

2025



AGRONOMY

RESEARCH SUMMARY

Pioneer Agronomy Sciences



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CONTRIBUTING AUTHORS

PIONEER AND CORTEVA AGRISCIENCE

Logan Anderson, *Senior Research Associate*

Logan is a Senior Research Associate in the Trait Characterization and Development team within the Biotechnology department. His primary area of work is leading small plot research implementation and trait collection for crop modeling, cropping systems, and environmental measurement trials.

Peter Baas, Ph.D., *Biostimulant Biology Characterization Leader*

Peter Baas is the Biostimulant Biology Characterization Leader within the Plant Health Discovery group at Corteva Agriscience, located in Indianapolis, IN. Peter earned his B.S. in biology and M.S. in plant biology at Utrecht University in Utrecht, Netherlands, and Ph.D. in soil microbial ecology from the University of Georgia.

April Battani, *Senior Graphic Designer*

April earned a B.A. in Graphic Design and a B.A. in Creative Advertising from Drake University in Des Moines, Iowa. She currently works as a Senior Graphic Designer for the Creative Services team supporting Agronomy Sciences. Her role includes the design, publication, and project management of web-based and printed materials.

Jim Bing, Ph.D., *Program Leader, Insect Control Traits*

Jim has held various roles in Dow AgroSciences and Corteva Agriscience traits R&D since 1990. At Dow AgroSciences, he led the biology team responsible for characterizing events that became the Herculex® family of insect resistance traits. He received his B.S. in Forest Management and Master's in Forest Entomology at Stephen F. Austin State University, and his Ph.D. in Entomology/Host Plant Resistance from Iowa State University.

Dann Bolinger, M.S., *Dairy Specialist*

Dann earned his B.S. and M.S. in Animal Science from Purdue University. He has served as Pioneer Dairy Specialist based in Michigan since 2007. Previously, Dann spent 10 years as a Dairy Extension Educator with Michigan State University. He also has experience in research and commercial dairy herd management.

Lucas Borrás, Ph.D., *Senior Research Scientist*

Lucas Borrás is a Senior Research Scientist in Farming Solutions & Digital, 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.

Liam Bracken, CCA-ON, *Territory Manager*

Liam earned his B.S. in Agricultural Sciences at the University of Guelph. He has held various roles with Pioneer starting in university with summer positions, to Associate Territory Manager for Eastern Ontario and Territory Manager/Agronomist for East Coast of Canada. Liam resides on his family farm in Eastern Ontario.

Linda Byrum, *Staff Associate Investigator*

Linda Byrum is a Staff Associate Investigator working for the Seed Business Unit, and has been with Corteva Agriscience for 29 years. Linda is currently responsible for product characterization at the Grain Quality and Global Forages Lab in Johnston, Iowa.

Matt Clover, Ph.D., *Agronomy Innovation Data Leader*

Matt earned his B.S. in Crop Sciences and M.S. in Soil Fertility from the University of Illinois, and a Ph.D. in Soil Science from Iowa State University. After working in the fertilizer industry for 9 years in agronomy and research and development roles, Matt joined Pioneer in 2017 as an Agronomy Research Manager within the Pioneer Agronomy Sciences group. He is now the Agronomy Innovation Data Leader for North America.

Brian Dahlke, *Research Scientist*

Brian Dahlke is the site manager for the Champaign Research Station in Illinois, working in Seed Product Development. Brian is responsible for food grade corn field characterization and phenotyping, and oversees most of the food grade corn initiatives from the company. Brian has worked for Corteva Agriscience for 22 years.

James D'Aoust, CCA-ON, *Field Sales Agronomist*

James earned his B.S. in Agriculture from the University of Guelph. He started his career working as a Territory Manager for the DuPont Crop Protection business and then transitioned to Pioneer and has held multiple roles within sales and agronomy. James currently resides with his family on a farm in Central Ontario.



Jason DeBruin, Ph.D. *Global Biotech Trait Characterization Project Scientist*

Jason is a Global Biotech Trait Characterization Project Scientist in the Trait Characterization and Development team within the Biotechnology department. He manages trials investigating next generation herbicide tolerance traits in corn and soybean. Jason holds a Ph.D. from Iowa State University and has been with Corteva 15 years.

Matt Essick, M.S., *Agronomy Innovation Leader*

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.

Scott A. Eversgerd, *Field Agronomist*

Scott earned his B.S. in Plant and Soil Science from Southern Illinois University at Carbondale. After working as Crop Consultant on High Management Wheat in KY and in the Crop Protection industry in IN and NC, Scott joined Pioneer in 2004 as an Account Manager and then in 2006 transitioned to an Area Agronomist/Field Agronomist in Southern Illinois where he continues in that role.

Mary Gumz, Ph.D., *Agronomy Innovation Leader*

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

Robert Gunzenhauser, *Research Scientist*

Bob works in Innovative Crop Solutions, a team within Farming Solutions & Digital, as a part of Corteva's Research & Development efforts. His primary area of work is studying the proper management of Corteva seed and crop protection products with an eye towards enabling decision science tools. He holds an MBA from Iowa State University and lives on a farm with his family in south-central Iowa.

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.

Paul Hermans, CCA-ON, *Sales Agronomist.*

Paul earned his B.S. in Agriculture from the University of Guelph. He has held numerous roles within the company including Territory Manager and Digital Effectiveness Manager. His passion for agronomy research includes corn and soybean population, fungicides in beans and nitrogen in corn. Paul resides in Eastern Ontario.

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

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.

Jeffrey Klever, *Research Investigator*

Jeff joined Pioneer in 2009 and is located in Johnston, IA. He has served on several biotech R&D teams overseeing field testing and characterization of insect control products. He is currently an Efficacy Lead in the Trait Characterization & Development group responsible for testing pipeline and commercial corn rootworm traits.

Adam Krull, DVM, Ph.D., *Senior Nutritionist and Veterinarian*

Adam provides technical support to dairy producers on forage management with a focus on improving animal productivity and health. He earned his B.S. in dairy science, DVM, and Ph.D. in veterinary microbiology from Iowa State University. Before joining Pioneer, Adam worked as a dairy practitioner in Wisconsin and later as a Clinical Assistant Professor at Iowa State University. He and his wife also run a small hobby farm with registered Black Angus cattle.

Don Kyle, M.S., *Soybean Breeder and Eastern U.S. Evaluation Zone Lead*

Don is a long-time soybean breeder in the Eastern U.S., focusing on maturity group 2 and 3 products for the U.S. market. He is passionate about bringing improved soybean varieties to farmers with high yield, stronger disease resistance, and excellent agronomics. He is an Illinois native, has a M.S. in plant breeding from University of Illinois, and currently resides in Northern IL.

Nelson Lobos, Ph.D., *Nutritionist*

Nelson has a M.S. and Ph.D. in Dairy Science from the University of Wisconsin-Madison and has an undergraduate degree in Agribusiness from the Universidad Austral de Chile. He joined the Global Nutritional Sciences Team in 2021 to focus on supporting sales to livestock accounts with nutrition and product training, managing service calls, field trials, and interacting with key influencers.

Tim Mabry, M.S., *Field Scientist*

Tim is a Central Illinois native, affiliated with the Champaign, IL research station. Tim has a B.S. in Biology from Illinois State University and an M.S. in Integrated Pest Management from the University of Illinois. He has 21 years' experience in the ag industry and joined Pioneer in 2010. In his current role in Trait Characterization and Development, he conducts field trials for biotech traits, SAT, and biologicals in corn and soybean.

Mike Moechnig, Ph.D., *Field Sciences Biology Team Leader*

Mike Moechnig is a Field Sciences Biology Team Leader at Corteva Agriscience and is located in Toronto, SD. He received his Ph.D. from the University of Wisconsin.

Sheila Murphy, M.S., *Technical Services Manager, Eastern Canada*

Sheila earned her B.S. in Agronomy and M.S. in Plant Breeding from the University of Guelph. She joined Pioneer in 2010 in Seed Product Development as Research Operations Lead at the Woodstock Research Station and later joined the commercial group as Product Agronomist for Eastern Canada. She is now the Technical Services Manager for Eastern Canada.

Christian Michel Navarro, Senior Research Associate

Christian is Senior Research Associate within Field Experimentation, a team within Farming Solutions & Digital, a part of Corteva's Research and Development team. Christian is located in California where her focus is implementation of managed stress environments for drought, increasing capacity for high throughput phenotyping and implementation of complex protocols in row crops and specialty crops.

Tim Nowatzki, Ph.D., *Biotech Capability Leader – Trait Efficacy*

Tim earned his B.S. in Crop and Weed Science and M.S. in Entomology from North Dakota State University and Ph.D. in Entomology from Iowa State University. After completing a post-doc at University of Nebraska-Lincoln in Entomology, he joined Pioneer in 2003 as Research Scientist in Discovery. He is now a Capability Leader for trait efficacy in the Biotechnology, Trait Characterization & Development group based in Johnston, IA.

