicator at R1 (green silk). Precipitation and soil moisture were adequate until R5. Droughty, hot conditions during the harvest period (R5 to ¾ milk line, ML) provided significant plant stress. During this time, some hybrids began to show susceptibility to tar spot, northern leaf blight, and/or Fusarium crown rot. However, disease is believed to be secondary to moisture stress in attributing to plant health decline.

Samples of 1/1000th acre strips alternating between the center two rows were harvested at 6 inches within a uniform area of field. Harvest samples were collected weekly corresponding to plant maturities: R5, ¼ ML, ½ ML, and ¾ ML. Yield samples were weighed to nearest 0.5 pound (i.e. ~0.25 T/A@35%DM). Chopped whole plant samples were analyzed by Rock River Laboratory, Inc., Watertown WI. Data is summarized by seed brand (n=3). Plant health was visually assessed in addition to measuring whole plant percent dry matter (DM).

WIDENING THE HARVEST WINDOW

All three brands entered the harvest window (32%-42%DM) within 24 hours of each other (Figure 1). Pioneer brand products stayed green and healthy longer (Images 1 and 2, page 3). Trendline predictions of days within the harvest window (32%DM-42%DM) varied by brand:

- Pioneer brand products had a harvest window of 15.9 days, which is 30% and 60% more days than Dekalb (12.2d) and Enogen (10.2d), respectively.
- Pioneer brand products exited the harvested window (>42%DM) at approximately ¾ milk line, while Dekalb and Enogen brands exited the harvest window (>42%DM) at approximately ½ milk line.

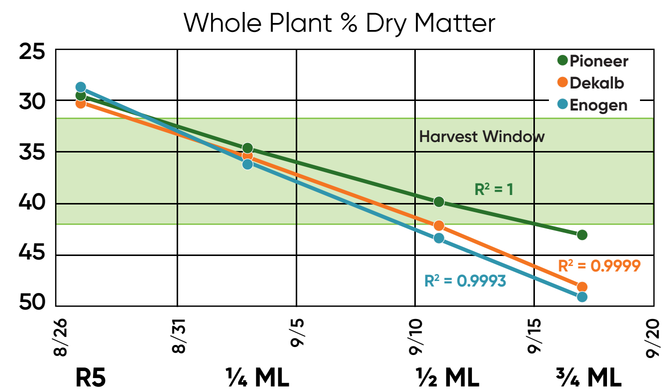
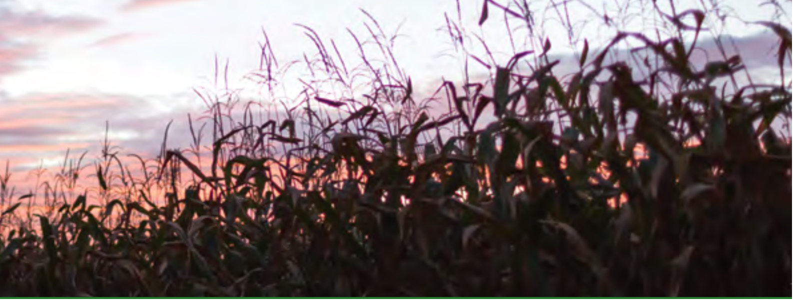


Figure 1. Whole plant dry matter from R5 (dent) through ¾ milk line sampling points relative to harvest window (shaded area, 32%DM-42%DM).



ENHANCING YIELD POTENTIAL

As expected, whole plant yield increased with the crop's physiological maturity represented by milk line progression (Figure 2). Starch deposition in the kernels accounted for the additional tons per acre over time (data not shown). The magnitude of the Pioneer yield advantage increased with time and crop maturity (Figure 2). This observation is likely associated with healthier plants being better able to maintain photosynthetic sugar and starch production, while less healthy plants were losing capacity to capture radiant energy.

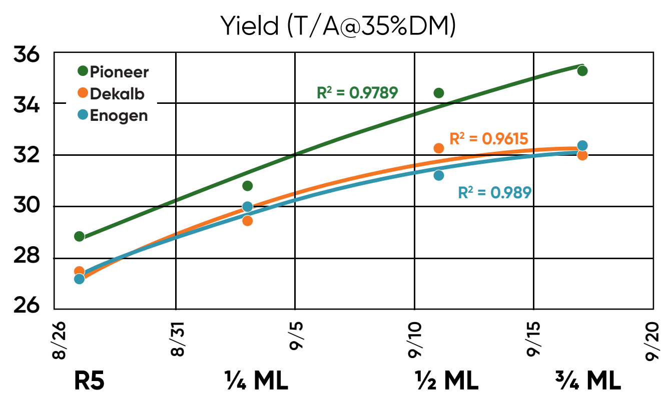


Figure 2. Whole plant silage yields relative to harvest timing and kernel milk line (ML) progression.

INCREASING STARCH VALUE

There was little difference between brands in %starch and starch accumulation rates relative to harvest date or milk line (Figure 3). Relative to harvest %DM basis, Pioneer demonstrated higher starch content (+1.7% & +2.2% over Dekalb & Enogen, respectively). This advantage reflects an advanced milk line at comparable %DM (42.1%- 43.0%DM) at differing milk line (½ vs. ¾ ML, Figure 3). This is a consequence of better late season plant health.

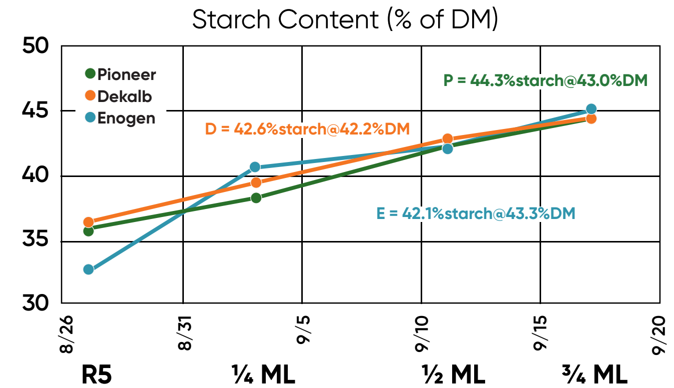


Figure 3. Starch content as percent of whole plant dry matter over time and physiological maturity.

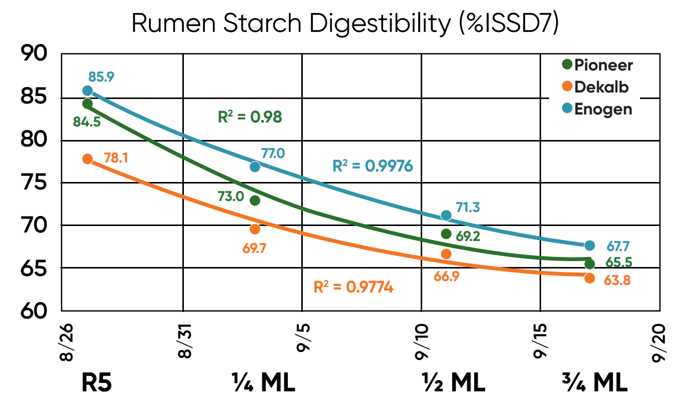


Figure 4. Rumen in situ starch digestibility at 7 hours (%ISSD7) with time and kernel maturation.

Rumen starch digestibility (%ISSD7) of fresh, pre-ensiled corn is not a reliable predictor of %ISSD7 post-fermentation, however it is worth exploring for the sake of discussion. Brand differences measured at the same kernel milk line are small and not likely biologically meaningful for the cow (Figure 4). The rate of deposition of starch exceeds the rate of decline in %ISSD7, thus rumen digestible starch yield is greater at more advanced kernel milk line regardless of brand genetics (Figure 5). Whole farm, seed to feed, profitability favors harvesting a more mature kernel for this reason.

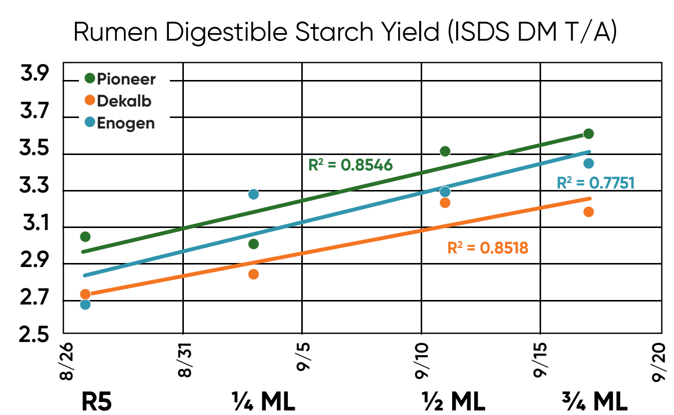


Figure 5. Rumen 7 hour in situ digestible starch (ISDS) dry matter yield demonstrating relationship of starch yield, digestibility, and crop maturity.

Fiber digestibility (%NDFD30) between brands was not biologically significant (Figure 6). For all brands, %NDFD30 remained constant from R5 through ¾ milk line (Figure 6). This lack of decline is unexpected as previous studies have shown a modest decrease of 0.2%NDFD30 for each 1%DM increase through the harvest window.

ACKNOWLEDGEMENT

Special thanks to field trial cooperator Wilson Centennial Farms, Inc., Carson City, Michigan.

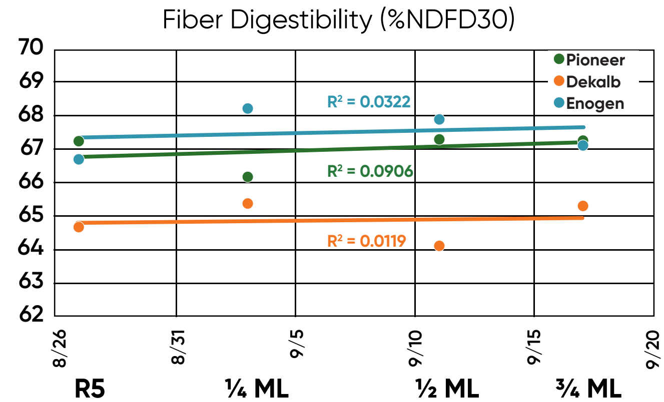


Figure 6. Fiber digestibility (%NDFD30) with time and kernel maturation.

Figure 7 & 8. Hybrid product visual differentiation of plant health with concurrent milk line observations (BL=R6, black layer). Grain corn relative maturity (CRM) ratings listed as advertised by respective brand.

Pioneer – P1: P04511V, P2: P0732Q, P3: P0720Q

Dekalb – D1: DKC105-25RIB, D2: DKC106-98RIB, D3: DKC107-33RIB

Enogen – E1: E105Z5-D1, E2: E107C1-D1, E3: E110F4-D1

Plenish® Full-Fat Soybean Meal Roasting & Processing Survey

DANN BOLINGER, M.S., DAIRY SPECIALIST

SUMMARY

- Plenish® full-fat soybean meal (FFSBM) oleic content is very stable with mean of 77.3% (SD =1.3) of total fatty acids (TFA).
- There is notable variation in Plenish FFSBM roasting efficacy and particle size suggesting a need for improved quality control.
- Protein Dispersion Index (PDI), as a measure of roasting efficacy, is accurate across a population of samples, but less reliable for evaluating individual samples.
- PDI<14 is a reasonable target for adequate heat treatment relative to rumen undegraded protein (RUP) and urease activity.
- Mean particle size (MPS) of Plenish FFSBM <1,000µm is associated with more desireable fecal fat levels, especially when milk yield ≥90 lbs/cow/day. Range in particle size may also be favorable to support sustained release of fatty acids in the rumen.

INTRODUCTION

Adoption of high oleic Plenish FFSBM is rapidly growing across the U.S. Most recommendations and research pertaining to roasting and feeding full-fat soybeans are circa the late 1900s. Modern dairy cows have different, typically greater, nutritional needs associated with today's higher levels of performance. With numerous centralized and on-farm processers of Plenish FFSBM, roasting practices and particle size reduction are not standardized. A survey of Michigan and Ohio dairy farms was conducted to quantify the variation in Plenish FFSBM as well as identify best practices associated with Plenish soybean processing.

SURVEY DESIGN

Samples and herd information was collected during June 2025 from Holstein or Holstein-crossbred dairy herds (n=19) with established history of feeding Plenish FFSBM.

Samples collected and analyzed as follows:

- Plenish FFSBM (Dairyland Labs, Inc.)
  - Complete nutritional analyses (NIR)
  - Particle size
  - Fatty Acid profile (wet chemistry)
  - Protein Dispersions Index (PDI) & urease activity
  - Rumen Undegraded Protein (Ross assay)
- High Production Group TMR (Dairyland Labs, Inc.)
  - Complete nutritional analyses (NIR)
  - Fatty Acid profile (wet chemistry)
- High Production Group Feces (Rock River Laboratory, Inc.)
  - Fecal fat analysis (wet chemistry)

HERD OBSERVATIONS & NUTRITIONAL COMPOSITION

Surveyed herds' milk yield (MY) averages above the industry mean, while milk fat and protein composition are comparable to current industry means (Table 1). Inclusion rates of Plenish FFSBM and palmitic fat were not well correlated with milk yield, fat, and protein (±r≤0.3).

Plenish FFSBM nutrional components are comparable to commodity full-fat roasted soybeans (Table 2), with the anticpated exception of the fatty acid profile (Table 3). Oleic content exceeds minimum expectations with reliably high oleic fraction of TFA, mean=77.4% (SD=1.2). Simultaneously, polyunsaturated fatty acid (PUFA) content is consistently low.

Table 1. Herd TMR inclusions and average milk production (n=19)

	Plenish FFSBM lbs/c/d	Palm Fat lbs/c/d (n=7)	Milk Yield lbs/c/d	Milk Fat %	Milk Protein %
Average	6.2	0.7	92.7	4.2	3.2
St.Dev.	1.1	0.3	7.3	0.2	0.1

Table 2. Plenish FFSBM basic nutrition analyses.

	% Dry Matter (DM)	% Crude Protein (CP)	% Ether Extract Fat (EE)	% Total Fatty Acids (TFA)
Average	94.9	38.8	22.3	19.9
St.Dev.	1.1	1.3	0.9	0.7

Table 3. Plenish FFSBM fatty acid profile (%TFA).

	Palmitic Acid C16:0	Stearic Acid C18:0	Oleic Acid C18:1	Linoleic Acid C18:2	Linolenic Acid C18:3
Average	6.2	4.5	77.4	5.9	6.0
St.Dev.	0.1	0.4	1.2	0.8	1.2

ROASTING EFFICACY

Roasting of soybeans increases protein value via greater Rumen Undegraded Protein (RUP), while denatureing urease enzymes and improving palatability. Protein Dispersion Index (PDI) in combination with RUP are considered the best currently available tools for assessing soybean heat treatment. PDI of 9-11 is considered optimal (Hsu and Satter, 1995). Samples with PDI of 11-14 are identified as slightly underheated (Dairyland Labs, Inc.). Of the samples surveyed, the average PDI is 13.6 (SD=1.9) with 8 of 19 samples underheated (PDI>14) and only two samples within the optimum range (Table 4). No samples with PDI>14 has

>70%RUP, while no samples PDI<14 has urease activity greater than 0.1 pH change (Figure 1). Thus, this sample population affirms PDI<14 as a reasonable maximum value for achieving adequate heat treament. Heat treatment had no effect on Undigested Crude Protein (UCP), which represents total tract protein availability. The correlation of RUP to PDI is fairly strong (r=-0.6). However, PDI is less reliable for predicting RUP of an individual sample (R2=0.33). With 42% of samples being underheated (PDI>14), there is significant opportunity for improving heat treatment, i.e. roasting efficacy, of the Plenish FFSBM represented in this survey.

Table 4. Plenish FFSBM roasting efficacy and particle size analyses.

	PDI %	Urease Activity (pH Δ)	RUP	UCP	Mean Particle Size (microns)	St.Dev. Particle Size
Average	13.6	0.1	63.3	7.6	1,698	2.1
St.Dev.	1.9	0.1	10.9	1.6	1,212	0.5

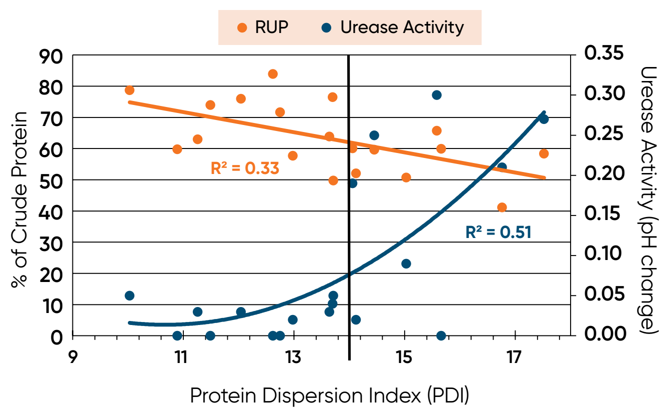


Figure 1. Protein Dispersion Index (PDI) in relation to Rumen Undegraded Protein (RUP) and urease activity in roasted Plenish FFSBM.

REDUCING PARTICLE SIZE

Historical recommendations of halving and quartering roasted full-fat soybeans for lactating dairy cows are based on research conducted more than 25 years ago (Dhiman, et.al., 1997). Since then, cow milk output has greatly increased driven by higher dry matter intakes and rumen passage rates. This has led to uncertainty of optimum particle size for Plenish FFSBM as represented by the notable variation in mean particle size (MPS) in this survey (Table 4).