Andres Reyes, Ph.D., *Research Scientist*

Andres is a Research Scientist within Field Experimentation, a team within Farming Solutions & Digital, a part of Corteva's Research and Development team. Located in California, his focus is implementation of managed stress environments for drought, increasing capacity for high throughput phenotyping, and implementation of complex protocols in row crops and specialty crops. Andres holds a Ph.D. from The University of Queensland in Australia and has been with Corteva 20 years.

Jose Rotundo, Ph.D., *Research Scientist*

Jose 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.





Andrea Salinas, *Research Scientist*

Andrea is a Research Scientist within Field Experimentation, a team within Farming Solutions & Digital, a part of Corteva's Research and Development team. Located in Chile, her expertise is in high-throughput plant phenotyping under managed drought-stress environments. Andrea has been with Corteva for 20 years. She holds a degree in Agricultural Engineering with a specialization in fruit production from Universidad de Chile.

Jerron Schmoll, M.S., *Product Life Cycle Manager*

Jerron Schmoll earned his B.S., M.S., and MBA from The Ohio State University. He has worked in various field sales, agronomy, and product management roles in the eastern half of the U.S. Jerron is currently serving as a product manager for the Northeastern U.S.

Greg Schulenberg, *Senior Technician – Soil Microbiology*

Greg Schulenberg is a Senior Technician within the Biostimulant Biology Characterization team at Corteva Agriscience, located in Indianapolis, IN. His work is focused on molecular analysis, including qPCR assay development, gene expression quantification, high-throughput optimization, and nucleic acid purification.

Stephen Strachan, Ph.D., *Research Agronomist*

Dr. Strachan served in many research roles for DuPont Crop Protection, Pioneer, and Corteva Agriscience. His roles in crop protection involved the discovery and development of new herbicides. His roles in seed production involved the testing and production of corn parent lines. Dr. Strachan obtained his M.S. degree in soil chemistry and his Ph.D. degree in plant physiology from Purdue University.

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 16 years working as a Research Scientist at the UW Marshfield Agricultural Research Station, 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.

UNIVERSITY CONTRIBUTORS

Craig Drury, Ph.D., *Soil Biochemist*

Dr. Drury is a soil biochemist at the Harrow Research & Development Centre, Agriculture and Agri-Food Canada. His current research involves the development of nutrient management practices which decrease ammonia volatilization and nitrous oxide emissions and increase crop yields.

David Hooker, Ph.D., *Associate Professor*

Dr. Hooker is an Associate Professor in the Department of Plant Agriculture at the University of Guelph. His research focuses on achieving a greater efficiency and sustainability of corn, soybean, and wheat production using an applied systems hypothesis-driven approach, through a better understanding of interactions among genotype, environment, and other crop response factors and input variables.

Jongwon Kang, Ph.D. *Student*

Jongwon is pursuing a Ph.D. at the University of Guelph. His research focuses on corn physiology and the modeling of soil-crop interactions to mitigate greenhouse gas emissions. Jongwon earned his master's degree from Chungbuk National University in South Korea.

John Lauzon, Ph.D., *Associate Professor*

Dr. Lauzon is an Associate Professor in the School of Environmental Sciences at the University of Guelph. His research focuses on nutrient cycling and management within the agroecosystem.

Joshua Nasielski, Ph.D., *Assistant Professor*

Dr. Nasielski an assistant professor of agronomy at the University of Guelph in Ontario, Canada, and holds the MacSon Professorship in agronomy for eastern and northern Ontario. Dr. Nasielski earned a Ph.D. from the University of Guelph.

2024 GROWING SEASON IN REVIEW

The 2024 growing season was one in which rainfall – often too much or too little – was commonly the main factor that determined how the season unfolded. 2023 ended with much of the Midwest and the South under drought. Water levels in the Mississippi River were low enough in fall of 2023 to cause disruptions to barge traffic on the river.

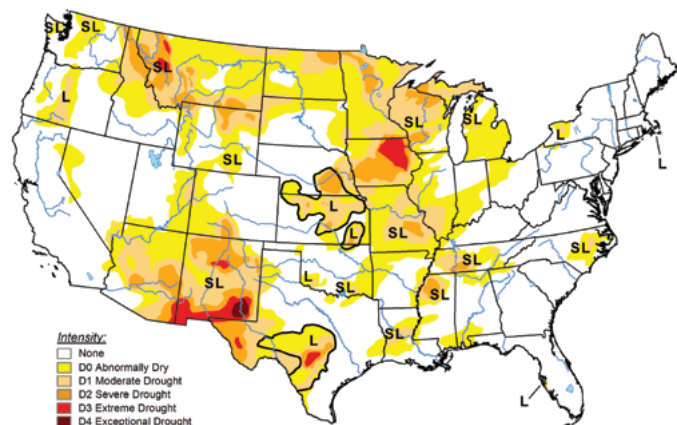


Figure 1. U.S. Drought Monitor map, March 5, 2024 (National Drought Mitigation Center, University of Nebraska–Lincoln).

The drought mostly broke for the South over the winter, but much of the Midwest and southern Plains picked up 2024 right where 2023 left off, with many areas still under some degree of drought stress (Figure 1). A warm spell in early March had several of us at the Pioneer office in Iowa nervously noting that the set up for the growing season was feeling eerily similar to what we had experienced going into 2012.

It's amazing how quickly things can change.

In April, the rains returned; a welcome turn of events, although one that would eventually become less welcome as continued rainfall began to disrupt planting activities in some areas. Much of the crop production area of the U.S. experienced above average rainfall through the early part of the season (Figure 2).

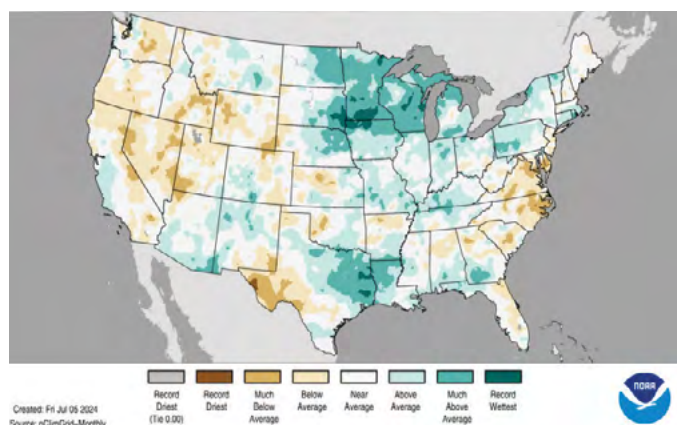


Figure 2. Total precipitation percentiles for April–June 2024 (NOAA).

Corn planting got off to a good start in late April but was held up in early May as rain kept the planters out of the field (Figure 3). The delays became significant in some areas. Excessively wet conditions in parts of central Illinois, and especially southern Minnesota and central Wisconsin, kept some of the crop from getting planted and had negative effects on the crop that was already in the ground. Corn planting progress for the U.S. ended up running around a week behind that of 2023.

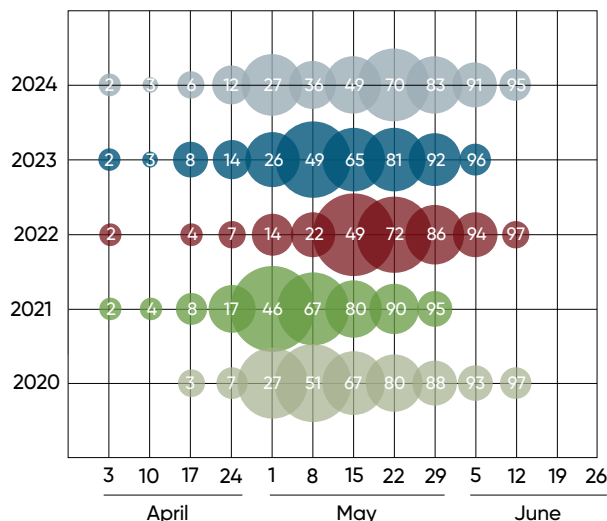


Figure 3. U.S. corn planting progress 2020–2024 (USDA–NASS).

For the crop that got into the ground in a timely manner, regular rainfall through the early part of the season was tremendously helpful for early growth and reaching canopy closure. By early June, drought conditions were largely gone for most of the South, Midwest, and Plains (with central and western Kansas being a notable exception) (Figure 4).

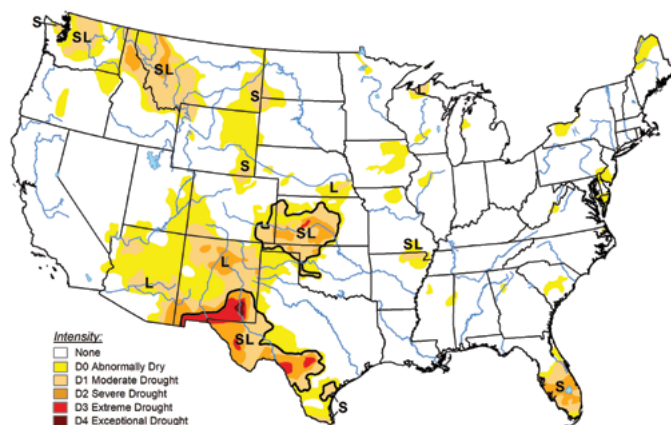


Figure 4. U.S. Drought Monitor map, June 4, 2024 (National Drought Mitigation Center, University of Nebraska–Lincoln).