Better Dairy Production with Plenish® high oleic Soybeans
- Forward-thinking Farming Webinar

Presumably, too large of particle size will result in incomplete utilization of fat and elevated fecal fat. It is recommended that fecal fat not exceed 3% of total fecal DM for optimum dietary fat digestion (Diepersloot, et.al., 2024). In this survey, MPS is correlated to fecal fat (r=0.46, Figure 2). Of herds with FF ≤3%, all had MPS<2,000µm and 83% (5/6, exception MY <90 lbs/c/d) were <1,050µm. The relationship of MPS to FF is confounded by TMR-TFA which is highly correlated to FF (r=0.70). Using the Fat Ratio of feces to TMR (FF:TMR-TFA), reduces the correlation (r=0.47). However, the feeding of other fat supplements continues to bias the analysis. For greater clarity in optimizing MPS, only herds feeding no other supplemental fat sources are considered. Even with the less robust data set of herds not feeding supplemental fat sources (n=10), a strong relationship between MPS and FF:TMR-TFA can be observed as highly predictive (R2=1.00) for herds with MY≥90 lbs/c/d (Figure 3).

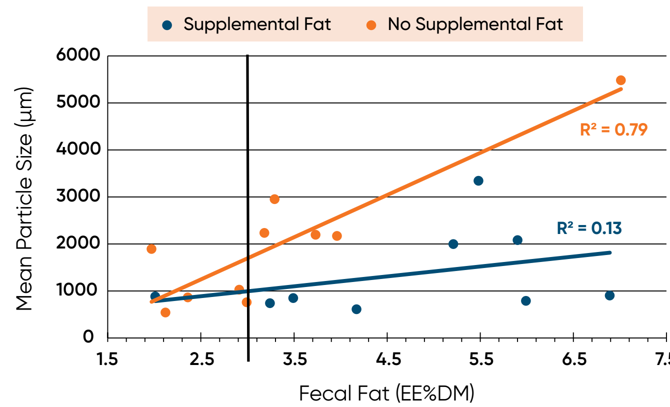


Figure 2. Plenish FFSBM mean particle size in relation to fecal fat for herds with and without other supplemental fat sources (e.g. palm) in the diet.

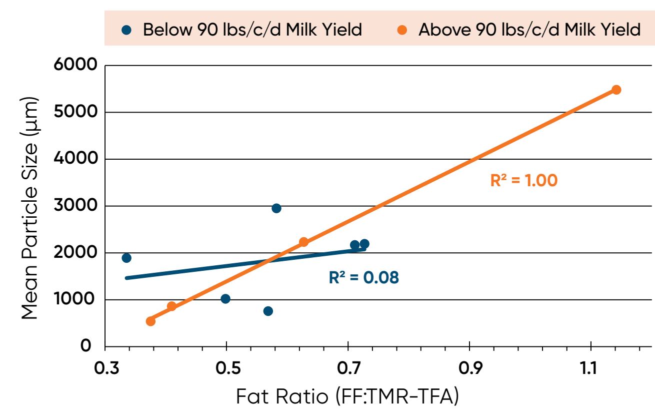


Figure 3. Fat Ratio [Fecal Fat to TMR total fatty acids (FF:TMR-TFA)] in relation to Plenish FFSBM mean particle size in herds not feeding other supplemental fat sources with average milk yield ± 90 lbs/cow/day.

Herds with MY ≥90 lbs/c/d, regardless of other supplemental fat sources, show a correlation between MPS and Fat Ratio (r=0.53). However, the negative correlation of range in particle size within the sample (reported as Standard Deviation Particle Size) and Fat Ratio is even greater (r= -0.63). This relationship is logical as range in particle size implies sustained availability of fat to the rumen between meals. Further investigation into the merits of more range, less uniform particle size is warranted.

This data set is insufficient to assess whether particle size can be too fine with implications to RUP and rate of fat availability in the rumen.

RECOMMENDATIONS

Pending controlled research to provide greater certainty, this survey suggests:

- Plenish FFSBM heat treatment should target PDI<14.
- Plenish FFSBM MPS<1,000µm is preferred, especially for high producing dairy cows.

Mean Particle Size: 594 µm; PS SD: 1.1

Mean Particle Size: 2,077 µm; PS SD: 1.7

Mean Particle Size: 756 µm; PS SD: 2.8

Mean Particle Size: 3,340 µm; PS SD: 1.6

Mean Particle Size: 1,023 µm; PS SD: 1.9

Mean Particle Size: 5,478 µm; PS SD: 1.1

Soybean Seeding Rate and Stand Establishment

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- There are many factors that affect soybean stand establishment, which means that optimum seeding rates can vary by region, cropping practice, and field.
- Germination and emergence rates must be taken into account when determining seeding rates, as not all seeds that are planted will germinate and not all of those that germinate will successfully emerge.
- Soybean seeding rates should be high enough to provide some degree of protection against less-than-ideal conditions at emergence.

SOYBEAN SEEDING RATE

- Establishing healthy and uniform stands is important to maximize soybean profitability.
- Yield of soybeans is generally less responsive to plant density than some other crop species such as corn due to the inherent adaptability of the plant.
- The ability of soybean plants to increase their lateral branching in low density environments gives them some capacity to compensate for poor stand establishment.
- Because there are many factors that affect soybean stand establishment, optimum seeding rates can vary considerably by region, cropping practice, and field.

YIELD ENVIRONMENT

- Yield environment is an important consideration for soybean seeding rates.
- Research has shown that seeding rates should be higher in areas of lower productivity and lower in areas of high productivity (Gaspar, 2019; Jeschke, 2023).
- The need for higher soybean seeding rates in lower productivity environments is primarily due to limitations on plant growth rate and branching.
- Plant growth can be limited due to many factors, such as precipitation, soil water holding capacity, nutrient supply, or rooting depth.
- These factors, which are commonly limiting in low productivity areas, can challenge the ability of soybean plants to maximize season-long light interception.
- Increased plant density is therefore required to maximize light interception and yield in these lower productivity environments.

STAND ESTABLISHMENT

- An important consideration in soybean seeding rate decisions is the fact that plant density at the end of the season can be considerably less than the number of seeds that went into the ground.

GERMINATION AND EMERGENCE

- Germination and emergence rates must be taken into account when determining seeding rates, as not all seeds that are planted will germinate and not all of those that germinate will successfully emerge.
- Corteva Agriscience conducts warm germination and other seed quality tests to ensure that its seed meets quality standards that lead the industry. Warm germination results are printed on the seed tag.
- In most years, germination scores are 90% or greater; however, in cases where weather conditions affect seed production over a wide area, some soybean varieties may be tagged with a standard warm germination score of less than 90%.
- In Canada, soybean varieties will be tagged as Canada Certified No. 2 if the standard warm germination score is less than 85%.
- Modern soybean seed treatments have improved stand establishment rates by protecting germinating and emerging seedlings from soil-borne pathogens. However, abiotic factors such as soil crusting, crop residue, and imbibitional chilling can still impact emergence rates.

SURVIVAL

- Soybeans naturally undergo some amount of plant attrition during the growing season, so the number of plants per acre at the end of the season will not be equal to the number of plants that originally emerged.

- Attrition is important to consider when targeting a minimum final stand. The rate of attrition increases with plant density. Research has found that attrition rates of 10 to 20% are typical with current seeding rates. Assuming a 15% attrition rate (85% survival), an initial plant stand of 120,000 plants/acre at V2 would result in a final stand of 102,000 plants/acre.

CALCULATING SEEDING RATE

- To achieve a target final stand, it is necessary to account for non-germinating seeds, non-emerging seeds, and plant survival to calculate seeding rate, using the following equation:

$$\frac{\text{Targeted Final Stand}}{\text{Germination x Emergence x Survival}} = \text{Seeding Rate}$$

- The following examples show the seeding rate necessary to achieve a harvest stand of 100,000 plants/acre under different scenarios:

Example 1: Normal germination, good emergence

$$\frac{\text{100,000 plants/acre}}{0.90 \times 0.95 \times 0.85} = \text{137,600 seeds/acre}$$

Example 2: Normal germination, challenging emergence

$$\frac{\text{100,000 plants/acre}}{0.90 \times 0.80 \times 0.85} = \text{163,400 seeds/acre}$$

Example 3: Low germination, challenging emergence

$$\frac{\text{100,000 plants/acre}}{0.80 \times 0.80 \times 0.85} = \text{183,800 seeds/acre}$$

- Always start by checking the seed bag tag for the warm germination score.

IMPORTANCE OF ADEQUATE SEEDING RATES

- Soybean seeding rates should be high enough to provide some degree of protection against less-than-ideal conditions at emergence. Pushing seeding rates too low can increase the risk of needing to replant if everything does not go exactly right.
- Replanting soybeans can mean losing some of the higher yield potential with timely planting. Recent data suggest that modern soybean varieties have a greater yield response to earlier planting (Propheter and Jeschke, 2017; Van Roekel, 2019), making timely planting important to maximize yield potential.
- Earlier planting allows soybeans to take advantage of longer day lengths during mid-summer and can extend the duration of reproductive growth (Parker et al., 2016).

ADDITIONAL SOYBEAN SEEDING RATE CONSIDERATIONS

- **Soil type:** Soils with high clay content are much more likely to crust and restrict soybean emergence and can promote seedling diseases in wet springs.
- **Planting date:** Early planting usually means colder, wetter soil, slower emergence, and reduced stands. Soybeans planted very late, including double-crop beans, require higher rates because they are destined to be shorter and produce fewer pods per plant.
- **Tillage/residue cover/seedbed condition:** No-till systems provide a less hospitable environment for soybean emergence due to colder soils, more residue, and possible seed placement/soil contact challenges. Cloddy soils may also reduce seed-soil contact.
- **Planter or drill:** Planters have traditionally done a better job of seed singulation and placement, increasing plant counts and stand uniformity. Growers using drills may need higher seeding rates to establish equally productive stands.
- **Seedling disease risk:** Some regions have higher seedling disease risk due to soil types, weather patterns, and pathogen race shifts. Higher seeding rates are needed to establish target stands in areas or fields with a history of higher disease risk.
- **Iron deficiency chlorosis risk:** Recent research studies have shown the value of high seeding rates in reducing chlorosis symptoms.
- **White mold risk:** In fields with a historically high risk of white mold, very high seeding rates are not recommended.

Achieving 100 bu/acre Yields in Soybeans

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- A total of 381 Pioneer on-farm soybean trial entries in the U.S. and Canada exceeded 100 bu/acre in 2024, a new record high.
- 100 bu/acre was achieved with numerous different soybean varieties across a wide range of maturities.
- Over 2/3 of 100 bu/acre entries were planted to a new Pioneer® brand Z-Series soybean variety.
- 100 bu/acre yields were achieved across a range of different environments and agronomic practices.

INCREASING YIELDS IN SOYBEANS

- Improvements in genetics and management have driven substantial gains in soybean yields in the U.S. over the past 50 years, at a rate of 0.48 bu/acre/year (Figure 1).
- U.S. average soybean yields topped 50 bu/acre for the first time in 2016 and again in 2018, 2020, 2021, and 2024.

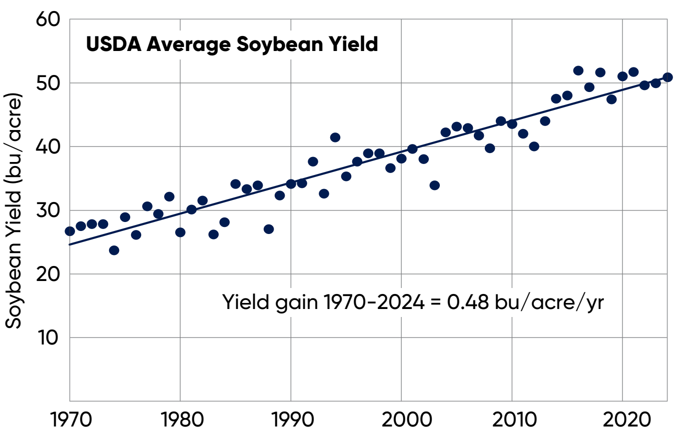


Figure 1. U.S. average soybean yields 1970-2023 (USDA-NASS).

- 100 bu/acre has often served as a target yield level for farmers seeking to see how high they can push yields with optimized management and the newest genetics.
- Across all of the on-farm genetic and agronomic trials Pioneer conducts each year in the U.S. and Canada, it has not been unusual for a few entries each year to top 100 bu/acre.
- Beginning in 2018, however; the number of entries exceeding 100 bu/acre increased dramatically (Figure 2).
- A total of 381 on-farm soybean trial entries exceeded 100 bu/acre in 2024, far exceeding the previous high of 256 in 2021.
- Over 2/3 of these entries were planted to a new Pioneer® brand Z-Series soybean variety.

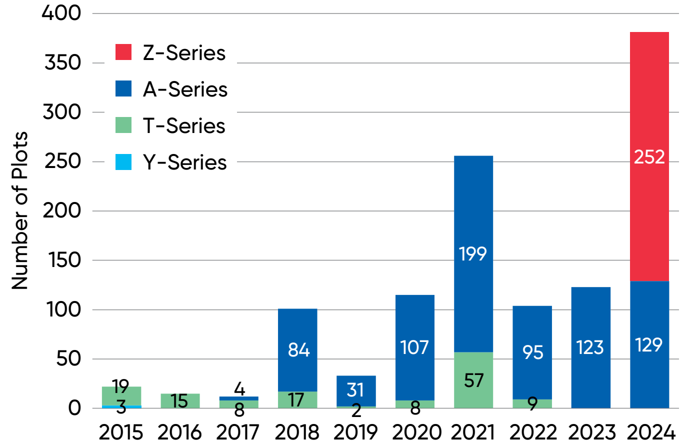


Figure 2. Series of Pioneer brand soybean varieties used in Pioneer on-farm trial entries exceeding 100 bu/acre, 2015-2024.

Table 1. Locations of Pioneer on-farm soybean trial entries exceeding 100 bu/acre, 2019-2024.

State	2019	2020	2021	2022	2023	2024
Arkansas	4	8	5	2	2	7
Delaware					4	
Georgia						1
Illinois	3	14	39	5	10	85
Indiana	1	13	1	2	18	43
Iowa	1		35	23	5	60
Kansas		14	13		2	5
Kentucky	7	3	1	5	3	2
Louisiana	3	4	5	3		4
Maryland	1					1
Michigan		1		1		
Minnesota		1	2		5	
Mississippi		2	2			5
Missouri	3	3	5	2	5	23
Nebraska	1	40	115	32	42	112
North Carolina	7	4	12	11	3	
Ohio		1	5	3	13	4
Pennsylvania		7	6			11
Quebec						1
South Dakota			1	1		
Tennessee	2				2	
Virginia			9	14	8	16
Wisconsin					1	1
Total	**33**	**115**	**256**	**104**	**123**	**381**

- Yields over 100 bu/acre were achieved over a relatively wide geography in 2024, including 16 U.S. states and one Canadian province (Table 1).
- 100 bu/acre was also achieved with large number of different varieties across a wide range of maturities, including 56 Pioneer® brand soybean varieties from maturity group 1.1 to 5.3 (Table 2).

Table 2. Pioneer brand soybean varieties used in 2024 Pioneer on-farm trials entries exceeding 100 bu/acre.

Variety/Brand[1]	Plots	Variety/Brand[1]	Plots
P11Z72E™ (E3)	1	P35A20	1
P17Z39E™ (E3)	1	P35Z76E™ (E3)	15
P19Z52E™ (E3)	2	P36Z47BE™ (Bolt,E3)	1
P20Z14E™ (E3)	3	P37A18E™ (E3)	7
P21A53E™ (E3)	2	P37Z06E™ (E3)	26
P21Z71E™ (E3)	3	P38Z63E™ (E3)	9
P21Z88E™ (E3)	1	P39A78	1
P22A67E™ (E3)	12	P40A23E™ (E3)	1
P23Z58E™ (E3)	6	P40Z57E™ (E3)	27
P23Z82E™ (E3)	2	P41Z80BLX™ (Bolt,LL,RR2X)	2
P25A16E™ (E3)	14	P42A84E™ (E3)	5
P26Z78E™ (E3)	4	P43Z44SE™ (STS,E3)	4
P27Z41E™ (E3)	24	P44A21X™ (RR2X)	1
P28A39E™ (E3)	8	P44A60LX™ (LL,RR2X)	1
P28A51X™ (RR2X)	3	P45A70LX™ (LL,RR2X)	2
P28A65E™ (E3)	11	P45A81E™ (E3)	2
P28Z30E™ (E3)	20	P45Z75E™ (E3)	5
P28Z89E™ (E3)	9	P46A09E™ (E3)	1
P30A75E™ (E3)	29	P46A90LX™ (LL,RR2X)	5
P31A73E™ (E3)	4	P46Z53E™ (E3)	1
P31A95BX™ (Bolt,RR2X)	2	P47A64X™ (RR2X)	1
P31Z03E™ (E3)	41	P47Z15BE™ (Bolt,E3)	3
P31Z32E™ (E3)	1	P48A04LX™ (LL,RR2X)	1
P32Z91E™ (E3)	19	P48A14E™ (E3)	3
P33A85E™ (E3)	1	P48Z70BLX™ (Bolt,LL,RR2X)	3
P33Z17E™ (E3)	13	P49Z02E™ (E3)	4
P34A50	1	P50Z95E™ (E3)	1
P34A98E™ (E3)	10	P53Z60LX™ (LL,RR2X)	1

[1] All Pioneer products denoted with ™ are brand names.

Pioneer® brand soybean varieties topping 100 bu/acre in on-farm trials in 2024 included:

- 42 Enlist E3® varieties
- 30 Z-Series varieties
- 11 varieties with Peking SCN resistance source

Top 3 Performing Varieties in 2024:

- P31Z03E™ - 41 entries over 100 bu/acre
- P30A75E™ - 29 entries over 100 bu/acre
- P40Z57E™ - 27 entries over 100 bu/acre

AGRONOMIC PRACTICES FOR SOYBEANS

- 100 bu/acre yields were achieved in a range of different environments and with a range of different agronomic practices.
- Analyses of management practices used in yield contest winners in other crops have produced similar findings (Jeschke, 2025), indicating that there is no single one-size-fits-all formula for achieving high yield potential.

TILLAGE

- The most common tillage system used at locations with 100 bu/acre plots over the past 4 years was conventional tillage, followed by no-till (Figure 3).
- Tillage practices varied by geography:
  - Conventional tillage was more common in the eastern Corn Belt, comprising around 2/3 of 100 bu/acre plots in Illinois, Indiana, Ohio, Pennsylvania, and Virginia.
  - Iowa plots were split roughly evenly between conventional tillage (48%) and no-till or strip-till (43%).
  - Over half of Nebraska plots were no-till or strip till (56%) and North Carolina plots were predominantly no-till (68%).

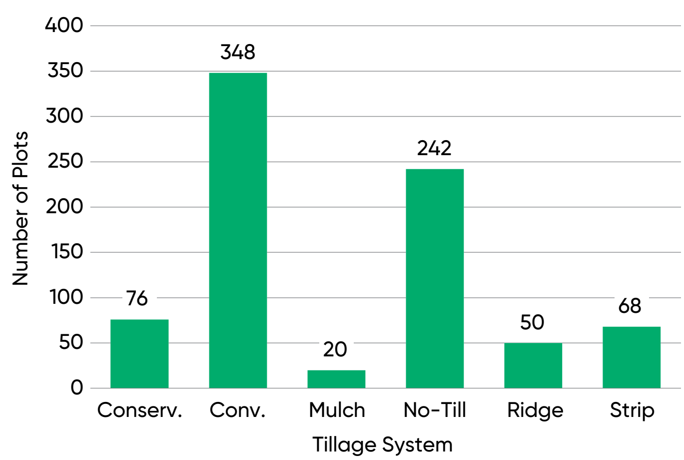


Figure 3. Tillage practices used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2021-2024.

SEEDING RATE

- Seeding rates used in plots yielding above 100 bu/acre ranged from 89,000 seeds/acre to 200,000 seeds/acre, with the majorty between 140,000 and 170,000 seeds/acre (Figure 4).

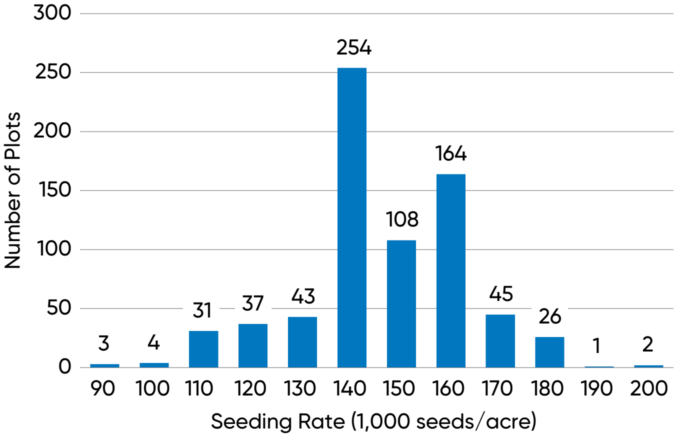


Figure 4. Seeding rate used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2021-2024.

PLANTING DATE

- Recent research has shown the importance of early planting for maximizing soybean yields (Van Roekel, 2019). Most trial locations with 100 bu/acre plots were planted in the latter half of April through the first week of May (Figure 6).

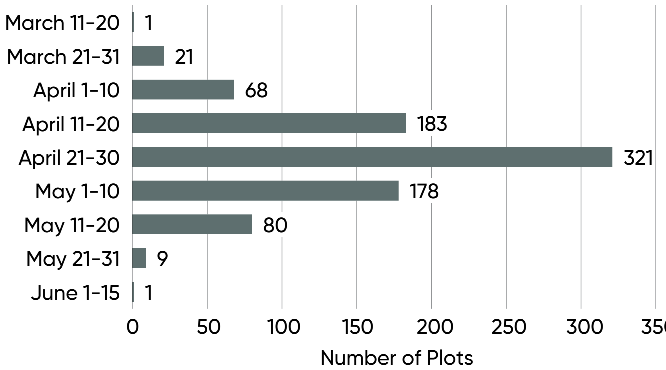


Figure 6. Planting date of Pioneer on-farm trials with entries exceeding 100 bu/acre, 2021-2024.

ROW SPACING

- The most common row spacing of 100 bu/acre plots was 30-inch rows, followed closely by 15-inch rows (Figure 5).
- Geographic distribution of row spacing practices roughly corresponded with findings of recent USDA surveys, with 30-inch rows most common from Iowa west and narrower rows more common from Illinois east (Jeschke and Lutt, 2016).

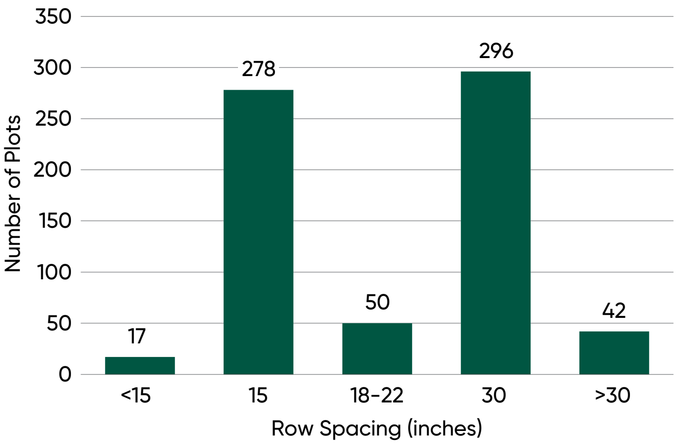


Figure 5. Row spacing used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2021-2024.

Soybean Canopy Development and Closure Following Dicamba Injury

JOHN MICK, KEVIN KELLER, GARRETT KENNEDY, FIELD AGRONOMISTS
DAN ILTEN, AGRONOMY INNOVATION MANAGER — **MARK JESCHKE, PH.D.,** AGRONOMY MANAGER

KEY FINDINGS

- A study conducted across multiple locations in 2024 examined the impact of low-level dicamba injury on growth and canopy closure of non-dicamba-tolerant soybeans.
- Dicamba-injured soybeans had an initial delay in canopy coverage but were generally able to recover within two to three weeks.
- Dicamba injury tended to trigger development of additional branches lower on the plants, which resulted in a different shape to the soybean canopy with a lower point of closure.

BACKGROUND AND OBJECTIVE

- Dicamba use for post-emergence weed control has increased in both corn and soybeans in recent years to control glyphosate-resistant weeds.
- Soybeans without dicamba tolerance are extremely sensitive to dicamba and can be injured by off-target movement or contaminated spray equipment, which shows up as cupping of newly developed leaves (Figure 1).
- Soybean exposure to dicamba resulting in minor symptoms typically will not impact yield; however, the potential for yield loss increases at higher levels of exposure (Werle et al., 2018). The potential for yield loss depends on the amount of dicamba and the growth stage of soybeans at the time of exposure.
- Soybeans exposed during vegetative growth are more likely to recover and not experience yield loss; however, dicamba injury can cause a delay in canopy closure, particularly for soybeans in 30-inch rows.
- In 2024, canopy measurements were taken at numerous locations across southern Nebraska and northern Kansas where dicamba-tolerant (DT) and non-dicamba-tolerant (non-DT) soybeans were planted adjacent to each other to evaluate the impact of dicamba injury on canopy development in non-DT soybeans.

STUDY DESCRIPTION

- Canopy measurements were taken at 44 locations in Nebraska and Kansas where DT and non-DT soybeans were planted in adjacent fields and dicamba application resulted in some degree of injury to the non-DT soybeans (Figure 2).
- Canopy closure was measured using overhead sUAS imagery with leaf coverage quantified using the Canopeo app developed by Oklahoma State University (Figure 3).

Figure 1. Soybean plants showing upward leaf cupping characteristic of dicamba injury. Symptoms are limited to newer growth, with older leaves unaffected.

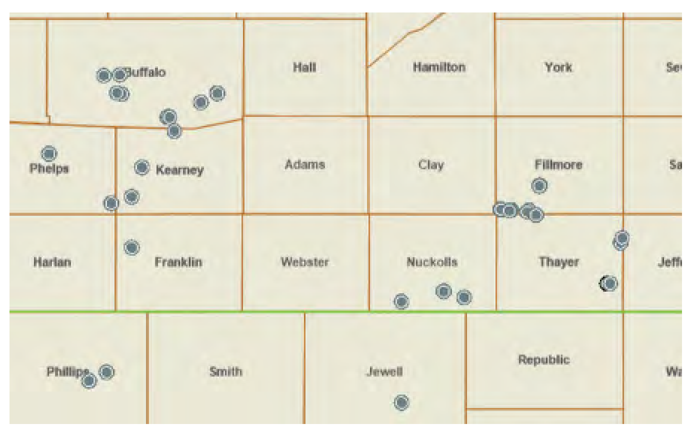


Figure 2. Soybean canopy development study locations in southern Nebraska and northern Kansas in 2024.

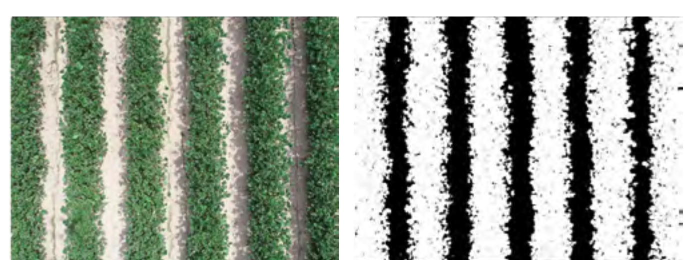


Figure 3. Example of an overhead sUAS image of a soybean field and the same image as processed by the Canopeo app to calculate the percentage of ground area covered by the crop canopy.

- Canopy images were taken approximately weekly from July 2 through July 29, corresponding to the R1/R2 growth stage through R3/R4 growth stage.
- Of the 44 study locations, 33 were under full irrigation, 2 had limited irrigation, and 9 were dryland.
- A total of 18 different DT soybean varieties and 21 different non-DT varieties were used across the study locations.
- Injury symptoms consistent with dicamba exposure were observed in the non-DT soybeans at all locations included in the study.

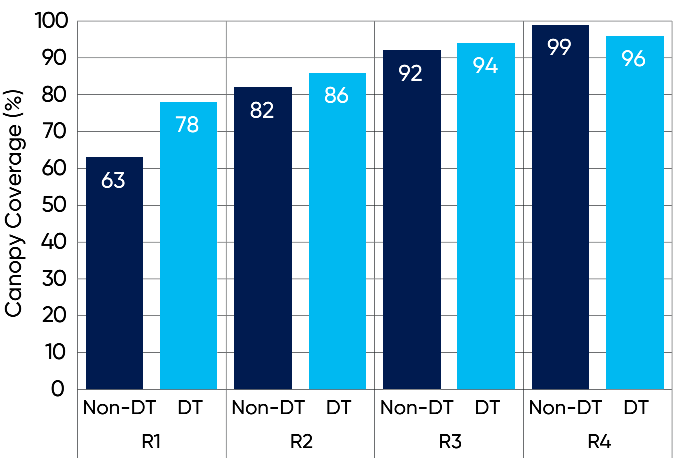


Figure 4. Average canopy coverage of dicamba-injured non-DT soybeans compared to DT soybeans at the R1, R2, and R3 growth stages.

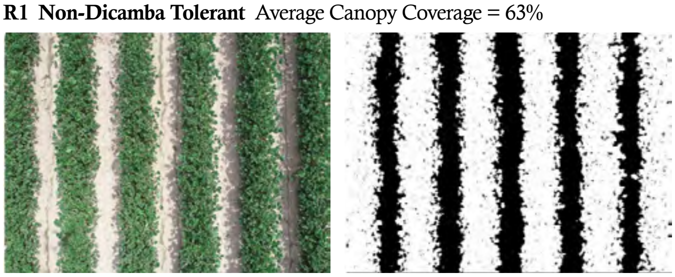
RESULTS

- Soybean canopy imagery from across all study locations showed an initial reduction in canopy coverage in non-DT varieties compared to DT varieties as a result of dicamba injury.
- In imagery taken at the R1 growth stage, non-DT varieties averaged 63% canopy coverage compared to 78% coverage for DT varieties (Figure 4).
- However, this difference in canopy coverage did not persist. By the R2 stage, the non-DT varieties had largely closed the gap, with an average of 82% canopy coverage compared to 86% for DT varieties (Figure 5).
- Differences in canopy coverage were further diminished by the R3 stage and were completely gone by the R4 stage.
- Dicamba has been shown to reduce yield of non-DT soybeans in cases where exposure levels are high enough to cause severe injury; however, no effect on yield was generally observed in this study unless another source of significant plant stress was also present.

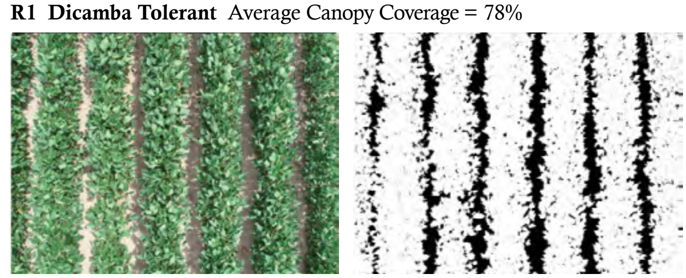
SECONDARY STRESS FACTORS

- Results of this study showed that non-DT soybean varieties were able to recover from dicamba injury within 2-3 weeks unless an additional significant stress factor was also present.
- Soil compaction and drought stress were two stress factors observed at study locations that delayed soybean recovery from dicamba injury and canopy closure (Figure 6).

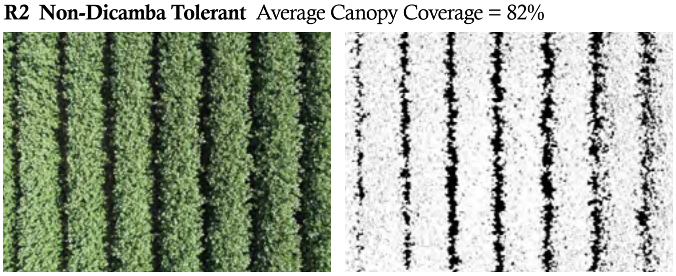
R1 Non-Dicamba Tolerant Average Canopy Coverage = 63%



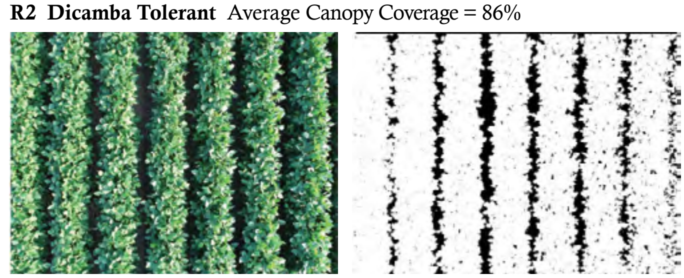
R1 Dicamba Tolerant Average Canopy Coverage = 78%



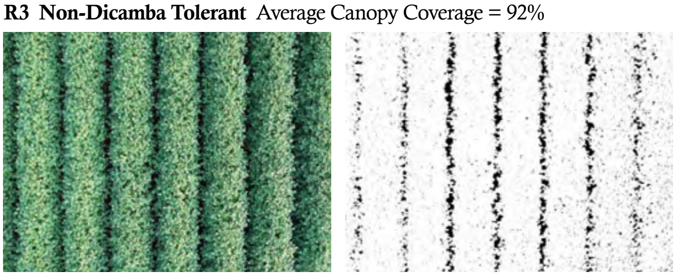
R2 Non-Dicamba Tolerant Average Canopy Coverage = 82%



R2 Dicamba Tolerant Average Canopy Coverage = 86%



R3 Non-Dicamba Tolerant Average Canopy Coverage = 92%



R3 Dicamba Tolerant Average Canopy Coverage = 94%

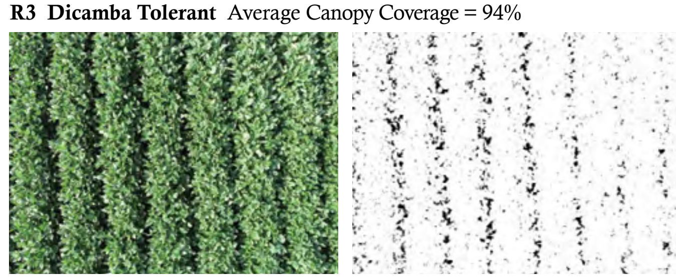


Figure 5. Overhead sUAS imagery and Canopeo-processed imagery showing canopy coverage of dicamba-injured non-DT soybeans compared to DT soybeans at the R1, R2, and R3 growth stages.