Temperatures in the U.S. were generally above average in 2024. Globally, 2024 was the hottest year on record, breaking the previous record set in 2023. However, in the Midwest, Plains, and Mid-South temperatures stayed right around normal for

The mild temperatures and regular rainfall during the summer made it seem like 2024 could be a big year for foliar diseases in corn. However, for the most part, this did not end up being the case. Common foliar diseases mostly remained at low to moderate levels and tar spot was widely observed but rarely of major concern. At the Pioneer research farm in Johnston, IA, rainstorms often moved through quickly, without creating the extended periods of leaf wetness that favor foliar diseases.

Another noteworthy disease that showed up in 2024 was corn stunt. Corn stunt is a bacterial disease of corn that is transmitted by corn leafhoppers. It is one of the worst diseases of corn in Latin America, but outbreaks rarely occur in the U.S. and usually only in the southernmost corn growing regions. In 2024, however, a large outbreak occurred in Texas and Oklahoma. Corn stunt symptoms were observed in Kansas and Missouri for the first time ever, and corn leafhoppers were found as far north as Wisconsin. Whether the 2024 outbreak turns out to be the start of a trend or a one-off fluke is yet to be determined.

Intensity:

- None
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

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

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Mark Jeschke, Ph.D.
Agronomy Manager



PIONEER AGRONOMY SCIENCES HISTORY AND LEGACY

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.

This book is the latest edition of the *Pioneer Agronomy Research Summary*, a publication that has been produced annually by Pioneer Agronomy Sciences for over 30 years. Within its pages you'll find a compilation of research results and agronomy articles that provide a snapshot of what Pioneer Agronomy Sciences is all about.

This book summarizes a year's worth of work, but it represents just a small part of a history that spans decades. Agronomy has long been a core part of Pioneer. From the very beginning, Pioneer's leaders recognized the importance of agronomic support for ensuring customer success with Pioneer products. And the continually evolving nature of crop production has meant that Pioneer Agronomy has evolved as well.

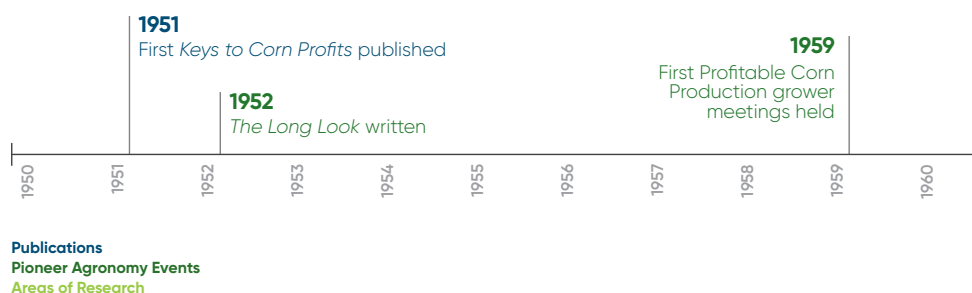
This *Pioneer Agronomy Research Summary* is part of a legacy that has spanned massive change – both in how crops are produced and in the Pioneer business itself. The following pages provide a brief look at that legacy, including some of the key people, events, and innovations that shaped Pioneer Agronomy over the years.

The Long Look

The essential role of agronomy in the Pioneer business 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.

Foundations

Throughout its history, Pioneer Agronomy has been comprised of three essential components. The first is the Pioneer Agronomist – the crop management experts and trusted advisors that combine agronomic expertise with the local in-field experience necessary to provide a level of support to Pioneer Sales Representatives and customers unrivaled in the industry. The second and third components comprise the support system backing up the Pioneer Agronomist – scientifically sound agronomic research and the information delivery and training systems necessary to bring the insights gained from that research to the Pioneer Agronomists and, ultimately, to Pioneer customers.



Pioneer Agronomy had humble beginnings, it started slowly like a seed germinating in cool, wet soil, but emerged and grew as a rapidly expanding source of agronomic information for farmers. As the service expanded, the expertise spread to all major corn, soybean, sorghum, alfalfa, sunflower, and wheat growing areas. Today it is one of the most helpful sources of crop management information available to farmers in the United States and around the world.

Changes Ahead

The origin of Pioneer Agronomy can be traced back to the years after World War II, when scientific advances put new crop management tools in the hands of farmers – such as synthetic fertilizers, herbicides, and insecticides – that created new possibilities as well as new complexities for crop production. Hybrid corn was already widely adopted at this point, having surpassed 50% of all U.S. corn acres in 1942, and corn yields were reaching unprecedented new heights. Farmers interested in improving their cropping programs were asking for better information on topics like planting date, depth of planting, planting rate, fertility, insecticides, and herbicides.

By the early 1960s, the growing complexity of crop production made apparent the need for a new department within the company dedicated specifically to crop management support. As Pioneer Production Agronomist and future Pioneer Technical Service leader Al Leffler noted at the time, “The change to hybrid corn took about 10 years to accomplish. It was a very simple management shift compared with changes which lie ahead.”

Taking Shape

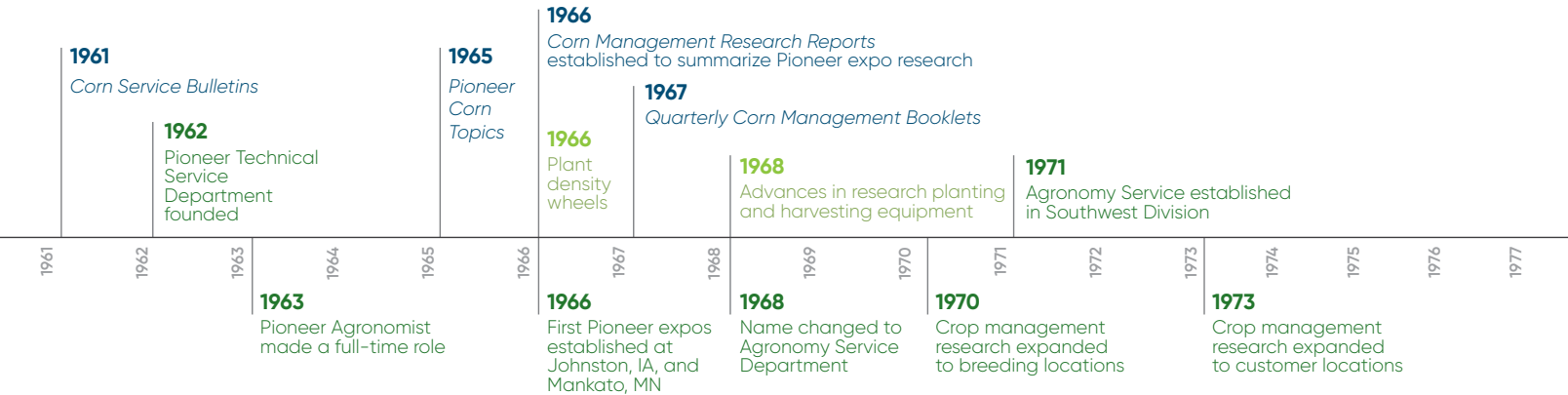
In 1962, the formation of the Pioneer Technical Service Department was formally announced by James W. Wallace, president of the Pioneer Hi-Bred Corn Company. In announcing the new department and appointments, Mr. Wallace said, “We believe this type of service can be very beneficial to our Research Department, Production Department, our salesmen, and our customers.” At this time, research was the only corporate function of the company, with all other functions organized under five geographic



Corn harvest, late 1960s.

divisions – Central, Eastern, Illinois-Wisconsin, Southwest, and Canada. Technical Service Departments were established in the Central, Eastern, and Illinois-Wisconsin divisions in 1962, Southwest in 1971, Canada in 1980, and the newly formed Plains division in 1984.

The inaugural class of Pioneer Agronomists consisted of four assistant managers at Pioneer seed production plants who conducted training meetings with Pioneer salesmen (as they were called at the time) and corn production meetings with customers on a part-time basis in addition to their regular production plant duties. Within a year, Pioneer Agronomist was made into a full-time role and the new department continued to develop and expand over the rest of the 1960s, being renamed the Agronomy Service Department in 1968. 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.



Research Advancements

It was during the 1960s that crop management research at Pioneer also began to take shape. One of the earliest agronomy research concepts utilized at Pioneer was field expositions, or “expos” as they were commonly called, the first of which were conducted at Johnston, IA, and Mankato, MN, in 1966. The expos were large sets of research plots that featured breeding research, corn management research, and showcased new leader hybrids. This concept expanded through the 1970s and 1980s to numerous Pioneer research stations across the U.S., giving thousands of Pioneer customers the chance to visit a Pioneer expo and see the field research plots firsthand.

Starting in 1970, crop management research was conducted at breeding locations in addition to the expo locations. In 1973, customer locations were added. As personnel and equipment became available, the research was expanded to include the needed locations for statistical analysis and interpretation of data.