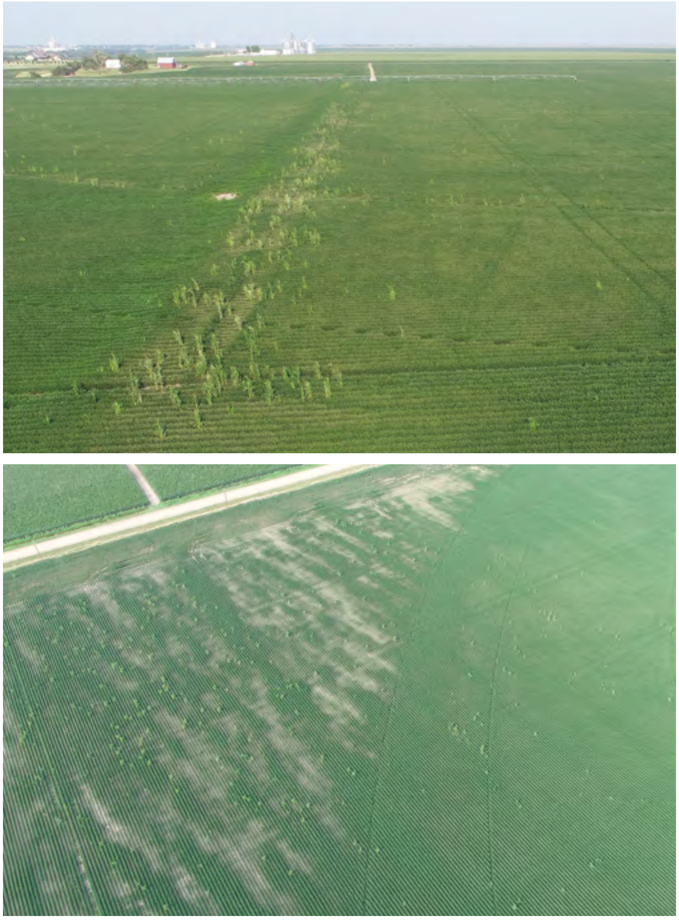


Figure 6. Study locations where soybean recovery from dicamba injury was inhibited by one or more additional stress factors. **Top:** Recovery inhibited by stress associated with historical soil compaction where a lane once existed in the field. **Above:** Recovery inhibited by drought stress in the pivot corner, compounded by soil compaction (visible as streaks in the pivot corner), as well as injury from an additional group 4 herbicide (triclopyr).

CANOPY SHAPE

- Dicamba injury can result in a different shape to the soybean canopy compared to non-injured soybeans, even if percent canopy coverage is the same.
- When dicamba enters a soybean plant, it is translocated to the meristematic region at the top of the plant, where it can cause injury to new growth.
- Damage to the apical meristem can trigger development of new branches lower on the plant (Figure 7).
- The growth of additional branches lower on the plant can result in a triangular shape to the plants, with a lower point of canopy closure (Figure 8).
- This lower point of canopy closure can create the impression that the impact of dicamba injury on canopy coverage is worse than it actually is. When viewed from the road, soybeans may appear to have not closed canopy yet even though they have.
- A lower point of canopy closure can actually benefit soybean plants by allowing light to penetrate deeper in the canopy and enabling plants to maintain and fill pods lower on the plant.

Figure 7. Soybean plants that developed additional branches lower on the plant following dicamba injury to the apical meristem.

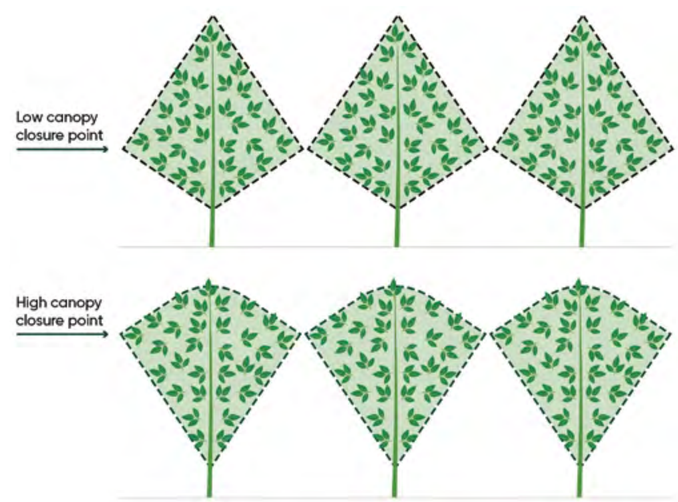


Figure 8. Visual representation of lower and higher soybean canopy closure points resulting from different plant shapes.

White Mold Management in Soybeans

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- White mold (*Sclerotinia sclerotiorum*) is a fungal disease of soybean that has become a more frequent issue over the past 30 years in the Northern U.S. and Canada.
- White mold is a disease of high yield potential soybeans – the better the establishment and growth of the crop, the greater the risk of white mold.
- White mold is favored by cool and wet weather and dense soybean canopies that help retain these conditions under the crop canopy.
- Integrating several cultural practices is the most effective means of managing white mold. Cultural practices include variety selection, crop rotation, weed management, no-till, and if necessary, limiting dense canopy formation.
- Several fungicides are labeled for white mold but must be applied before the appearance of symptoms and generally will not provide complete control.
- Foliar chemical applications should be targeted at early flowering (R1); penetration of spray to the lower soybean canopy is necessary for treatments to be effective.

A GROWING PROBLEM IN SOYBEANS

White mold (*Sclerotinia sclerotiorum*) is a fungal disease that can attack hundreds of plant species. Also known as Sclerotinia stem rot, white mold was first observed on soybeans in central Illinois in 1948 and for many years was only a sporadic soybean disease in Minnesota, Wisconsin, and Michigan. However, since the 1990s it has become a more frequent threat to northern states from Minnesota to New York, as well as the northern areas of states bordering to the south.

The reason for the abrupt increase in the frequency and severity of white mold infection is not fully understood. Changes in soybean management practices likely have played a role. Practices such as earlier planting, longer maturity varieties, and narrow row spacing that have been important in driving higher soybean yields also tend to create a more favorable environment for white mold disease development by accelerating canopy closure during the season. Changes in genetic resistance of commercial soybean varieties, as well as changes in the pathogen itself may also be factors.

A successful management plan for white mold in soybean needs to take factors such as variety selection and agronomic management into account, in addition to any chemical control treatments.

Figure 1. White fungal mycelia visible on the stem of a soybean plant infected with white mold.

LIFE CYCLE AND SYMPTOMS

White mold is a monocyclic disease, which means that it goes through one development cycle per crop cycle (Figure 2). White mold persists in soybean fields over time by survival structures called sclerotia. These dark, irregularly shaped bodies about ¼ to ½ inch long are formed within the white, cottony growth both inside and outside the stem. Sclerotia contain energy reserves and function much like seeds, surviving for years in the soil and eventually germinating, producing millions of spores beneath the plant canopy.

In the most common form of germination, a sclerotium produces one or more germ tubes or stipes that grow upward from a depth of two inches or less in the soil. When it reaches the soil surface, the germ tube is triggered by light to produce a small, flesh-colored structure much like a mushroom, called an apothecium. One sclerotium can produce numerous apothecia simultaneously or sequentially throughout the growing season. Each apothecium produces millions of spores beneath the plant canopy, which are periodically released and spread to the plants.

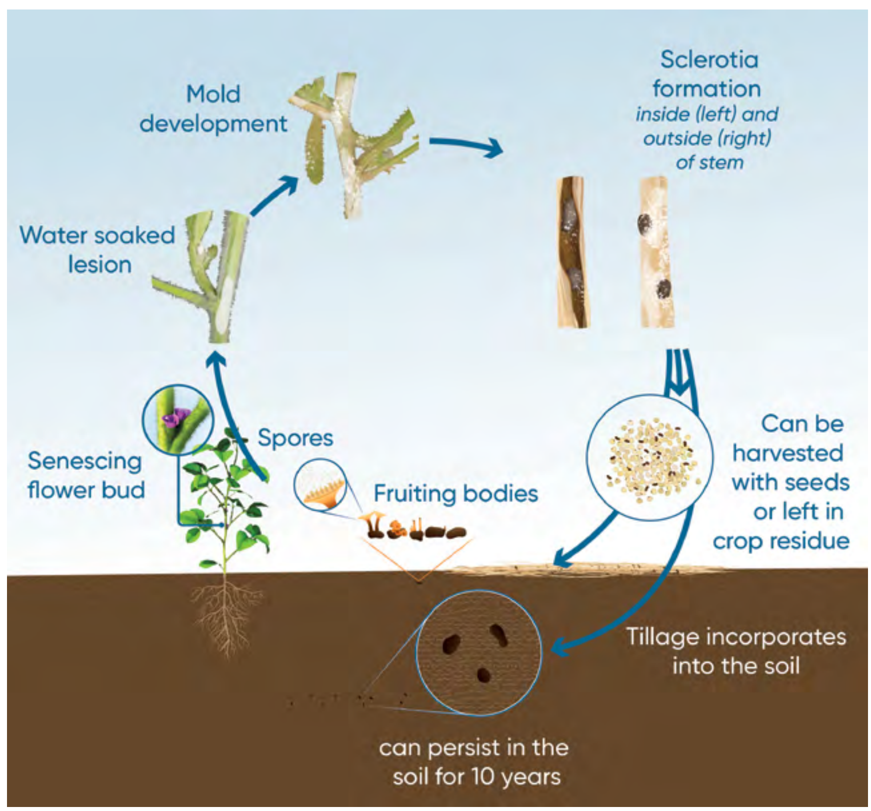


Figure 2. White mold disease cycle.

White mold spores are not able to invade plants directly but must colonize dead plant tissue before moving into the plant. Senescing flowers provide a ready source of dead tissue for colonization (Figure 3). Flowers start senescing as soon as they open. From these senescing flowers in the branch axils or stuck to developing pods, the fungus spreads to healthy tissue.

It takes around two to three weeks from initial infection for the fungus to colonize the plant and erupt. The first symptom of white mold infection appears as a water-soaked stem lesion originating from a node. If the lesion remains wet, it becomes overgrown with white mold. The disease can then spread directly from plant to plant by contact with this moldy tissue. Sclerotia are formed within the moldy growth and inside the stem to complete the disease cycle (Figure 4). The shape of the sclerotia can vary based on where they form. Those that form outside the plant will be more spherical, while those that form inside the plant stem will be more oblong. Plant damage is incurred as tissue rot and formation of sclerotia inside the stem result in rapid wilting and death of the upper part of the plant. As the disease progresses, premature death of the entire plant can occur.

Figure 3. Senescing flowers are the entry point for the white mold pathogen to infect the plant.

Figure 4. White mold sclerotia on a soybean stem.

FAVORABLE CONDITIONS

Wet, cool conditions are required throughout the white mold disease cycle, including germination of the sclerotia in the soil, spore release, infection of soybean flowers by spores, and spread of white mold from plant to plant.

- Sclerotia in the soil require 7 to 14 days of high soil moisture to germinate and produce apothecia (fruiting bodies). Temperatures between 40 and 60°F are optimal for this process.
- Spores are forcibly ejected from the fruiting bodies during wet weather conditions.
- After spores are released, a wet surface on senescing flowers or other dead or dying tissue is required for spore germination. Specifically, two to three days of continuous wetness, or more than 12 hours of daily wetness for three to five days is required.
- White mycelial growth develops on stem lesions that remain wet, and spreads by contact to neighboring plants. Temperatures under 85°F are favorable for disease spread.

Wet, cool conditions are required throughout the white mold disease cycle.

Early establishment of a dense soybean canopy increases the likelihood that the high-humidity conditions required for white mold development will occur. Early canopy closure is a goal for many soybean producers, especially in northern locations and growing environments where solar radiation may be limited, as it important for maximizing light interception and yield. Soybean management practices such as early planting and narrow rows can help achieve earlier canopy closure. Unfortunately, these practices can also encourage white mold development.

Figure 5. White mold sclerotia on soybean stem.

MANAGEMENT OF WHITE MOLD

White mold is a disease of high yield potential soybeans. Often, the better the establishment and growth of the crop, the more likely it will be damaged by white mold. Management practices that may be useful for reducing the severity of white mold infection may also limit the yield potential of the crop; consequently, an integrated management strategy for white mold often involves weighing the tradeoffs between pushing for maximum yield vs. protecting against disease based on the white mold risk in a given field.

No single practice will be effective in completely controlling white mold.

No single practice will be effective in completely controlling white mold, but several options are available to help reduce disease pressure. Current options include disease avoidance, variety selection, changes in cropping systems including tillage and rotation, and adjusting production methods such as planting practices, chemical applications and weed control.

DISEASE AVOIDANCE

White mold spreads either by movement of spores or sclerotia from field to field. Spores are airborne and may originate from any field that has had white mold in the past. However, spores generally do not move long distances, as they originate near the soil surface and commonly stay contained below the crop canopy. Spread over longer distances is usually due to movement of sclerotia.

Figure 6. Infected soybean stem.

Sclerotia move from field to field in harvest equipment or in contaminated seed. Harvest equipment should be thoroughly cleaned when moving from infected to non-infected fields. Harvesting infected fields last provides additional safety. Because sclerotia are roughly the size of soybean seed, they can't be easily separated by the combine. Soybeans harvested from infected fields are likely to be loaded with sclerotia. Planting these soybeans would place them at the ideal depth for germination and infection of that crop and field. Growers should absolutely not save seed from infected fields.

RISK FACTORS FOR WHITE MOLD

The North Central Plant Health Initiative has developed the following list of risk factors for white mold.

SEASONAL RISK FACTORS FOR WHITE MOLD DEVELOPMENT

Weather: Moderate temperatures (<85°F), normal or above normal precipitation, soil moisture at field capacity or above, and prolonged morning fog and leaf wetness (high canopy humidity) at and following flowering into early pod development.

Early canopy closure due to early planting, high plant population, narrow rows, excessive plant nutrition and optimal climatic conditions creates dense canopy and increased apothecia density.

History of white mold in the field, density of the white mold pathogen, apothecia present on soil surface at flowering, distribution of pathogen/disease in field.

Soybean variety planted: Plant structure and physiological functions govern variety reaction to white mold. Varieties range from partially resistant to highly susceptible.

LONG-TERM RISK FACTORS FOR WHITE MOLD DEVELOPMENT

Field/cropping history: Pathogen level will gradually increase if:

- Other host crops are grown in rotation with soybean.
- 1- to 2-year intervals occur between soybean crops.
- White mold susceptible varieties are grown.

Weed management systems: Inoculum will increase if control of broadleaf weeds is ineffective. Some herbicides used in rotation systems may be suppressive to white mold.

Topography of field: Pockets of poor drainage, tree lines, and other natural barriers that impede air movement will create a favorable microenvironment for white mold development.

Pathogen introduction:

- Contaminated and infected seed.
- Movement of infested soil with equipment.
- Wind-borne spores from apothecia from area outside fields.

Corteva Agriscience avoids growing seed beans in fields with a history of white mold. In addition, seed is thoroughly cleaned and inspected to ensure that it is disease-free. Seed cleaning with a gravity table or centrifugal tower is essential to remove sclerotia. Fungicide seed treatments can help ensure that no disease is transmitted by mycelia present on seed.

VARIETY SELECTION

There is no absolute resistance available to white mold (all varieties can get the disease under severe pressure), but differences in tolerance exist between varieties. Pioneer variety ratings range from 2 to 7 on a scale of 1 to 9 (9 = resistant). Ratings reflect varietal differences in the rate at which infection develops as well as the extent of damage it causes and are based on data from multiple locations and years. Choosing varieties that rate high for tolerance is an important management practice in areas that commonly encounter white mold. Your local Pioneer sales professional can suggest white mold tolerant varieties with a complete package of traits needed for top soybean production in your area.

Variety maturity is also an important consideration. Longer maturity varieties can help maximize yield potential, but they also have a longer window of flowering, which extends the period of time that senescing flowers are present and susceptible to infection.

NO-TILL

Research studies have shown that no-till is generally superior to other tillage systems in limiting white mold development by leaving sclerotia to deteriorate on the soil surface. Sclerotia germinate from the top two inches of soil. Below that depth, they can remain dormant for five or more years. Because of its longevity in the soil, it is difficult to devise a strategy to control white mold with tillage. Deep tillage buries sclerotia from the soil surface but may also bring prior sclerotia into their zone of germination.

CROP ROTATION

Rotation with a non-host crop can help reduce disease pressure in a field. Non-host crops include corn, sorghum, and small grains. Susceptible crops to avoid in a rotation include alfalfa, clover, sunflower, canola, edible beans, potato, and others. Depending on soybean tolerance, field history and other factors, more than one year away from soybeans may be required. Including a small grain crop in the rotation can be particularly helpful, as the canopy is dense enough to trigger formation of apothecia from the sclerotia in the soil but there is no host crop to infect. However, because of the longevity of sclerotia in the soil, crop rotation is only a partial solution.

PLANTING DATE

Later planted soybeans are generally shorter and less branched and therefore later to reach canopy closure. Some planting date studies show that later planting results in less incidence of white mold. However, yields are generally reduced when planting is delayed past mid-May in northern states. The tradeoff between less yield reduction due to white mold but more yield reduction due to late planting may not be favorable, especially in years of low disease pressure.

ROW SPACING AND SEEDING RATE

Row spacing and seeding rate both influence soybean canopy closure and density, which affect development of white mold. However, given that early canopy closure is generally favorable to yield, adopting wider row spacings or lower seeding rates to manage white mold may also reduce yield potential.

The most common row spacings for soybeans in the U.S. are 15 inches and 30 inches. Drilled soybeans in row spacings less than 15 inches were once common but have declined in recent years. Numerous studies over many years have demonstrated a yield advantage for narrow-row (<30 inches) soybeans. A Pioneer review of several university trials found an average yield benefit of around 4 bu/acre for drilled or 15-inch row soybeans compared to 30-inch rows (Jeschke and Lutt, 2016).

Research has shown that seeding rate is likely a more important factor affecting white mold development than row spacing (Lee et al., 2005). In fields with high risk of white mold, seeding rates should be sufficient for uniform stand establishment, but shouldn't be aggressively high. Actual rates will vary depending on planting date, seedbed conditions, and seed quality. A multi-state university study found that wider rows and reduced seeding rates were both effective at reducing white mold severity, but also reduced soybean yield when white mold did not develop (Webster et al., 2022). Results suggested that wider rows and reduced seeding rates as tactics to manage white mold should be reserved for fields with a history of white mold where disease is likely to occur.

WEED CONTROL

White mold has over 400 plant hosts, including many broadleaf weeds. Host weeds that are also common weed species throughout soybean growing areas include lambsquarters, ragweed, pigweed, and velvetleaf. In addition to acting as host to the disease, weeds can also increase canopy density, which favors disease development.

CHEMICAL TREATMENTS FOR WHITE MOLD

Despite the best use of cultural practices to limit the incidence of white mold, weather and other conditions conducive to disease development may still cause heavy infestations. In cases of high disease risk, a foliar application of a chemical product or a soil application of a biological product may help reduce disease severity and protect soybean yield.

Products labeled for white mold control or suppression include several foliar fungicides (Table 1), a biological fungicide (Contans® fungicide), and the herbicide lactofen (active ingredient in Cobra® herbicide and Phoenix® herbicide).

Table 1. Fungicides labeled for control of white mold in soybeans with an efficacy of "fair" or better (Wise, 2025).

Fungicide Trade Name	Active Ingredient	White Mold Efficacy
Aproach® 2.08 SC	picoxystrobin	good
Proline® 490 SC	prothioconazole	fair
Domark® 230 ME	tetraconazole	fair
Topsin-M®	thiophanate-methyl	fair
Omega® 500 DF	fluazinam	good
Endura® 0.7 DF	boscalid	very good
Propulse® 3.34 SC	fluopyram, prothioconazole	good
Delaro® 325 SC	trifloxystrobin, prothioconazole	fair
Delaro® Complete 3.83 SC	fluopyram, trifloxystrobin, prothioconazole	fair
Viatude® 2.09 SC	picoxystrobin, prothioconazole	fair

Chemical treatments generally will not provide complete control of white mold. Reduction of disease in university field trials has ranged from 0 to 60% (Mueller et al., 2015). Consequently, chemical treatments need to be used as part of an integrated management strategy for white mold.

FOLIAR FUNGICIDES

Optimum application time of fungicides for white mold control in soybeans is the R1 to R2 growth stage, also known as the beginning bloom or first flower stage (Mueller et al., 2015). For much of the U.S. Corn Belt, the R1 stage coincides with the first two weeks of July when the vegetative growth stage is typically about V7 to V10 (Pedersen, 2009). Fungicides applied up to the R3 stage can provide some benefit in reducing white mold.

Fungicides have little activity on established disease and must be applied prior to white mold invasion of senescing flowers. Applications made just prior to pathogen invasion have helped reduce disease severity in some studies. Because soybeans normally flower for 30 days or more (R1 to R5) and fungicides for white mold control have maximum residual activity of about two weeks, a second application may be necessary if conducive environmental conditions persist into mid-summer.

Fungicides have little activity on established disease and must be applied prior to white mold invasion of senescing flowers.

One drawback to later (R3) fungicide application is the potential for reduced canopy penetration. Though soybeans grown in 30-inch rows at moderate seeding rates may allow for good penetration of the lower canopy at R1, spray coverage of the lower nodes becomes increasingly difficult with continued vegetative growth. The lower canopy can remain relatively wet or humid, providing the appropriate environment for pathogenicity. Thus, it is essential for spray droplets to reach the lower two-thirds of the soybean canopy in order to obtain satisfactory disease control.

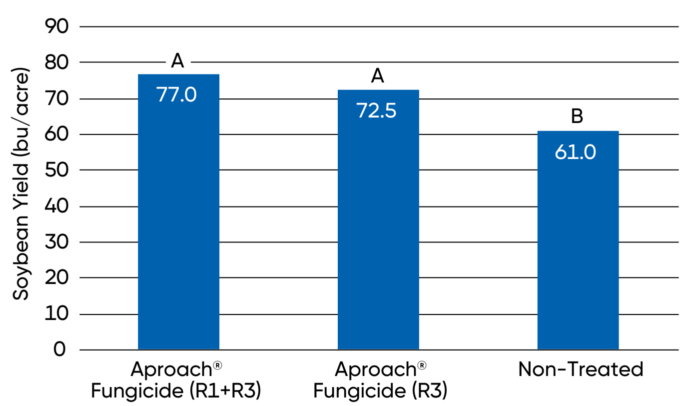


Figure 7. Yield of soybeans treated with Aproach® fungicide at the R3 growth stage and the R1 and R3 stages compared to non-treated soybeans in a Univ. of Wisconsin trial at Hancock, WI, in 2016 (Smith et al., 2016).

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

FUNGICIDE RESEARCH RESULTS

A University of Wisconsin research trial conducted near Hancock, WI in 2016 found significant increases in soybean yield associated with Aproach® fungicide treatment under high levels of white mold pressure (Figure 7). A single treatment at the R3 growth stage increased yield by 11.5 bu/acre and sequential applications at the R1 and R3 stages increased yield 16 bu/acre compared to the non-treated check.

Corteva Agriscience on-farm research trials were conducted in 2017 at locations near Orchard, NE and Edgar, WI that experienced high white mold pressure. Both trials compared sequential applications at the R1 and R3 growth stages and single-pass treatments at both R1 and R3 to a non-treated check. The Wisconsin trial was non-replicated, and the Nebraska trial included two replications. The two-pass fungicide program increased yield by an average of 13.3 bu/acre in these trials (Table 2). The R3 and R1 treatments increased yield by an average of 8.7 and 6.7 bu/acre.

Table 2. Soybean yield associated with Aproach® fungicide treatments in on-farm trials with heavy white mold pressure in Wisconsin and Nebraska.

Fungicide Treatment	Edgar WI	Orchard NE	Average	Yield Advantage
		bu/acre		
Aproach® (R1+R3)	66.6	55.9	61.3	**+13.3**
Aproach® (R3)	57.7	55.6	56.7	**+8.7**
Aproach® (R1)	61.9	47.4	54.7	**+6.7**
Non-Treated	54.8	41.2	48.0	

COBRA® HERBICIDE

Lactofen, the active ingredient in Cobra herbicide, and Phoenix® herbicide is for post-emergence weed control in soybeans. In addition, it is a potent elicitor of the phytoalexin glyceolin (Nelson et al., 2001). Phytoalexins are antimicrobial substances produced by plants in response to invasion by certain pathogens or by chemical or mechanical injury (Agrios, 1988).

Studies have shown that the optimum application time for Cobra herbicide is at R1, which is identical to timing recommendations for foliar fungicides. Although small yield improvements were observed with V4 to V5 Cobra herbicide treatments, yield increases were larger and more consistent with applications at R1. Cobra herbicide has been shown to reduce disease incidence and increase yield of susceptible soybean varieties (Oplinger et al., 1999). However, a moderately resistant variety showed no response to Cobra herbicide and produced a higher yield than a treated susceptible variety. Due in part to unpredictable disease levels and variations in varietal tolerance to white mold, yield increases with Cobra herbicide have tended to be highly variable (Nelson et al., 2002).

Herbicides with PPO inhibiting sites of action, such as Cobra, herbicide usually cause moderate levels of leaf necrosis. Although the reduction in leaf area from this necrosis is likely a contributing factor in white mold control with Cobra herbicide, yield loss may result in the absence of disease (Dann et al., 1999; Kyle, 2014). Producers should use caution when considering the widespread use of Cobra herbicide, especially on moderately resistant varieties when environmental conditions do not favor disease.

CONTANS® WG FUNGICIDE

Contans fungicide is a biological control agent of white mold. The product contains the soil fungus *Coniothyrium minitans*, which acts as a parasite attacking the overwintering survival structures (sclerotia) of white mold. Contans fungicide is applied to the soil, its spores germinate with sufficient moisture, and the fungus can destroy sclerotia if given adequate time. According to the manufacturer, Contans fungicide should be applied at least three months prior to white mold infection, and soil-incorporated immediately following application to a depth of at least four inches. Contans fungicide has been evaluated in both greenhouse and field studies (Hao et al., 2010). In both cases, efficacy has been good, as reduced apothecia number and improved soybean yield have been observed. Although Contans fungicide may be fall- or spring-applied, fall applications have performed better than those done in spring.

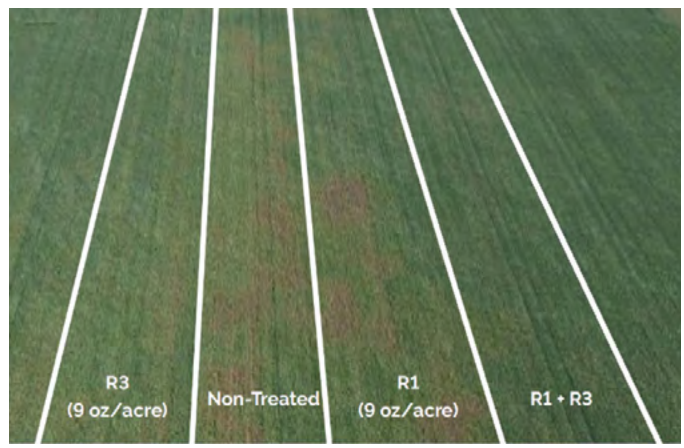


Figure 8. Corteva Agriscience on-farm fungicide research trial near Edgar, WI comparing Aproach® fungicide applied at R1, R3, and R1+R3 growth stages to a non-treated check under heavy white mold pressure (September 11, 2017).

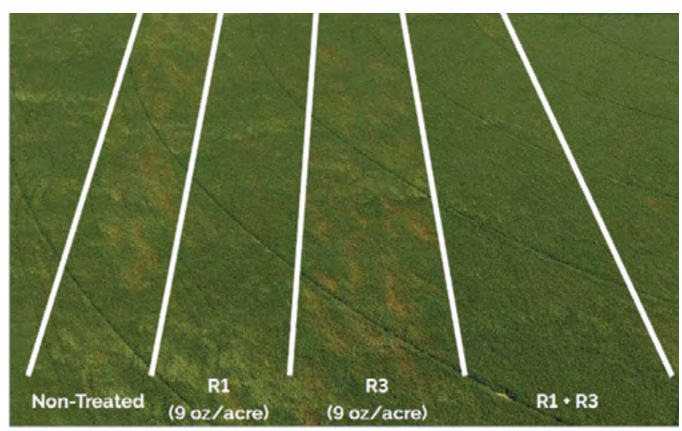


Figure 9. Corteva Agriscience on-farm fungicide research trial near Orchard, NE comparing Aproach® fungicide applied at R1, R3, and R1+R3 growth stages to a non-treated check under heavy white mold pressure (August 23, 2017).

Sudden Death Syndrome of Soybeans

MARK JESCHKE, PH.D., AGRONOMY MANAGER

KEY POINTS

- Sudden death syndrome (SDS) is a fungal disease of soybeans that infects the roots early in the season.
- The fungus produces a toxin that is translocated up the plant and causes foliar symptoms, which typically appear later in the season.
- SDS-tolerant varieties, fungicide seed treatments, management of SCN, and improved soil drainage can help minimize damage from SDS.
- Foliar fungicides have no effect since the infection is in the roots.

A MAJOR DISEASE OF SOYBEAN

- Sudden death syndrome (SDS) is one of the most economically important yield-limiting diseases of soybean in North America.
- Since its initial discovery in Arkansas in the early 1970s, it has spread to infect soybean fields in almost all U.S. soybean-growing states and Ontario, Canada.
- SDS is capable of causing significant yield loss in soybeans, with reductions exceeding 50% in the most severe cases.

CAUSAL PATHOGEN

- In North America, SDS is caused by the fungal pathogen *Fusarium virguliforme*, formerly known as *F. solani* f. sp. *glycines.*
- *F. virguliforme* is believed to be an invasive pathogen that originally evolved in South America.
- *F. virguliforme* survives in root debris and soil as chlamydospores, which are thick-walled, asexual fungal spores.
- As the soil warms up in the spring, chlamydospores germinate and can infect nearby soybean roots.
- Infection of soybean plants occurs early in the growing season, often as early as germination to just after crop emergence.
- The fungus colonizes cortical tissue of the roots. It has been isolated from both the taproots and lateral roots, but infection does not extend above the crown of the plant.
- Later in the season, the fungus will penetrate the xylem tissue in the roots and produce a toxin that is translocated up the plant and causes the characteristic foliar symptoms (Figure 1).
- *F. virguliforme* produces spores (macroconidia) on the surface of infected roots during the summer, which then convert to chlamydospores and are sloughed off of the plant.
- Within a growing season, these spores will only spread a short distance from infected plants, but flowing water and movement of soil can spread the pathogen over greater distances.

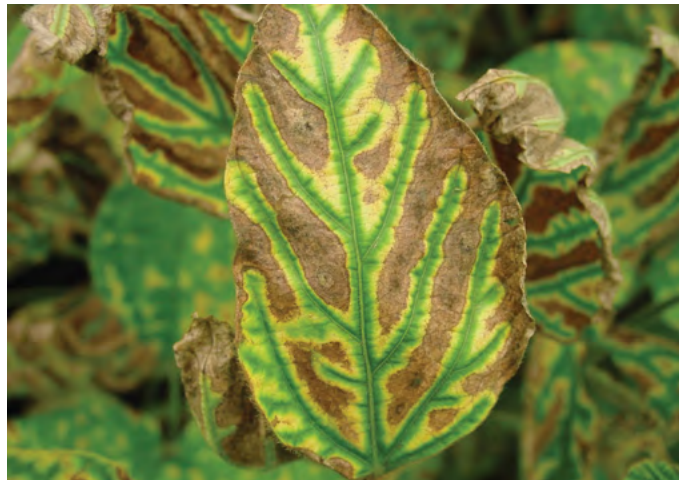


Figure 1. Soybean leaf showing classic symptoms of sudden death syndrome infection, with yellow and brown areas contrasted against a green midvein and green lateral veins.

ROOT AND STEM SYMPTOMS

- SDS begins as a root disease that limits root development and deteriorates roots and nodules, resulting in reduced water and nutrient uptake by the plant.
- On severely infected plants, a blue coloration may be found on the outer surface of tap roots due to the large number of spores produced (Figure 2).
- Splitting the root will reveal that the cortical cells have turned a milky gray-brown color while the inner core, or pith, remains white (Figure 3).

Figure 2. Microscopic view of blue colored spore masses on the root of a soybean plant infected with SDS (left) and *F. virguliforme* growth on artificial media (right).

LEAF SYMPTOMS

- Leaf symptoms usually do not appear until the reproductive stages of crop development.
- Leaf symptoms of SDS first appear as yellow spots, usually on the upper leaves, in a mosaic pattern. The yellow spots coalesce to form chlorotic blotches between the leaf veins (Figure 4).

- As these chlorotic areas begin to die, the leaf symptoms become very distinct, with yellow and brown areas contrasted against a green midvein and green lateral veins.
- Rapid drying of necrotic areas can cause curling of affected leaves. Leaves drop from the plant prematurely, but leaf petioles remain firmly attached to the stem.

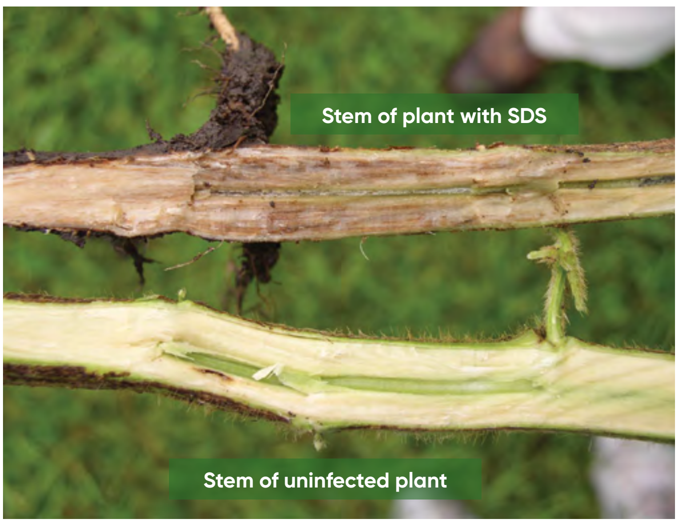


Figure 3. Split soybean plant stems showing the discolored cortical tissue of a SDS-infected plant compared to a healthy plant.

Figure 4. Field view of sudden death syndrome symptoms. Note yellow and brown areas contrasted against a green midvein and green lateral veins. Rapid drying of necrotic areas can cause curling of affected leaves.

CONDITIONS FAVORING DISEASE DEVELOPMENT

- SDS often appears first in localized spots in the field, such as low, poorly drained, or compacted areas (Figure 5).
- Higher incidence of SDS often occurs when soybeans have been exposed to cool, moist soil conditions early in the growing season.
- SDS symptoms are usually more severe if SCN is also problematic in the field. SCN increases the stress on the soybean plant and also provides wounds through which the SDS pathogen can enter the roots.
- The appearance of symptoms is often associated with weather patterns that bring cooler temperatures and significant rainfall to an area during flowering or pod-fill.
- Wet soils can increase the production and translocation of the toxin responsible for foliar symptoms.

Figure 5. Aerial view of a soybean field with SDS. Symptoms are more prevalent near waterways and areas with poor drainage.