Other critical agronomy research innovations during the 1960s involved development of new planting and harvesting equipment that would vastly expand the scale of field research that could be done. In 1968, Pioneer developed a four-row cone planter, which allowed two agronomists seated on the planter to dump packets of seed for each individual plot into the planter row unit. This method of planting allowed many more plots and studies to be handled with a small crew.

The next bottleneck to be mastered for plot research was mechanical harvesting. The Pioneer machine shop modified an old Massey Ferguson 35 combine to weigh and sample corn in a custom-fabricated cab. These machines lacked capacity to harvest 150–200-bushel corn and parts for repairs became scarce over time. John Deere and Oliver combines were also modified but the Gleaner K2 eventually became the combine of choice used by Pioneer breeders and agronomy researchers.



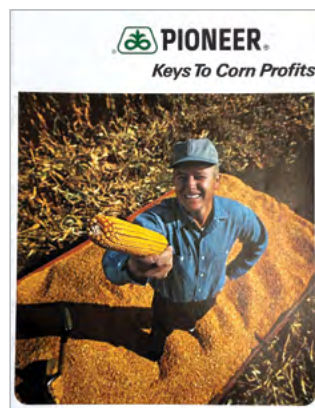
Gleaner K2 research combine.

Bringing Insights to Customers

Information delivery has been an essential component of Pioneer Agronomy that evolved right alongside crop management research. Agronomy fact sheets and books of various forms have long been an important way of sharing crop management information with sales reps and customers, often distributed and discussed at customer meetings.

One of the first formal Pioneer Agronomy publications was *Keys to Corn Profits*, which was first produced in the 1950s and continued up through the 1970s. The typical *Keys to Corn Profits* booklet from the 1970s contained a review of the past year’s growing conditions, followed by 8 to 10 articles on various corn production topics such as fertility management, planting practices, and insect control.

Following the establishment of the Pioneer expos in the mid-1960s, annual *Corn Management Research Reports* were published to summarize key findings of field experiments conducted that year.



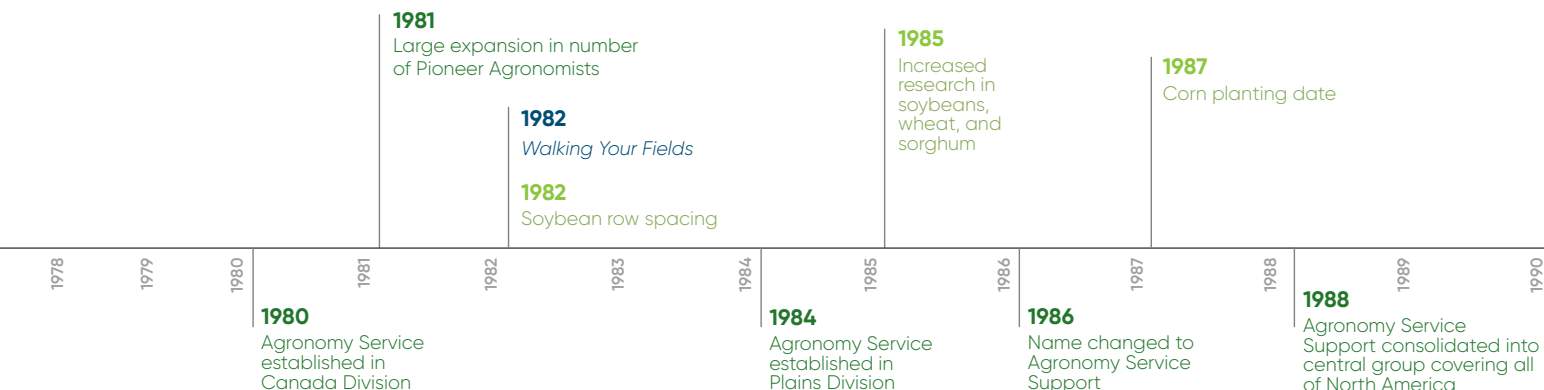
Pioneer Keys to Corn Profits (1968)



Pioneer Corn Management Research Report (1973).

Consolidation and Growth

The core components of Pioneer Agronomy that were established during the 1960s and 1970s underwent significant growth and evolution during the 1980s and 1990s. Two corporate restructurings during the 1980s significantly impacted agronomy at Pioneer. The first of these occurred in 1986 and involved a significant expansion in the number of Pioneer Agronomists. Pioneer marketing was reorganized



into eastern and western regions for North America. The newly named Agronomy Service Support Department was organized within the marketing regions, with support staff for the eastern region based in Tipton, IN, and the western region in West Des Moines, IA.

A second reorganization in 1988 consolidated Agronomy Service Support into a single organization covering all of North America under the leadership of Ivan Wikner, who had served in a number of Pioneer Agronomy roles since the early 1960s. The two main priorities for the new North American Agronomy Service Support Department were information delivery and crop management research. Significant advances in both areas in the years that followed brought Pioneer Agronomy to a new level of influence and respect in the industry.

Agronomy Publications



Pioneer Walking Your Fields Newsletter (1991).

Agronomy information delivery underwent a substantial leap forward in quality, sophistication, and coordination during this time. Several familiar newsletters and publications used by Pioneer Agronomy up through the present day have their origins in this era. *Walking Your Fields*, an agronomy newsletter delivered to customers by mail, was established by the Illinois-Wisconsin sales division in 1982. This easy-to-read publication was produced by the farmers' local agronomist and contained concise, localized information of immediate interest. Pioneer Agronomists from the time recall stories of farmers walking down the driveway to pick up the day's mail, putting the latest *Walking Your Fields* on top of the stack, and reading it over by the time they got back to the house. By 1990, *Walking Your Fields* newsletters were being produced across all of North America and it continues to this day as an email newsletter.

The high-quality agronomy articles that have long been synonymous with Pioneer trace back to this era as well, when Steve Butzen joined the North America Agronomy Service Support Department as Agronomy Information Specialist in 1991. Pioneer *Crop Insights* – the flagship Pioneer Agronomy publication that provided in-depth reviews of high priority national-interest topics – was started the same year.

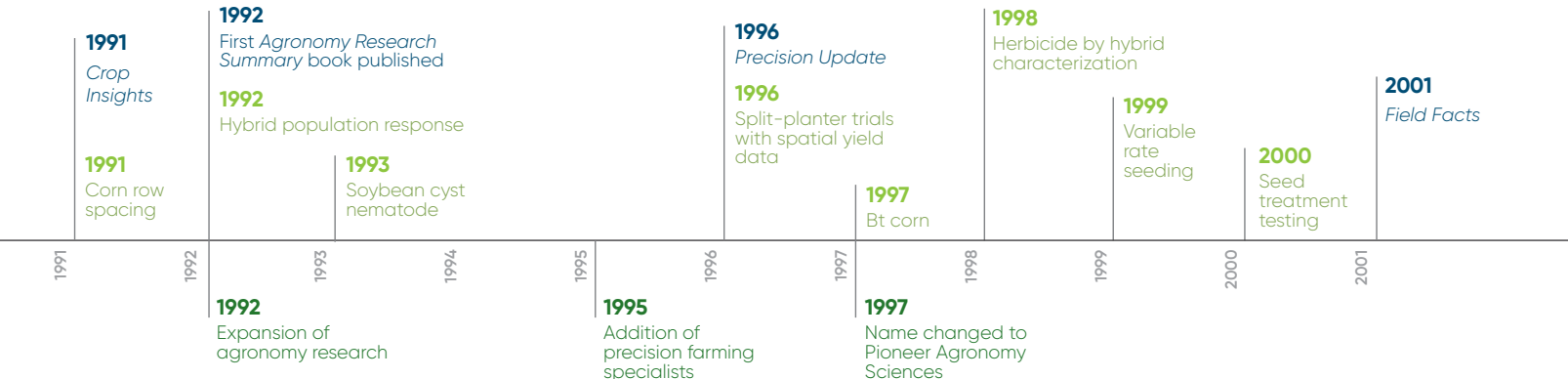
Now in its 35th year of continuous publication, *Crop Insights* has earned a reputation for quality and scientific rigor that has made it one of the most respected agronomy publications in the industry. Additional Pioneer Agronomy publications followed in the footsteps of *Crop Insights*. *Field Facts* was started in 2001 to provide comprehensive reviews of important agronomy topics of more regional interest, and *Crop Focus* was established in 2009 as a shorter form publication providing bulleted highlights of agronomic topics. In total, nearly 2,000 Pioneer Agronomy articles have been published since *Crop Insights* was established in 1991.



Crop Insights has been Pioneer Agronomy's flagship agronomy publication for 35 years.

Pioneer Agronomy Sciences

Pioneer's investment in agronomy research also made a big step forward in the early 1990s. Agronomy Service Support underwent a major expansion in 1992 when it took over corn planting rate testing from the plant breeding department for the U.S. and Canada. Dr. Steve Paszkiewicz had been hired to lead Pioneer crop management research the previous year, and several more research scientists and support staff were added to the team over the next few years to conduct plant population testing and numerous other crop management research studies.