MANAGEMENT

- There are no management options available to protect yield once foliar symptoms of SDS begin to appear. Foliar fungicides have no effect since the infection is in the roots.
- Scouting and management strategies are focused on mitigating disease impact in subsequent seasons.
- The first line of defense against SDS is genetic tolerance of soybean varieties.
- Soybean varieties can differ significantly in susceptibility to SDS infection, with tolerance exhibited primarily as a reduction in symptom severity.
- SCN resistance is also an important consideration for variety selection, since SCN injury can exacerbate SDS problems.
- ILEVO® HL fungicide (active ingredient: fluopyram) is a seed treatment that provides protection of soybean seedlings from *F. virguliforme* infection.
- Improving field drainage and reducing compaction can help reduce severity of SDS.

Soybean Aphid Biology and Management

DEBORA MONTEZANO, PH.D., AGRONOMY RESEARCH MANAGER

KEY POINTS

- The soybean aphid is a major pest of soybean crops in the North Central U.S., potentially causing up to 40% yield loss.
- Native to Asia, the soybean aphid was first detected in North America in 2000 and has since become a persistent issue for soybean farmers.
- The soybean aphid has a complex life cycle involving both asexual and sexual reproduction, and can produce up to 18 generations in a season.
- Soybean aphid development is strongly influenced by environmental factors, with ideal temperatures between 77-82°F for population growth. Extreme heat above 95°F slows reproduction.
- Soybean aphids can feed on all parts of the plant, causing leaf distortion, yellowing, and stunted growth.
- Soybean aphids produce honeydew, which promotes sooty mold growth, reducing photosynthesis.
- The primary management strategy for soybean aphid is regular scouting, followed by insecticide applications when the population exceeds the economic threshold.
- Natural predators, parasitoids, and pathogens can helpsuppress soybean aphid populations and are beneficial in maintaining aphids population below the economic threshold.

INTRODUCTION

The soybean aphid (*Aphis glycines*) is a major pest of soybean in the North Central United States, capable of reducing yields by up to 40% if left unmanaged (Figure 1). Native to Asia, it was first detected near Lake Michigan in 2000 and has since become a persistent and economically significant threat to Midwest soybean production (Ragsdale et al., 2004) (Figure 2). Soybean aphids feed by extracting plant sap, causing localized tissue damage and physiological stress. Their feeding leads to leaf distortion, stunted growth, and ultimately reduced yield.

Figure 1. Soybean aphids on the stem of a soybean plant.

Understanding the biology and life cycle of the soybean aphid is essential for anticipating population trends and applying timely management practices. Its complex life cycle, which includes multiple generations and two host plants, enables rapid population growth and field-wide colonization under favorable conditions.

An integrated management approach, combining field scouting, economic thresholds, selective insecticide use, and conservation of natural enemies, offers the most reliable strategy for minimizing aphid-related yield loss.

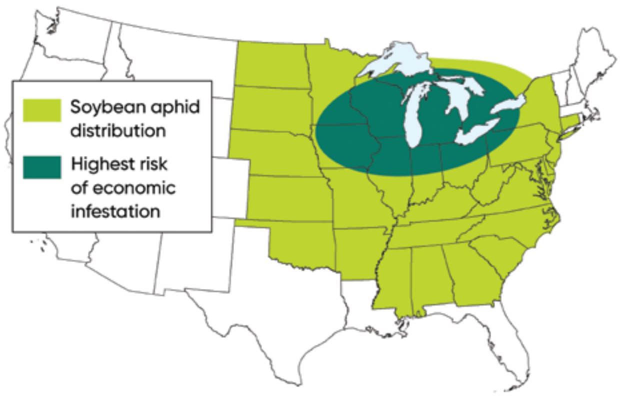


Figure 2. Soybean aphid distribution and area of greatest risk for soybean production in North America.

LIFE CYCLE

The life cycle of the soybean aphid is highly optimized for rapid population growth and is also complex, involving two different physical forms – wingless and winged – and two host plants (Figure 3). The primary host for soybean aphids is buckthorn (*Rhamnus* spp.) (Figure 4), while soybean is considered a secondary host. Buckthorn is a deciduous shrub commonly found in shelterbelts and woodlands across northern states and plays a crucial role in the soybean aphid life cycle, serving as the overwintering host when soybean plants are not available.

During the growing season, soybean aphids produce approximately 15 asexual generations on soybeans and three or more generations on buckthorns, reaching up to 18 generations per season (Figure 3).

On soybean plants, soybean aphids reproduce parthenogenetically, meaning without mating. During this reproductive phase, the population consists entirely of females, each capable of cloning themselves and producing three to eight offspring. Reproductive rate will vary depending on temperature. These offspring are born pregnant, further accelerating the aphid population's growth. This reproductive strategy reflects a highly refined system that drives rapid and large-scale population buildup under favorable conditions.

Throughout the summer, several generations of wingless female aphids develop on soybean plants. As late summer and early fall approach, winged females and males are produced. The main causes and the rate at which aphids produce winged offspring are still under investigation; studies suggest multiple factors may be involved, including increased population density, plant nutrition, temperature, plant phenology, and the presence of predators. The winged offspring are produced to facilitate population spread, colonization of other areas of the field and movement to overwintering locations. They may disperse actively by flight or passively via wind currents.

By the end of the soybean growing season, winged soybean aphids migrate back to their primary host, buckthorn, in a process regulated by photoperiod and temperature. Winged females leave soybeans to find buckthorn trees, where they feed and lay wingless, sexual females. Mating occurs when winged males from soybeans locate these wingless sexual females on buckthorn, followed by the deposition of overwintering eggs along buckthorn buds (Figure 4).

The reproductive strategy of soybean aphid is highly refined to drive rapid population buildup.

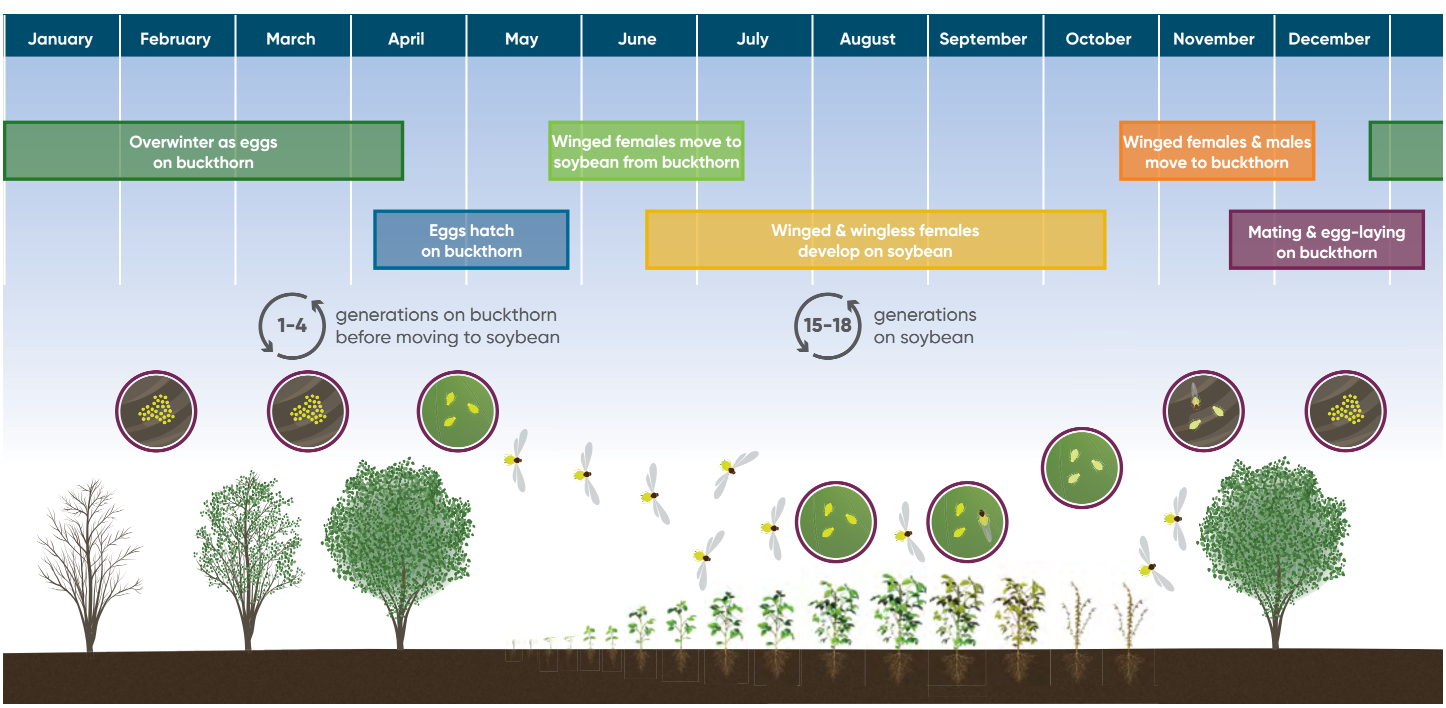


Figure 3. Soybean aphid lifecycle.

Figure 4. Top left: Common buckthorn plant (*Rhamnus cathartica*), the primary host for soybean aphid. Bottom left: Close up of leaves and berries of common buckthorn. Right: Bud on a common buckthorn branch with two soybean aphid eggs visible on it. The eggs overwinter on buckthorn and will hatch the following spring.

IDENTIFICATION

Adult soybean aphids can occur in two different forms, wingless or winged. The wingless soybean aphid has a distinctive pear-shaped body, measuring approximately 1/16th inch (1.5 mm) in length. Its color ranges from pale yellow to vibrant lime green, providing excellent camouflage on soybean plants. Later in the season, some aphids may appear pale and smaller due to the decrease of plant nutrients. A notable characteristic of adult wingless aphids is the presence of dark-tipped cornicles, resembling tiny tailpipes, located at the rear of their body (Figure 4). In contrast, winged soybean aphids have a darker thorax (central body segment) and cornicles, accompanied by transparent wings that extend noticeably beyond their abdomen (Figure 5).

Figure 5. Closeup of wingless soybean aphids with the characteristic dark-tipped cornicles resembling tailpipes at the rear of their bodies.

Soybean aphids cannot be distinguished from other aphids with the naked eye. However, the soybean aphid is the only aphid in North America known to extensively colonize soybean fields.

Figure 6. Winged soybean aphid.

LOOK-ALIKE SPECIES

Several insects can be mistaken for soybean aphids, making it important to understand their differences for effective scouting. The most common look-alike is the potato leafhopper nymph (*Empoasca fabae*), which is often misidentified as a soybean aphid due to its small size and similar light green color (Figure 7). There are some distinct differences that set them apart and are important to know to conduct effective scouting.

Figure 7. Potato leafhopper nymph (left), which can be mistaken for soybean aphid (right).

- **Body shape:** Soybean aphids are pear-shaped with small heads and large abdomens, whereas potato leafhoppers are triangular-shaped with large heads and tapered abdomens.
- **Physical features:** Aphids have cornicles at the end of their abdomen, while potato leafhoppers have hairy legs, white eyes, and no cornicles.
- **Behavior:** When disturbed, soybean aphids remain still, whereas potato leafhoppers will move or jump away.

FAVORABLE CONDITIONS

Environmental conditions are key drivers of the annual population dynamics of soybean aphids. While the presence of buckthorn, the primary overwintering host, is relatively constant from year to year and serves as a critical foundation for aphid survival, large-scale outbreaks across the Midwest occur sporadically and are primarily influenced by variable climatic factors. Mild winters and favorable temperatures during the growing season promote higher overwintering survival, rapid reproduction, and extended population growth, ultimately leading to significant field infestations.

Soybean aphid outbreaks occur sporadically and are primarily influenced by climatic factors.

Soybean aphid development is optimal within the range of 77-82°F (25-28°C). Research conducted by the University of Minnesota revealed that temperatures above 95°F (35°C) severely limit soybean aphid reproduction and reduce individual aphid survival to less than 10 days (McCornack et al., 2004). In contrast, ideal temperature conditions (77-82°F) enable soybean aphids to live for 20 or more days and maximize reproduction.

Monitoring environmental conditions, particularly temperature trends, is essential for predicting and managing soybean aphid infestations efficiently.

FACTORS INFLUENCING SOYBEAN APHID POPULATIONS

- **Temperature:** Soybean aphids thrive in moderate temperatures, with optimal population growth occurring between 77-82°F. Extreme heat, particularly above 95°F, can slow reproduction and increase mortality.
- **Rainfall:** Intense rainfall can physically dislodge aphids from plants, reducing their numbers. However, unless rainfall is prolonged or frequent, aphid populations often recover quickly.
- **Moisture:** Moderate moisture levels support healthy plant growth, indirectly benefiting aphids by ensuring a stable food source. However, excessive moisture can promote fungal pathogens that reduce aphid survival.
- **Natural Enemies:** Predators like lady beetles, lacewings, and pirate bugs, along with parasitoid wasps and fungal pathogens, play a crucial role in aphid population control. Disruptions caused by overuse of insecticide or environmental changes can decrease these natural defenses, leading to aphid outbreaks.

DAMAGE TO SOYBEAN

Soybean aphids primarily feed on the underside of newly emerged leaves of soybean plants (Figure 8), where nutrient concentrations are highest. As populations grow, aphids spread throughout the plant, feeding on various tissues.

Figure 8. Soybean aphids colonizing multiple parts of the soybean plant, including leaves and stems, demonstrating their ability to feed across the entire canopy.

Equipped with needle-like mouthparts, soybean aphids extract plant nutrients, causing localized leaf tissue damage and disrupting plant physiology. Their feeding activity produces honeydew, a sugary substance that promotes sooty mold growth on leaf surfaces (Figure 9), reducing photosynthetic capacity.

Aphid feeding leads to various plant injuries including yellowing and distortion of leaves, stunted plant growth, leaf puckering and warping, reduced pod and seed counts, aborted flowers or pods, reduced plant vigor and growth rates, internode shortening, and plant dwarfing (Figure 10).

Figure 9. Honeydew accumulation from high aphid populations. Heavy aphid infestations result in visible honeydew deposits on soybean leaves, which can lead to sooty mold development and reduced photosynthesis.

Figure 10. Visible soybean damage from untreated aphid infestations. Field comparison showing significant plant stress and early senescence in untreated soybean (right), contrasted with healthier plants in the treated area (left).

Furthermore, soybean aphids can transmit several plant viruses, such as soybean mosaic virus, alfalfa mosaic virus, and others. There are no studies indicating that these viral diseases significantly impact soybean yield; therefore, they have not been considered in aphid management strategies.

As with many fluid-feeding insects, soybean aphid-induced plant injury can remain undetected until severe symptoms and yield loss occur. Regular scouting is crucial when soybean aphid populations are expected allowing timely detection for proper management.

MANAGING SOYBEAN APHID

SCOUTING

Current management recommendations for soybean aphids emphasize scouting and threshold-based application of foliar insecticides. To reduce the risk of economic injury, regular sampling during the growing season is crucial for tracking population growth rate and informing timely management decisions. Starting in June, it is recommended to monitor how populations are progressing on a weekly basis. If weather conditions are favorable for aphid population growth, more frequent scouting is recommended, as population can double quickly under ideal conditions.

The recommended treatment threshold is 250 aphids per plant and increasing, with over 80% of plants infested. This threshold is based on academic research that considered aphid population dynamics, potential yield loss, and the effectiveness of timely insecticide applications (DiFonzo, 2016; Koch et al., 2016). Fields approaching this threshold should be closely monitored to make timely insecticide application decisions. The 250 aphid per plant threshold is considered quite cautious, as it takes population levels nearly double that to cause measurable loss of soybean yield. There is no biological or economic justification for spraying at population levels below the recommended threshold (DiFonzo, 2016; Varenhorst et al., 2020).

The recommended treatment threshold for soybean aphid is 250 aphids per plant and growing with over 80% of plants infested.

To ensure comprehensive coverage of the field, it is recommend to use an M (zigzag) pattern scouting approach and to sample at least 20-30 individual plants per field, while avoiding sampling from field edges. This method allows informed decisions based on the field as a whole, rather than relying on small and potentially biased samples. When scouting individual plants, start at the base and inspect upward, thoroughly examining stems and leaves.

The recommended economic threshold should be used up through the R5 soybean growth stage. Due to changes in plant physiology, such as reduced production of new leaves and an increase in older tissue, soybeans at the R6 growth stage exhibit a higher tolerance to soybean aphid infestations. Additionally, because of the biology and behavior of aphids, infestations during late reproductive stages are uncommon. Consequently, no economic threshold has been established for aphid management in R6 soybeans. However, in years with severe outbreaks, yield losses may still occur during early R6.

SPRAYING CONSIDERATIONS

Once the threshold is reached, it's important to continue monitoring to determine if the population is growing or stabilizing. This threshold serves as a trigger to prepare for potential insecticide application within seven days or less, depending on population growth rates. If conditions are ideal for aphid growth, this timeframe may be shorter.

It is essential to avoid spraying at low population levels, as damage to crops typically occurs at higher aphid densities. Spraying too early can lead to wasted money and insecticide, as well as accelerate development of resistance in insect populations. Instead, continue scouting fields with lower infestations to make informed, economically smart application decisions. This approach helps minimize unnecessary chemical use and preserves beneficial insects.

Table 1. Foliar insecticide products for soybean aphid management.