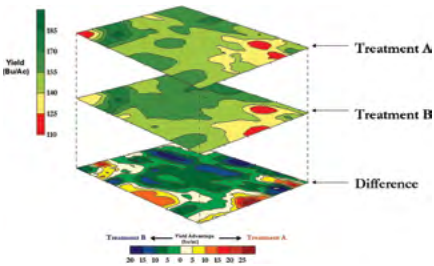
Ivan Wikner retired in 1993 after 30 years of service with Pioneer, and Dr. Paul Carter was hired as the new Agronomy Service Support Manager. The increased focus of the agronomy group on rigorous crop management research led to its renaming as Pioneer Agronomy Sciences in the mid-1990s. This publication, the *Pioneer Agronomy Research Summary*, was first produced in 1992 as an annual summary of all agronomy field experiments that had been conducted over the previous year. Agronomy Sciences research continued to grow through the mid-1990s to address the need for more agronomy research and technical expertise and to support the launches of new transgenic technologies.



Pioneer Agronomy Research Summary (1992).

Precision Agriculture

Over its history, Pioneer Agronomy often served as an incubator, developing new ideas and services that were ultimately spun off into standalone teams within the company. One such example was in the mid-1990s with the new field of precision agriculture and yield mapping. The first Pioneer Precision Farming Specialist was hired into the Agronomy Sciences group in 1995, and several additional positions focused on precision agriculture were added over the following few years. During this time, Pioneer Agronomy Sciences was at the forefront of precision agriculture and conducted important early work in variable rate seeding as well as some of the first field-scale split planter trials using spatial yield data.



Yield difference map from a Pioneer split planter trial in the mid-1990s.

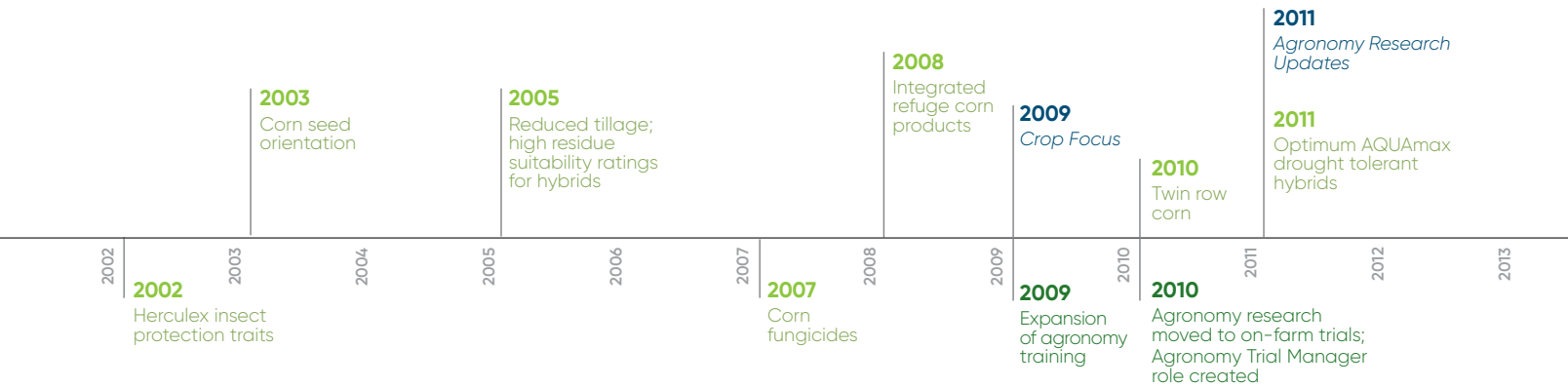
Traits and Technologies

Insect protection traits and seed treatments were major research priorities in the early 2000s. Pioneer Agronomy Sciences conducted extensive field research evaluating the efficacy and yield performance of the Herculex® I and Herculex RW traits, co-developed by Pioneer and Dow AgroSciences. Numerous studies evaluated performance of the rapidly expanding array of seed treatments for corn and soybeans. To meet the demand for research data, additional personnel dedicated specifically to seed applied technologies were added to the group and eventually spun off into a separate team. In 2008, the entire research arm of Agronomy Sciences was redeployed into trait characterization research, while agronomy research was transitioned to on-farm trials.

On-Farm Research

The 2010s saw a dramatic expansion in Pioneer on-farm agronomy research. The Pioneer Agronomy Trial Manager position was created in 2010 to coordinate the increased trial workload. On-farm trials allowed new products and technologies to be tested in more locations under a wider range of growing environments. This advantage would prove to be important for some of the new products Pioneer brought to market during this time.

Optimum® AQUAmax® drought tolerant hybrids were introduced by Pioneer in 2011. From 2010 to 2012 these hybrids were tested in hundreds of on-farm trials to evaluate yield performance and seeding rate response under a wide-range of water-limited and well-watered environments. Insect protection products with integrated refuge – Optimum AcreMax® 1, Optimum AcreMax, and Optimum AcreMax Xtra – were also widely tested in on-farm trials during this time. Not only did on-farm trials provide performance data under a diverse range of conditions, they also allowed trial cooperators to get a first look at new products and technologies on their own farms.



Agronomy Training

Another big advancement for Pioneer Agronomy during the 2010s was in agronomy training. Training on agronomy topics for Pioneer Agronomists and sales reps had long been a part of the Pioneer business and historically had been included as a component of sales training. However, in 2009, agronomy training was moved into the Agronomy Sciences group, where it was greatly expanded in scope.



Pioneer Agronomist Jerome Lensing trains a group of Pioneer sales reps in Minnesota in the mid 1990s.

The most significant advancement came in 2014 with the launch of the Pioneer Agronomy Essentials program. This 12-week training program provided a structured introduction to agronomy designed specifically for Pioneer field sales team members. The program built a base knowledge of crops, soils, and pests to equip Pioneer employees and reps with the expertise to offer the best solutions to our customers.

The Agronomy Essentials program was originally targeted at Pioneer Sales Professionals and Sales Associates in the United States and Canada, but it has since expanded to encompass participants from throughout the company globally. Over 3,300 employees and sales professionals have now completed the program since its inception.



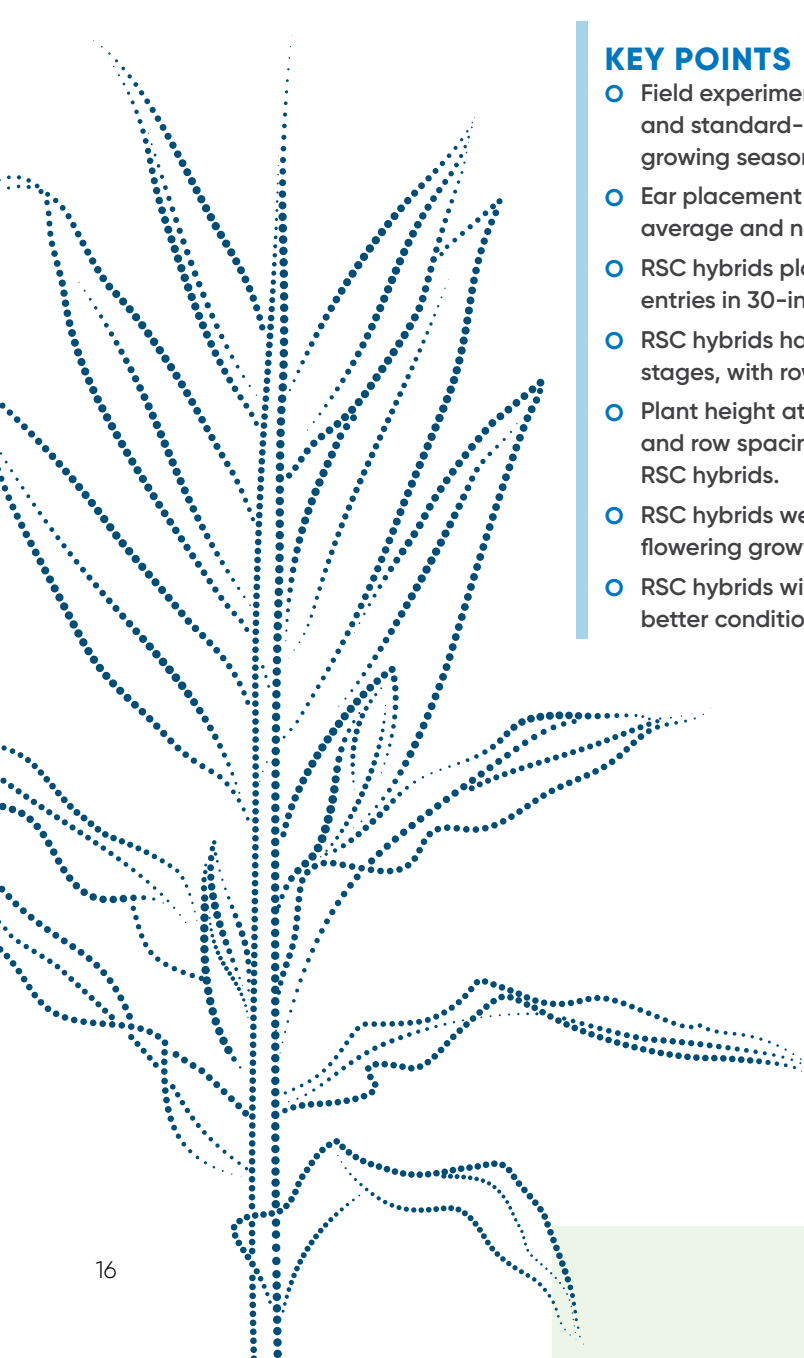
Serving Pioneer Customers

Crop production practices have changed dramatically since the Technical Service Department was created at Pioneer in 1962. The agricultural industry and Pioneer itself have evolved considerably over that time as well. However, the goal of Pioneer Agronomy has remained the same – to provide Pioneer customers with the highest level of agronomy support in the industry. So too have the foundational elements for achieving that goal – talented and dedicated people, sound crop management research, and timely and accurate crop management information.