Insecticide Name	Active Ingredients	Active Pyrethroid	IRAC MOA Groups	Mode of Action	Rate
Sefina®	afidopyropen		9D	TRPV (transient receptor potential vanilloid) channel modulator	3.0 fl oz/A
Sivanto® Prime	flupyradifurone		4D	nAChR agonist (butenolide class)	7.0-14.0 fl oz/A
Transform® WG	sulfoxaflor		4C	nAChR modulator (distinct from neonicotinoids)	0.75-1.0 fl oz/A
Endigo® ZC	lambda-cyhalothrin + thiamethoxam	lambda-cyhalothrin	3A + 4A	sodium channel modulator + nAChR agonist	3.5-4.0 fl oz/A
Leverage® 360	beta-cyfluthrin + imidacloprid	beta-cyfluthrin	3A + 4A	sodium channel modulator + nicotinic acetylcholine receptor (nAChR) agonist	2.8 fl oz/A
Renestra®	alpha-cypermethrin + afidopyropen	alpha-cypermethrin	3A + 9D	sodium channel modulator + TRPV (transient receptor potential vanilloid) channel modulator	6.8 fl oz/A
Ridgeback®	bifenthrin + sulfoxaflor	bifenthrin	3A + 4C	sodium channel modulator + nAChR modulator (distinct binding site from 4A)	8.6-10.3 fl oz/A

FOLIAR INSECTICIDE SELECTION AND CONSIDERATIONS

- **Insecticide Mode of Action (MOA):** Use an insecticide with a proven MOA against aphids and rotate different MOA when possible. This helps prevent resistance buildup and maintains long-term control options.
- **Residual Activity:** Some insecticides offer extended residual control, reducing the need an additional application. Shorter residual insecticides require additional monitoring to determine if reapplication is necessary.
- **Selectivity and Impact on Beneficial Insects:** Avoid broad-spectrum insecticides that harm beneficial insects. Using selective products helps maintain a balanced ecosystem and supports natural aphid suppression.
- **Application Timing and Coverage:** Apply insecticides only when aphid populations exceed the economic threshold to maximize cost-effectiveness. Ensuring thorough coverage of plant surfaces enhances efficacy.
- **Weather and Environmental Considerations:** Avoid spraying during windy conditions to minimize drift and off-target impact. Temperature and humidity also affect insecticide performance and evaporation rates.
- **Pre-Harvest Interval (PHI) and Label Compliance:** Scout fields up to the R5 stage to avoid late-season treatment challenges. PHI for insecticides labeled for soybean aphid ranges from 7 to 60 days. Late-season applications require insecticides with a short PHI, especially for early maturity soybean varieties.
- **Tank Mixing with Herbicides:** Adding an insecticide to an early herbicide application is not recommended because it may reduce beneficial insects. This can also result in suboptimal timing for both weed and insect control.
- **Post-Application Monitoring:** Continuing to monitor soybean aphid populations after insecticide application is crucial to evaluate the effectiveness of the treatment and to detect potential signs of insecticide resistance.

Avoiding insecticide applications at low infestation levels is critical, as it gives natural enemies, such as predators, parasitic wasps, and fungal pathogens, a chance to control aphid populations. Allowing these organisms to act can often decrease the need for chemical control (DiFonzo, 2016).

INSECTICIDE OPTIONS

When insecticide application becomes necessary to protect soybeans against soybean aphids, it is important to carefully evaluate and select the most suitable options. While various products are available on the market for aphid control, most fall into three primary chemical classes: organophosphates, pyrethroids, and neonicotinoids. However, many products share the same active ingredient group, effectively limiting chemical diversity and increasing the risk of resistance development.

Soybean aphid resistance to pyrethroid insecticides began emerging around 2015, and in recent years, multiple studies have confirmed resistance through laboratory bioassays and field trials. These studies have documented reduced field efficacy of pyrethroids in numerous regions (Hanson et al., 2017; Menger et al., 2022; Knodel and Beauzay, 2024).

In response, the industry has introduced insecticides with novel modes of action, such as sulfoximines, butenolides, and pyropenes, offering targeted aphid control and improved resistance management (Table 1). For example, sulfoxaflor (Transform WG® by Corteva Agriscience) has shown excellent efficacy against soybean aphids and causes less disruption to beneficial insect populations compared to broad-spectrum pyrethroids (Tran et al., 2016).

Pyrethroids are currently not recommended for aphid control unless other pests – such as caterpillars, grasshoppers, or bean leaf beetles, which pyrethroids effectively control – also exceed economic thresholds. In fields with mixed infestations, products that combine pyrethroids with other active ingredients effective against soybean aphid may be considered. However, this approach should be reserved for situations where multiple pest thresholds are met.

To ensure effective pest control and delay resistance development, always consider pest thresholds, active ingredient mode of action, spectrum of activity, and impact on beneficial species when selecting insecticides. Preemptive insecticide treatments made prior to reaching the economic threshold or application of broad-spectrum insecticides can unintentionally increase aphid pressure or cause secondary outbreaks of soybean aphids and other pests, such as spider mites, due to the reduction or elimination of natural enemies.

INSECTICIDE SEED TREATMENTS

Some insecticidal seed treatments are labeled for soybean aphid control and have shown efficacy – especially when fields are planted late – providing protection for about 30 to 40 days after planting. Research has demonstrated seed treatment effectiveness in reducing early aphid infestations and improving early plant vigor, contributing to healthier stands. However, it is important to recognize the limitations of seed treatments. They are not a season-long solution for aphids since late infestation or reinfestation can occur.

The timing of soybean planting relative to aphid colonization is a key factor in determining the effectiveness of seed treatments. Fields with a history of early soybean aphid infestations, those near abundant overwintering hosts (buckthorn), or areas prone to early infestations are strong candidates. Research recommendations are to use insecticidal seed treatments to delay soybean aphid population establishment, rather than as a standalone control measure. Once the protection window fades, aphid populations can rebound, making it essential to monitor the crop and determine if additional measures are needed. Using seed treatment for early defense, followed by scouting and timely foliar sprays, is a recommended approach. Seed treatments buy time by reducing the intensity of early infestations, which can make later management easier. Once the window of seed treatment efficacy has passed, traditional management strategies – including scouting and timely foliar insecticides – remain essential.

NATURAL ENEMIES

Field studies have revealed a diverse community of natural enemies that help suppress soybean aphid population growth. These natural enemies fall into three main categories: predators, parasitoids, and pathogens, which not only target soybean aphids but also other insect pests (Figure 11).

PREDATORS

Predators are the most abundant group of natural enemies that contribute to soybean aphid control. These insects actively feed on aphids at various life stages, helping to slow population growth, particularly during hot weather. Key predators include:

- Lacewings (*Chrysoperla* spp.)
- Lady beetles (*Coccinella septempunctata, Harmonia axyridis, Hippodamia convergens*)
- Syrphid flies (Hoverflies – Syrphidae family, e.g., *Eupeodes americanus*, *Toxomerus* spp.)
- Pirate bugs (*Orius insidiosus*)
- Damsel bugs (*Nabis* spp.)

PARASITOIDS

Parasitoids are wasps that lay their eggs in or on soybean aphid. The immature parasitoids will eventually kill their aphid hosts. A clear sign of parasitoid activity is the presence of aphid "mummies" – light brown, black, or white swollen aphids that are sheltering immature parasitoids (Figure 12). Once the adult wasps emerge from the soybean aphid, they reproduce and continue parasitizing more aphids, contributing to natural population control.

Figure 11. Natural enemies of the soybean aphid. The lady beetle (Coccinellidae, left) and parasitic wasps (Aphidiinae, right) play a critical role in regulating soybean aphid populations through predation and parasitism.

Following the initial appearance of soybean aphids in the Midwest, the USDA and university researchers made extensive efforts to introduce parasitic wasp species as a biological control method, given their previous success with other insect pests. However, these introduced wasps failed to establish, likely due to environmental challenges such as the cold winters in the Midwest. Later, the accidental introduction of *Aphelinus certus* showed promising results, with evidence that this wasp can significantly reduce the population growth rate (Kaser and Heimpel, 2018). Ongoing studies are being conducted to better understand its impact and effectiveness; however, comprehensive field data are still limited as research efforts are relatively new.

Figure 12. Left: A colony of soybean aphids with numerous nymphs and wingless adults, white shed skins, and dead aphids killed by a fungus, which are fuzzy brown in appearance. Right: A soybean aphid attacked by a parasitic wasp larva produces a tan, swollen "mummy", which contains the developing wasp.

PATHOGENS

Under suitable environmental conditions, fungal pathogens can infect and kill soybean aphids, sometimes leading to dramatic population declines. The presence of "fuzzy" aphid skeletons indicate that fungal pathogens are present in the field (Figure 12).

HOST PLANT RESISTANCE

Research on host plant resistance to soybean aphids began shortly after their arrival in North America and led to the discovery of multiple genes (known as resistance to *Aphis glycines*, or *Rag* genes) that confer antibiosis to soybean aphids. The utility of these genes has been challenged by aphid biotypes capable of overcoming these resistance genes already present in the United States. Consequently, host plant resistance has not been heavily utilized for soybean aphid management. However, the widespread occurrence of insecticide resistance in aphid populations has led to renewed interest in host plant resistance as a management tactic (Tilmon et al., 2021). Selecting elite, high-yielding soybean varieties adapted to the region is always recommended. This approach lays a strong foundation for healthy plant growth and consistent emergence, helping protect the crop from environmental stressors.

Cotton/Soybean Rotations in Reniform Nematode Infested Fields

JONATHAN SIEBERT, PH.D., AREA AGRONOMY LEADER

KEY FINDINGS

- Research studies were conducted to study the value of reniform and root-knot nematode resistance traits in cotton varieties in a cotton/soybean rotation.
- In the presence of moderate reniform nematode populations, REN + RKN trait cotton varieties yielded an average of 500 lbs/acre more than cotton without a nematode trait.
- Yields of soybean following cotton varieties with REN + RKN traits increased by an average of 8 bu/acre.

BACKGROUND

- Reniform nematode (*Rotylenchulus reniformis*) is widespread throughout the Southern United States and is a prevalent economic pest on cotton acres, potentially costing growers more than $60 per acre in management expense and yield loss.
- The southern root-knot nematode (*Meloidogyne incognita*) is also a major pest of cotton, as well as several other crops due to its wide host range.
- Even at moderate population levels, reniform nematode and root-knot nematode can reduce cotton yields enough for economic impact – sometimes without severe symptomology being apparent in the field.
- While seed treatments and other chemical control measures can provide short-term nematode suppression, the best management approach in cotton is to integrate nematode resistant varieties that reduce overall reniform nematode and root-knot nematode populations.
- In soybeans, the negative impacts of root-knot nematode and soybean cyst nematode are well known by producers, but reniform nematode is often overlooked as an economic threat.
- Many soybean varieties offer native resistance to root-knot nematode and soybean cyst nematode, but there are currently no soybeans that offer reniform nematode resistance.

RESEARCH OBJECTIVES

- Two recent research studies led by Assistant Research Professor Dr. Tessie Wilkerson of Mississippi State University were conducted to study the value of reniform and root-knot nematode resistance traits in cotton varieties in a cotton/soybean rotation.
- The first study evaluated the efficacy of nematode resistance traits and seed treatments for protecting cotton yields under high reniform nematode pressure.
- The second study focused on the effect of nematode resistance traits on cotton yield, reniform nematode population levels, and yield of soybeans grown the following season.

METHODS

EXPERIMENT 1

- Research was conducted over three years (2020-2022) near Stoneville, MS on Bosket VFSL soil under continuous cotton production with high reniform nematode population levels.
- The experiment was conducted at two locations each year for a total of six site-years of data.
- Each experiment was set up as a two-way factorial with three different nematode trait packages and two different seed treatments.
- **Nematode Traits**
  - No nematode trait
  - Root-knot nematode resistance (RKN)
  - Root-knot + reniform nematode resistance (RKN + REN)
- **Seed Treatments**
  - Base seed treatment
  - PhytoGen TRiO™ seed treatment
- Soil samples were collected from each treatment at the end of the season and tested for reniform nematodes to assess population levels.

EXPERIMENT 2

- Research was conducted over three years (2022-2024) near Stoneville, MS on Bosket VFSL soil with high reniform nematode population levels.

- In the first year of the cotton/soybean rotation, large plots (12 row x 600 ft) were planted with four different cotton varieties:
  - Competitive variety – no nematode trait
  - PhytoGen variety – 1 gene RKN trait
  - PhytoGen variety – 2 gene RKN trait
  - PhytoGen variety – RKN (1 or 2 gene) + REN trait
- Soil samples were collected at planting and harvest and tested for reniform nematodes to measure changes in population levels over the course of the growing season.
- In the second year of the cotton/soybean rotation, each of the large plots from the prior season was subdivided into a small-plot trial with eight different soybean varieties (two of which had resistance to root-knot nematodes).

RESULTS

EXPERIMENT 1

- Seed treatment did not influence stand counts, early season vigor, cotton yield, or reniform nematode populations.
- Yield was similar between cotton varieties with no nematode trait and varieties with a RKN trait (Figure 1).
- Cotton varieties with REN + RKN traits yielded an average of 175 lbs/acre more than those with no nematode trait or RKN trait only (Figure 1).
- End of season reniform nematode population levels averaged 30% lower in plots with REN + RKN trait varieties.

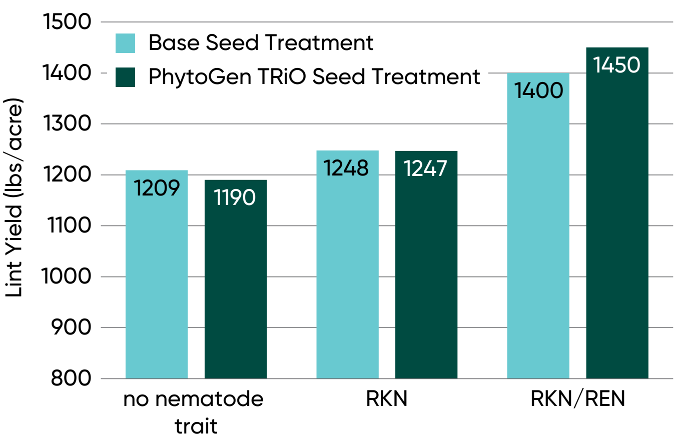


Figure 1. Average cotton yield (lbs/acre) over three years in two high reniform nematode locations as affected by seed treatment and resistance traits for root-knot (RKN) and reniform (REN) nematodes.

EXPERIMENT 2

- In the presence of moderate reniform nematode populations, REN + RKN traited cotton varieties yielded an average of 500 lbs/acre more than cotton without a nematode trait (Figure 2).
- Cotton varieties with RKN traits outyielded cotton without a nematode trait by 100 lbs/acre and 200 lbs/acre; for single and dual gene RKN resistant varieties, respectively (Figure 2).
- Reniform nematode populations increased by 500% over one year when cotton without nematode traits was planted (Figure 3).
- Yields of soybean following cotton varieties with RKN traits (single or dual gene) increased by an average of 4 bu/acre across varieties (Figure 4).
- Yields of soybean following cotton varieties with REN + RKN traits increased by an average of 8 bu/acre across varieties (Figure 4).
- The highest yield for each of the eight soybean varieties was achieved when planted following REN + RKN traited cotton.
- The two soybean varieties with root-knot nematode resistance did not have a yield advantage over non-RKN varieties in reniform nematode infested fields.

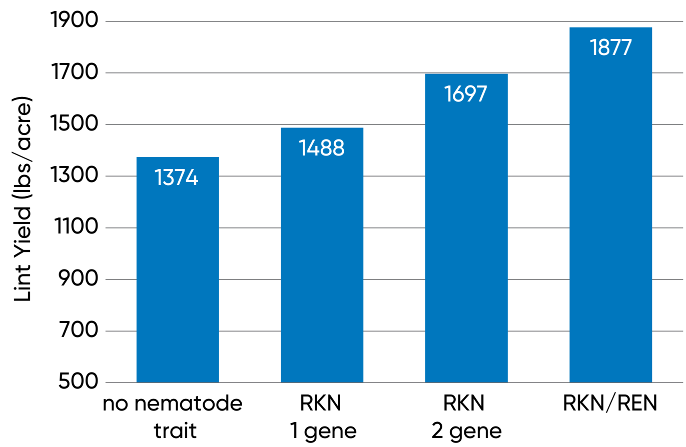


Figure 2. Average cotton yields (lbs/acre) of varieties with different root-knot (RKN) and reniform (REN) nematode resistance traits.

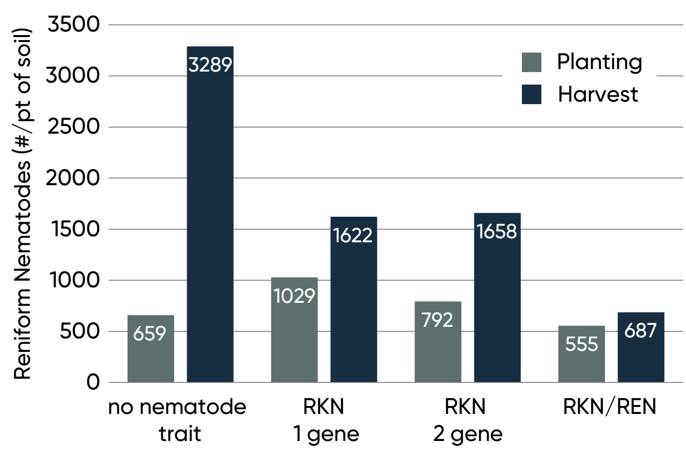


Figure 3. Average reniform nematode population levels (number/pt of soil) at planting and harvest of cotton varieties with different root-knot (RKN) and reniform (REN) nematode resistance traits.