Today, the scale of research, knowledge, and expertise supporting Pioneer customers through Pioneer Agronomy is unprecedented. Browse through the articles in this book or look over the list of contributing authors and you will see names of experts from throughout the Corteva Agriscience organization and around the world. The cover of the book says Pioneer Agronomy Sciences, but it has a vast industry-leading engine of crop research and innovation standing behind it, all to help Pioneer customers get the most from Pioneer products and meet the challenges of an ever-changing industry.

Mark Jeschke, Ph.D.,
Pioneer Agronomy Manager
January 2025





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Robert Gunzenhauser,
Research Scientist

FIELD EVALUATION OF REDUCED-STATURE CORN

KEY POINTS

- Field experiments to study management effects on reduced-stature (RSC) and standard-stature corn (SSC) hybrids were conducted during the 2024 growing season.
- Ear placement heights of RSC hybrids were between 25 and 26 inches on average and not significantly affected by row spacing or seeding density.
- RSC hybrids planted in 20-inch rows intercepted about as much light as SSC entries in 30-inch rows at the V8 growth stage.
- RSC hybrids had larger diameter stalks than SSC hybrids at key growth stages, with row spacing and seeding density as significant factors.
- Plant height at V8 was less in RSC hybrids than SSC, with seeding density and row spacing having a significant effect for SSC hybrids but less so for RSC hybrids.
- RSC hybrids were found to stand 23% better than SSC isoline pairs at pre-flowering growth stages after being tested by the Boreas wind machines.
- RSC hybrids withstood a post-hurricane windstorm and lodging event in better condition than SSC hybrids.

2024 REDUCED-STATURE CORN FIELD RESEARCH

The need to continue driving higher yield in corn as well as increase resilience against severe weather has brought about a renewed focus on the concept of reduced-stature corn (RSC). Reduced-stature corn brings with it a set of questions often raised by farmers, especially in management and cropping operations.

Changes in corn canopy architecture and biomass allocation over the years have come about gradually through decades of corn breeding. Reduced-stature corn represents an abrupt change in multiple plant characteristics. Leaves are shorter and wider and the vertical distance between leaves, as well as the depth of the crop canopy overall, is reduced. Changes in the architecture of the corn plant could require changes in how those plants are managed.



Figure 1. Reduced-stature corn next to a current commercial hybrid in the Corteva Agriscience Johnston Field Research Center at Johnston, IA.

During the 2024 growing season, experiments were conducted at multiple Corteva Agriscience research centers in the Midwestern United States to compare field performance of RSC hybrids with commercial standard-stature corn (SSC) hybrids subjected to different management practices of row spacings (20-inch and 30-inch) and seeding densities (34,000, 42,000, and 50,000 seeds/acre). Four pairs of SSC/RSC hybrids from the same genetic backgrounds were included, allowing for direct comparison of reduced stature and standard stature hybrids without confounding genetic effects.

The main purpose of these experiments was to evaluate the effects of row spacing and seeding density on plant characteristics and yield performance of RSC hybrids. The SSC hybrids were included to provide a baseline comparison for the RSC entries. At the time of publication, yield results were still being compiled.

Other key measurements were taken throughout the growing season to help address key questions on advantages and management of reduced-stature corn. These questions include ear placement height, canopy closure and implications for early season weed control, and standability under severe wind. Some measurements were taken across multiple locations, while others were taken only at select sites.

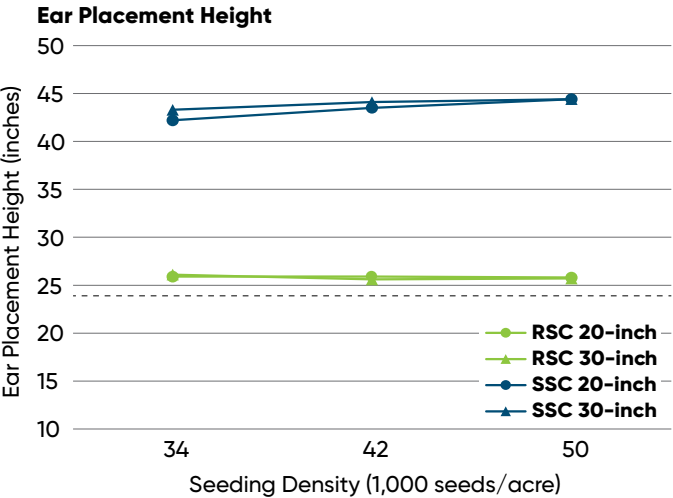
EAR PLACEMENT HEIGHT

A critical attribute of RSC hybrids is the placement of the ear on the stalk and the ability to effectively harvest it with current combine corn headers. Corteva Agriscience corn breeders actively select for RSC hybrids that have ear placement heights (measured to the shank on the stalk) of 24 inches (60 centimeters) or greater above the ground.

Ear height measurements were taken at 8 experiment locations in 2024. For each plot, 4 ear height measurements were taken, then averaged together.

Corteva Agriscience corn breeders select for RSC hybrids that have ear placement heights of at least 24 inches.

RSC hybrids had an average ear height just above the 24-inch threshold set by breeders (Figure 2). Ear placement height of RSC hybrids was very stable across management practices, with no significant effects of seeding density or row spacing. Ear placement height of SSC hybrids increased slightly at higher seeding densities, more so with 20-inch row spacing.



Stature	Row Spacing	Seeding Density		
		34K	42K	50K
	inches	inches		
RSC	20	25.9	25.9	25.8
RSC	30	26.1	25.6	25.7
SSC	20	42.2	43.5	44.4
SSC	30	43.3	44.1	44.4

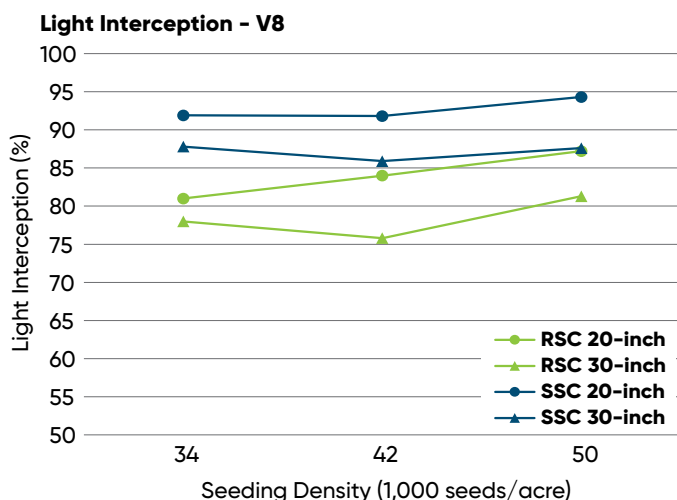
Figure 2. Average ear placement height (inches) by stature, row spacing, and seeding density at the R3 growth stage across 8 research locations.

Stature, stature x row spacing, stature x seeding density, and stature x row spacing x seeding density were all significant factors at 99.9% confidence.

EARLY SEASON LIGHT INTERCEPTION

RSC hybrids tend to produce shorter and wider leaves as compared to SSC hybrids, resulting in similar total effective leaf area to SSC hybrids but concentrating more of it closer to the stalk.

Typically, pre-emergence or early post-emergence herbicides with residual weed control activity are applied to corn fields. Weed control starts to weaken as the herbicide molecules break down in the soil and new weeds start to emerge. However, as the crop grows, it shades the soil more and more, reducing the likelihood of weed development. Greater shading reduces weed development. Any differences in shading with RSC hybrids compared to SSC hybrids could have implications for weed management.



Stature	Row Spacing	Seeding Density		
		34K	42K	50K
	inches	percent		
RSC	20	81.0	84.0	87.2
RSC	30	78.0	75.8	81.3
SSC	20	91.9	91.8	94.3
SSC	30	87.8	85.9	87.6

Figure 3. Average light interception (percentage) at the V8 growth stage by stature, row spacing, and seeding density at Johnston, IA.

Stature, row spacing, stature x row spacing, stature x seeding density, and stature x row spacing x seeding density were all significant factors at 99.9% confidence.

At the Johnston Field Research Center in Johnston, IA, light interception measurements were taken at the V8 growth stage, on two pairs of RSC/SSC isolines across both row widths and three seeding densities. The measurements were taken on a clear sunny day between 11:00 AM and 2:00 PM. For each plot, a reading from the light sensor, capturing photosynthetically active radiation (PAR), was taken above the canopy to capture the full sunlight level, then three measurements were taken under the canopy from the middle two of four rows of the plot. Care was taken to position the

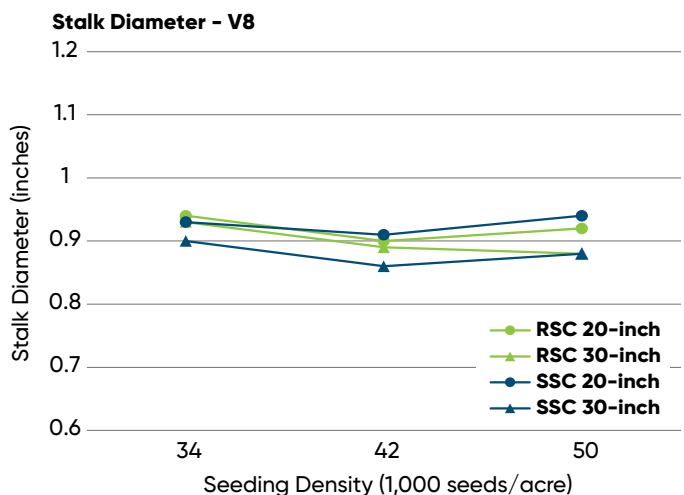
light sensor to capture the equivalent of one row's width and was adjusted based on 20-inch or 30-inch row width. The three below-canopy readings were averaged together and used to find the percentage of the above-canopy light reading that was being intercepted.

RSC entries planted at 20-inch row spacing and at 42,000 and 50,000 seeds/acre had very similar light interception values as SSC entries at 30-inch row spacing at the same seeding densities (Figure 3). RSC entries at 30-inch and SSC entries at 20-inch row spacings showed significant differences in light interception. Results suggest that lower light interception with RSC hybrids during vegetative growth could impact suppression of weed growth from shading by the crop but this difference could be mostly overcome by planting RSC hybrids in 20-inch rows.

STANDABILITY

One of the main benefits of reduced-stature corn is the greater ability to withstand high wind events that would usually cause standard-stature corn to lodge. Stalk diameter and plant height can play important roles in how a corn plant stands up to severe winds.

At the Windfall, IN, Research Center, stalk diameter measurements were taken from two isoline pairs of RSC and SSC entries. Measurements were taken at V8 and R1 growth stages across row widths and seeding densities.



Stature	Row Spacing	Seeding Density		
		34K	42K	50K
	inches	inches		
RSC	20	0.94	0.90	0.92
RSC	30	0.93	0.89	0.88
SSC	20	0.93	0.91	0.94
SSC	30	0.90	0.86	0.88

Figure 4. Average stalk diameter (inches) at the V8 growth stage by stature, row spacing, and seeding density; Windfall, IN.

Row spacing, stature x row spacing, and row spacing x seeding density were significant factors at 99% confidence.

Stature x row spacing and stature x seeding density were significant factors affecting stalk diameter at V8 and R1, respectively (Figures 4 and 5). This indicates that – along with the stature of the plant – stalk diameter is also affected by management, either by row spacing or seeding density, depending on the growth stage of the plant. At the R1 stage, stalk diameter of RSC hybrids at 50,000 seeds/acre was similar to that of SSC hybrids at 34,000 seeds/acre. Larger stalk diameters help contribute to greater strength during wind events.

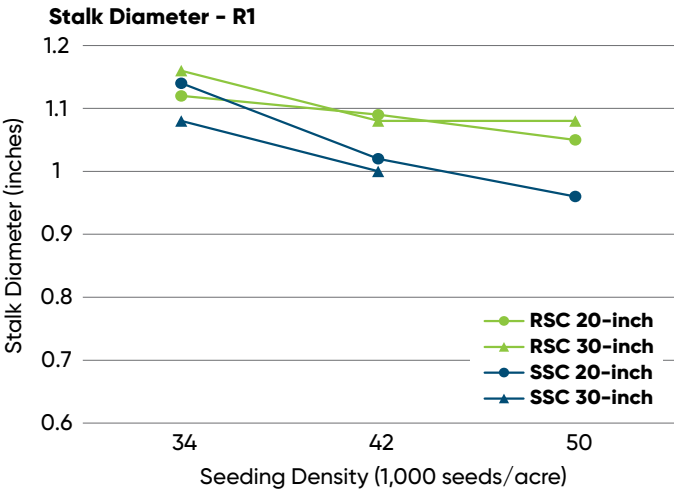


Figure 5. Average stalk diameter (inches) at the R1 growth stage by stature, row spacing, and seeding density; Windfall, IN.

Seeding density and stature x seeding density were significant factors at 95% confidence.



Figure 6. Corteva Agriscience's Boreas wind machine creates winds that can exceed 100 mph to test for standability in corn hybrids.

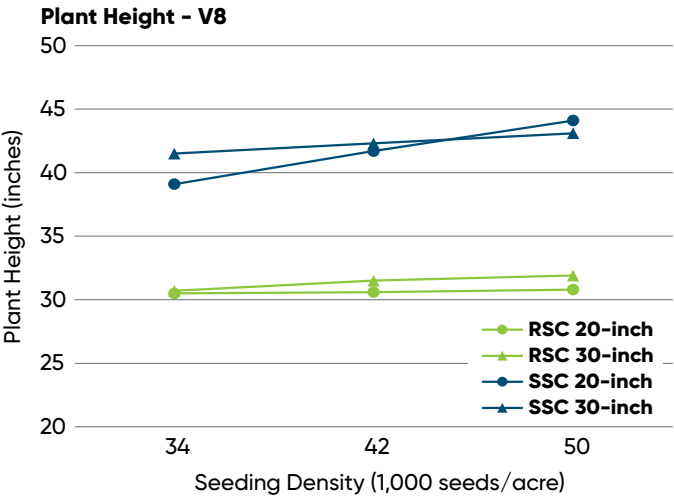
Plant height measurements were taken at V8. These showed significant differences in plant height between RSC and SSC, as would be expected. No measurements were taken at R1 due to a wind lodging event (see further).

In the SSC entries, plant height increased with seeding density, to a lesser extent in 30-inch rows and more so in 20-inch rows (Figure 7). This is due to competition for light during this period of rapid vegetative growth. RSC entries did not show the same degree of response to row spacing or seeding density as SSC entries, but plant height did increase slightly in 30-inch rows as seeding density increased.

These findings illustrate that – while SSC hybrids may be at greater risk for lodging at higher seeding densities – RSC hybrids are less prone to lodging due to their shorter plant height and relative insensitivity of plant height to seeding density.

Reduced-stature corn is less prone to lodging due to shorter plant height and greater stalk diameter.

To further test hybrids in development, Corteva Agriscience uses its Boreas wind machines for green snap and root lodging assessment (Figure 6). In 2024 trials, prospective pre-release RSC hybrids in the 108 to 113 CRM maturity range were found to have 23% fewer plants that lodged as compared to their SSC isoline siblings through testing using the Boreas machines in late-vegetative stages prior to flowering.



Stature	Row Spacing	Seeding Density		
		34K	42K	50K
	inches	inches		
RSC	20	30.5	30.6	30.8
RSC	30	30.7	31.5	31.9
SSC	20	39.1	41.7	44.1
SSC	30	41.5	42.3	43.1

Figure 7. Average plant height (inches) by stature, row spacing, and seeding density at the V8 growth stage; Windfall, IN.

Stature, stature x row spacing, stature x seeding density, and stature x row spacing x seeding density were all significant factors at 99.9% confidence.

LODGING EVENT

In July 2024, a lodging event occurred at the Windfall Research Center. The remnants of Hurricane Beryl, an early-season hurricane that made landfall in southeastern Texas, made its way north and east to central and north-central Indiana. One of the management experiments was in the path of the storm and received about 1.5 inches of rain over

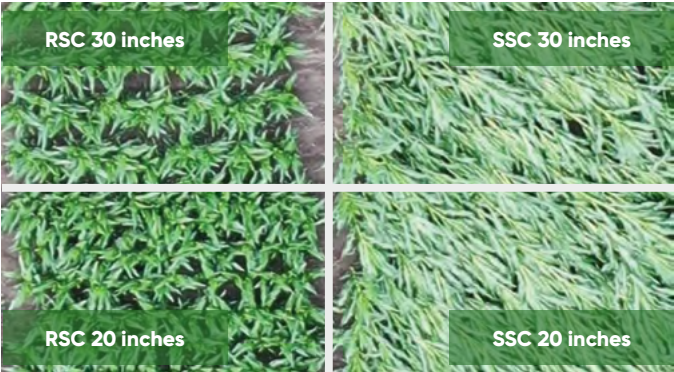


Figure 8. UAV-based image taken 1 day after the lodging event at Windfall, IN, at the intersection of RSC and SSC entries and 20-inch and 30-inch row spacings.