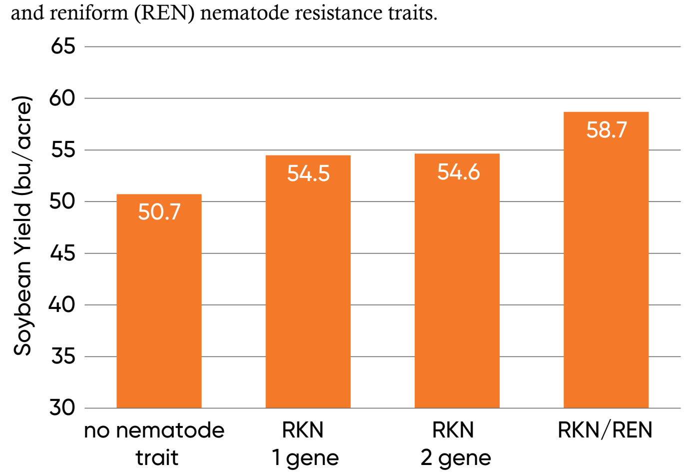


Figure 4. Average yield of eight soybean varieties planted following cotton with different root-knot (RKN) and reniform (REN) nematode resistance traits.

Figure 5. Roots of cotton plants exposed to reniform nematode. Plants on the left are a variety with reniform nematode resistance and plants on the right are a variety without reniform nematode resistance.

CONCLUSIONS

- Reniform nematodes are an often-overlooked pest that can negatively impact yield in both cotton and soybeans.
- One reason reniform nematode populations can devastate cotton and soybean yields is because populations can increase dramatically in one season.
- In these trials, reniform nematode populations increased fivefold in one season with a non-resistant cotton variety.
- RKN-only varieties provided limited benefit against reniform nematode, and population levels were still able to double over the season.
- The only cotton variety that successfully managed reniform nematode populations was the PhytoGen® brand variety with REN + RKN resistance.
- The yield benefits of planting a REN + RKN cotton variety carried over into soybeans planted the following season, demonstrating that successful management of reniform and root-knot nematodes in a cotton-soybean rotation begins with planting resistant cotton varieties.

Soybean Cyst Nematode Populations in Minnesota and Wisconsin

BRENT LARSON, M.S., FIELD AGRONOMIST — **JAY ZIELSKE,** FIELD AGRONOMIST

KEY FINDINGS

- Soybean cyst nematode (SCN) reproduction on soybean varieties with PI88788 and Peking SCN resistance was compared accross 30 locations.
- SCN populations increased substantially on the PI88788 variety at several locations but remained steady or decreased on the Peking variety at most locations.
- Soybean growers can reduce the risk of SCN damage by planting resistant varieties, rotating between PI88788 and Peking resistance sources, and using a nematode protectant seed treatment.

OBJECTIVE AND STUDY DESCRIPTION

- Soybean cyst nematode (SCN) samples were collected from 30 soybean fields in Minnesota and Wisconsin to determine SCN population levels.
- Study locations were sampled twice during the 2024 growing season, in June and again in September, to assess changes in SCN population levels during the growing season.
- Each study location included a soybean variety with PI88788 SCN resistance and one with Peking SCN resistance planted side by side, allowing a comparison of SCN population changes between the two varieties.
- Sample cores were taken to a depth of approximately 6 inches. Subsamples from across the PI88788 or Peking variety areas were blended into composite soil samples and submitted to Western Laboratories for analysis.

RESULTS

- SCN eggs were detected at at 24 of the 30 study locations with the June sampling and 26 of 30 locations with the September sampling (Table 1).
- Across 10 study locations with moderate to high SCN population levels (based on June sampling) SCN egg counts increased by an average of 251% from June to September on the soybean variety with PI88788 SCN resistance and decreased by an average of 8% on the soybean variety with Peking SCN resistance (Figure 1).
- Among moderate to high SCN locations, SCN eggs counts on the PI88788 variety increased substantially (>100%) at five locations and decreased at only one.
- SCN eggs counts on the Peking variety increased at only one location and were steady or decreased at all other locations.

Table 1. SCN population levels at study locations (based on the higher of the two sample counts) at the June and September sampling timings.

SCN Population (eggs/100 cc of soil)	June Sampling	September Sampling
	number of locations	
Zero	6	4
Low (<500 eggs)	14	8
Moderate (500-2000)	6	10
Mod-High (2000-5000)	4	7
High (5000-8000)	0	1

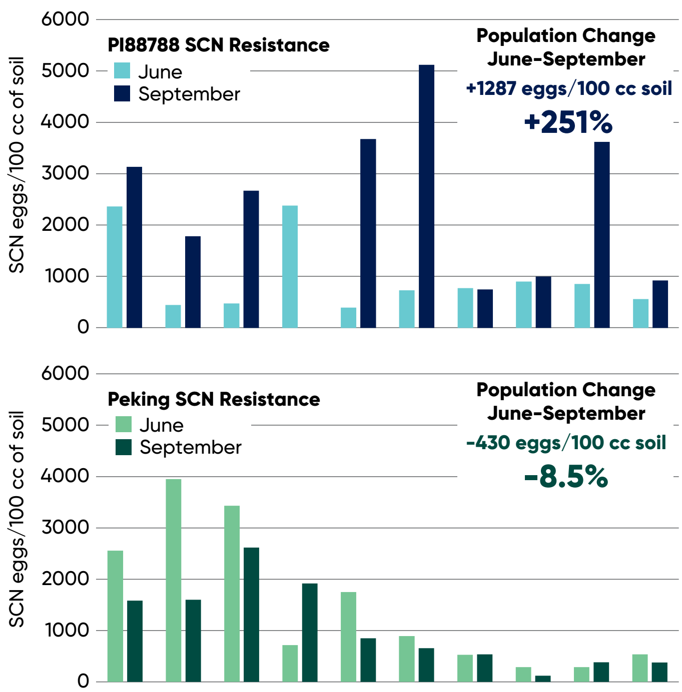


Figure 1. SCN egg counts in June and September samples at study locations with moderate to high SCN population levels.

SCN MANAGEMENT

DECREASED EFFICACY OF PI88788 RESISTANCE

- Beginning in the 1990s, the widespread availability of soybean varieties with PI88788 SCN resistance provided a largely effective management tool for SCN in North America.
- In recent years however, PI88788 has been losing its effectiveness as a SCN management tool.

- Levels of reproduction on PI88788 among Midwestern SCN populations have increased steadily over the last two decades – results from the current study are consistent with this trend.
- These results show that SCN populations are adapting to PI88788 resistance and the resistance is considerably less effective now compared to when it was introduced in the early 1990s.

MANAGEMENT RECOMMENDATIONS

- The SCN Coalition provides the following recommendations for developing a plan to manage SCN (www.thescncoalition.com):
- Test your fields to know your numbers.
- Rotate resistant varieties.
- Rotate to non-host crops.
- Consider using a nematode protectant seed treatment.

ROTATE RESISTANT VARIETIES

- If your SCN populations are found to be increasing, select varieties with sources of resistance other than PI88788.
- The most common source of resistance other than PI88788 is PI548402 or "Peking" resistance.

ROTATE TO NON-HOST CROPS

- Rotation to a non-host crop to reduce SCN pressure.
- Corn, alfalfa and small grains are the most common non-crop choices for reducing SCN numbers.
- Since SCN persists in the soil for many years, it cannot be totally eradicated by rotation.

SEED TREATMENTS

- Several nematicide seed treatments with activity against SCN are currently available and can provide added protection when used with a SCN-resistant soybean variety.
- Nematicide seed treatments are intended to supplement current SCN management strategies, not replace them. Seed treatments should therefore be used in coordination with SCN-resistant varieties and rotation to non-host crops.

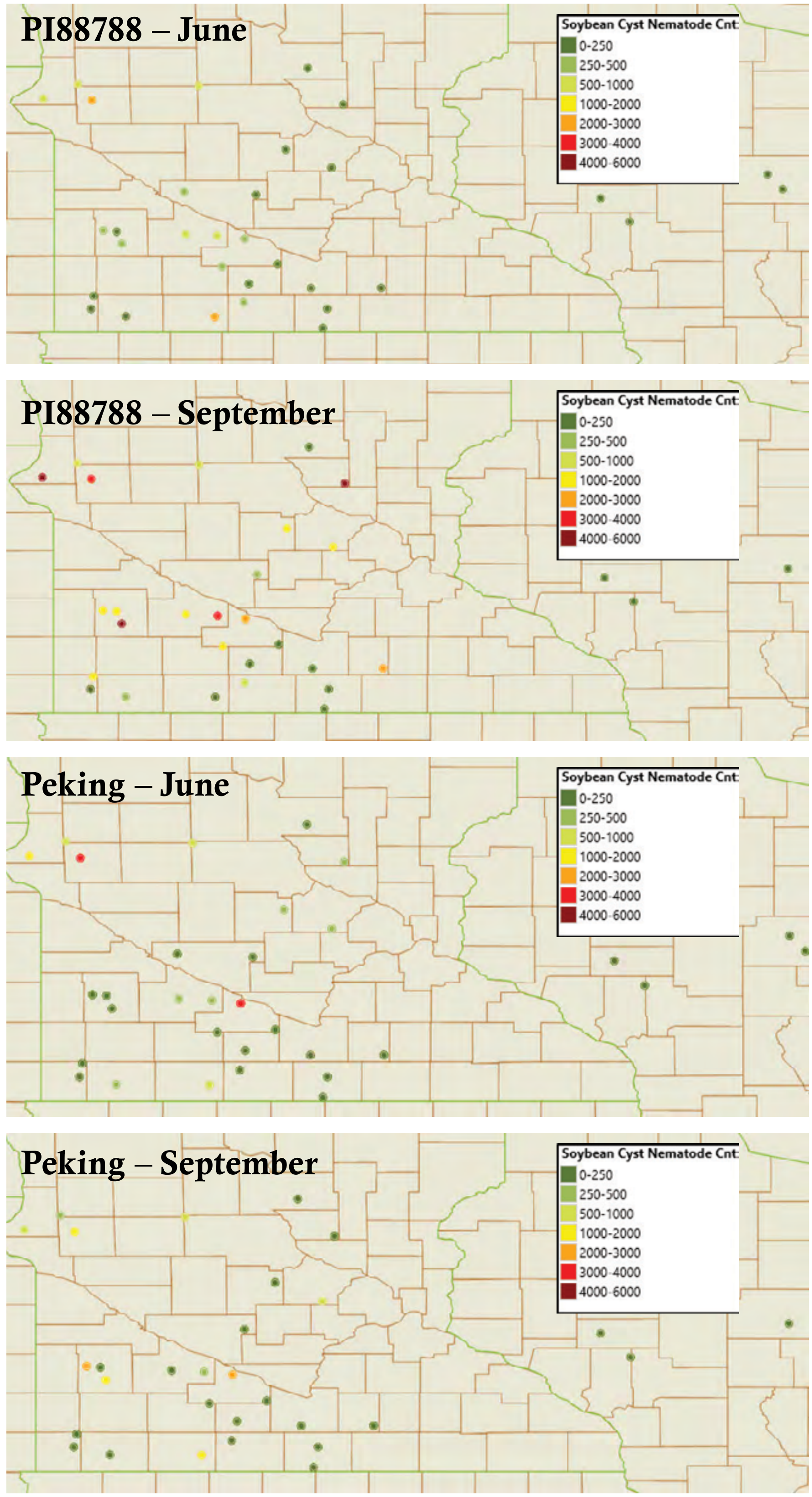


Figure 2. Study locations showing SCN egg counts in June and September on PI88788 and Peking varieties.

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PCE – Powercore® Enlist® Refuge Advanced® corn products with HX1, VTP, ENL, 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 PowerCore Enlist Refuge Advanced products.

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.

POWERCORE® is a registered trademark of Bayer Group. POWERCORE® multi-event technology developed by Corteva Agrisciene and Bayer Group.

LibertyLink® and the Water Droplet Design are registered trademarks of BASF.

®Roundup, Roundup Ready and Roundup Ready 2 Xtend® are registered trademarks of Bayer Group used under lisence.

Always follow IRM, grain marketing and all other stewardship practices and pesticide label directions. B.t. products may not yet be registered in all states. Check with your seed representative for the registration status in your state.

Following burndown, Enlist Duo® and Enlist One® herbicides with Colex-D® technology are the only herbicides containing 2,4-D that are authorized for preemergence and postemergence use with Enlist® crops. Consult Enlist® herbicide labels for weed species controlled. Enlist Duo and Enlist One herbicides are not registered for use or sale in all states and counties; are not registered in AK, CA, CT, HI, ID, MA, ME, MT, NH, NV, OR, RI, UT, VT, WA and WY; and have additional subcounty restrictions in AL, GA, TN and TX, while existing county restrictions still remain in FL. All users must check “Bulletins Live! Two” no earlier than six months before using Enlist One or Enlist Duo. To obtain “Bulletins,” consult epa.gov/espp/, call 1-844-447-3813, or email ESPP@epa.gov. You must use the “Bulletin” valid for the month and state and county in which Enlist One or Enlist Duo are being applied. Contact your state pesticide regulatory agency if you have questions about the registration status of Enlist® herbicides in your area. ALWAYS READ AND FOLLOW PESTICIDE LABEL DIRECTIONS. IT IS A VIOLATION OF FEDERAL AND STATE LAW TO USE ANY PESTICIDE PRODUCT OTHER THAN IN ACCORDANCE WITH ITS LABELING. ONLY USE FORMULATIONS THAT ARE SPECIFICALLY LABELED FOR SUCH USE IN THE STATE OF APPLICATION. USE OF PESTICIDE PRODUCTS, INCLUDING, WITHOUT LIMITATION, 2,4-D-CONTAINING PRODUCTS NOT AUTHORIZED FOR USE WITH ENLIST CROPS, MAY RESULT IN OFF-TARGET DAMAGE TO SENSITIVE CROPS/ AREAS AND/OR SUSCEPTIBLE PLANTS, IN ADDITION TO CIVIL AND/OR CRIMINAL PENALTIES. Additional product-specific stewardship requirements for Enlist crops, including the Enlist Product Use Guide, can be found at www.traitstewardship.com.

Always follow stewardship practices in accordance with the Product Use Guide (PUG) or other product-specific stewardship requirements including grain marketing and pesticide label directions. Varieties with BOLT® technology provide excellent plant-back flexibility for soybeans following application of sulfonylurea (SU) herbicides as a component of a burndown program or for double-crop soybeans following SU herbicides applied to wheat the previous fall.

DO NOT APPLY DICAMBA HERBICIDE IN-CROP TO SOYBEANS WITH Roundup Ready 2 Xtend® technology unless you use a dicamba herbicide product that is specifically labeled for that use in the location where you intend to make the application. IT IS A VIOLATION OF FEDERAL AND STATE LAW TO MAKE AN IN-CROP APPLICATION OF ANY DICAMBA HERBICIDE PRODUCT ON SOYBEANS WITH Roundup Ready 2 Xtend® technology, OR ANY OTHER PESTICIDE APPLICATION, UNLESS THE PRODUCT LABELING SPECIFICALLY AUTHORIZES THE USE. Contact the U.S. EPA and your state pesticide regulatory agency with any questions about the approval status of dicamba herbicide products for in-crop use with soybeans with Roundup Ready 2 Xtend® technology.

ALWAYS READ AND FOLLOW PESTICIDE LABEL DIRECTIONS. Soybeans with Roundup Ready 2 Xtend® technology contain genes that confer tolerance to glyphosate and dicamba. Glyphosate herbicides will kill crops that are not tolerant to glyphosate. Dicamba will kill crops that are not tolerant to dicamba.

IMPORTANT NOTICE: No dicamba herbicide has been approved for use in-crop with seed containing Roundup Ready® Xtend Technology for the 2025 spray season at this time. No dicamba herbicide may be used in-crop with this seed unless and until such use is approved or specifically permitted.

Corteva Agriscience is a member of Excellence Through Stewardship® (ETS). Corteva Agriscience products are commercialized in accordance with ETS Product Launch Stewardship Guidance and in compliance with the Corteva Agriscience policies regarding stewardship of those products. In line with these guidelines, our product launch process for responsible launches of new products includes a longstanding process to evaluate export market information, value chain consultations, and regulatory functionality. Growers and end-users must take all steps within their control to follow appropriate stewardship requirements and confirm their buyer’s acceptance of the grain or other material being purchased. For more detailed information on the status of a trait or stack, please visit www.biotradestatus.com.

STS® APPROVED HERBICIDE STATEMENT: This variety contains a trait providing enhanced tolerance to labeled specific sulfonylurea soybean herbicides. The STS® gene will not safeguard this variety against other herbicide chemistries which are labeled to be used only over-the-top of crops that have a different and specified herbicide resistant gene. Always read and follow herbicide directions prior to use. Not all herbicides are registered for sale or use in all states or counties in the United States or all provinces in Canada. Contact your local regulatory agency to determine if a product is registered for sale or use in your area. Always read and follow label directions. ACCIDENTAL APPLICATION OF INCOMPATIBLE HERBICIDES TO THIS VARIETY COULD RESULT IN TOTAL CROP LOSS. YOU MUST SIGN A TECHNOLOGY USE AGREEMENT AND READ THE PRODUCT USE GUIDE PRIOR TO PLANTING. The purchase of these seeds includes a limited license to produce a single soybean crop in the United States (or other applicable country). The use of seed from such a crop or the progeny thereof for propagation or seed multiplication or for production or development of a hybrid or different variety of seed is strictly prohibited. Resale or transfer of the seed is strictly prohibited.

LL - Contains the LibertyLink® gene for resistance to glufosinate.

The transgenic soybean event in Enlist E3® soybeans is jointly developed and owned by Corteva Agriscience and M.S. Technologies L.L.C.

Components of LumiGEN® seed treatments for soybeans are applied at a Corteva Agriscience production facility or by an independent sales representative of Corteva Agriscience or its affiliates. Not all sales representatives offer treatment services, and costsand other charges may vary. See your sales representative for details. Seed applied technologies exclusive to Corteva Agriscience and its affiliates. ILEVO® HL is a registered trademarks of BASF.

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