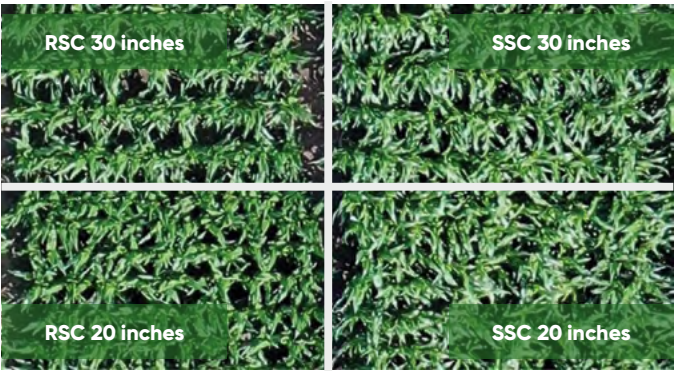


Figure 9. UAV-based image taken 8 days after the lodging event at Windfall, IN, at the intersection of RSC and SSC entries and 20-inch and 30-inch row spacings.



Figure 10. Images taken of RSC (left) and SSC (right) entries 8 days after lodging event occurred. Photos courtesy of Clayton Carley.

the course of the day on July 9. The site was hit with 50 mph winds the next day. With the slow rain and saturated soils, the plants were susceptible to root lodging. The corn was at V12 to V14 growth stage at the time of the incident.

Images were taken the next day after the lodging event and one week later. Lodging scores were taken from the experiment five days after the event. RSC entries were all standing, but the SSC entries experienced various levels of lodging based on row spacing and seeding densities. Lodging severity in SSC entries increased with seeding density in both 20-inch and 30-inch rows (Table 1).

Table 1. Average lodging scores of RSC and SSC entries by row spacing and seeding density at Windfall, IN, following a severe wind event in July 2024.

Stature	Row Spacing	Seeding Density			Average
		34K	42K	50K	
	inches	inches			
RSC	20	1.0	1.0	1.0	1.0
RSC	30	1.0	1.0	1.0	1.0
SSC	20	4.1	4.7	6.2	5.0
SSC	30	3.6	4.0	7.2	5.0

1 – slightly lodged but can collect data, 3 – more severe lodging but data can be collected, 5 – significant effort to collect data, 7 to 9 – plots damaged beyond data collection possibility.

SUMMARY

As reduced-stature corn is being developed for commercialization, Corteva Agriscience’s R&D team continues to generate data and gain a better understanding of how RSC hybrids can perform under varying management practices. This will help farmers with placement and management advice once the new corn hybrids are released.



Figures 11. RSC entries in 20-inch rows (left) and 30-inch rows (right) 8 days after lodging event. Photos courtesy of Clayton Carley.

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Robert Gunzenhauser,
Research Scientist

EXPLORING COUNTY LEVEL CORN YIELD TRENDS



KEY POINTS

- Over the course of the hybrid corn era, corn yield has steadily increased at a rate of 1.9 bu/acre/year and year-to-year variability has decreased.
- Corn yield trends have not been uniform across the entire corn production area of the Midwestern U.S.
- County level yield data from USDA NASS were used to explore variation in corn yield trends across 12 Midwestern states, as well as changes over time.
- The greatest yield increases during the hybrid corn era (1946–2023) occurred in central Illinois and the upper west parts of the Corn Belt (northwest half of Iowa, southern Minnesota, and eastern South and North Dakota), along with irrigated areas of Nebraska and southwestern Kansas.
- During the biotech era (1996–2023) there was reduction in yield variation across large areas of the Midwest, including previously variable regions, like the eastern Dakotas.
- Advances in genetics – particularly, improvements in drought tolerance – have reduced the impact of environmental extremes over time.

INTRODUCTION

As corn genetics and management have advanced and improved over time, yields have increased and become less variable. Advances in corn breeding and testing have allowed more genetic combinations to be tested each year in a diverse range of growing environments. Only those genetic combinations that can exceed the current class of hybrids in yield and yield stability are advanced into the marketplace. Technological advances such as biotech trait integration and double haploid inbred development have reduced the susceptibility of corn hybrids to pest pressures that historically caused high year-to-year yield swings, as well as increased the throughput of the hybrid product development pipeline.

Over the course of the hybrid corn era, corn yield has steadily increased at a rate of 1.9 bu/acre/year and year-to-year variability has decreased. However, these trends have not been uniform across the entire corn production area of the Midwest, nor over time periods. In this article we explore how the adoption of improved genetics and traits has translated into real-world results at the county level in the Midwestern United States over a key time period of seed corn development.

METHODOLOGY

County-level yield estimates are developed each year by the USDA National Agricultural Statistics Service through surveys with farmers. Since 2020, model-based county-level estimates have been incorporated into the process for row crop county estimates. Inputs include National Commodity Crop Productivity Index (NCCPI) values for the county, current survey ratios, and survey standard errors. These estimates are benchmarked against previously released county estimates.

For a county's estimate to be published, data must meet certain criteria, including a minimum number of reports where the respondent reported both harvested acreage and yield. Estimates that don't meet these standards are combined with other counties of the state and published as "other counties" totals and averages. Yield estimates for a county used here are from all production methods, including irrigated and non-irrigated, in a weighted average.

County-level yield estimates were extracted from the NASS Quick Stats 2.0 database, selecting years 1946 to 2023, for twelve Midwestern states (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, and Ohio). The starting year of 1946 was selected to represent the beginning of the hybrid corn era. Hybrid corn was rapidly adopted by farmers as it became widely available in the late 1930s and early 1940s and, by 1946, accounted for the majority of U.S. corn acreage. These data were analyzed for four time periods, the full hybrid corn era from 1946 to 2023 and three subperiods that correspond to significant advances in corn breeding:

- **Hybrid Corn Era:** 1946 to 2023
- **Double Cross Era:** 1946 to 1962, when double cross hybrids were most common. (Note: Kansas started reporting county-level corn yields in 1958.)
- **Single Cross Era:** 1963 to 1995, starting when single cross hybrids were introduced.
- **Biotech Era:** 1996 to 2023, during which corn hybrids with biotech traits were widely adopted.

For each period and county, a line was fitted to the data points of year and county yield. The slope of the line indicates the year-to-year increase in yield during the period. The relative yield variability of each period and county was also determined by taking the mean absolute error of county yearly yield versus the fitted line and dividing by the average yield for each period and county. Relative yield variability provides a measure of how much variability exists in yields year-over-year for a period and county.

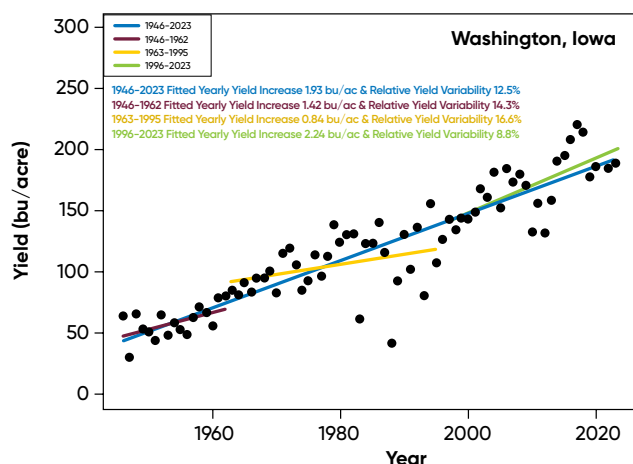


Figure 1. Average county corn yield (bu/acre) by year (1946–2023) and line fits for 4 time periods, Washington County, Iowa.

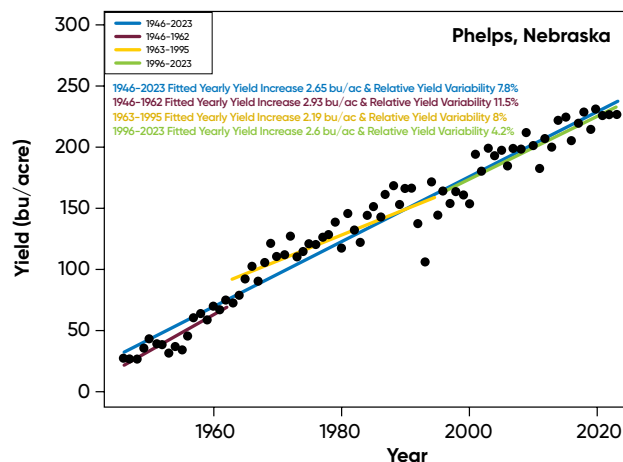


Figure 2. Average county corn yield (bu/acre) by year (1946–2023) and line fits for 4 time periods, Phelps County, Nebraska.

Corn yield data from two counties (Washington County, in southeastern Iowa and Phelps County, in south central Nebraska) provide examples of the output in Figures 1 and 2. Each black dot represents the yield reported for that year. The blue line is the yield increase fit line for all available years for the county, and red, yellow, and green lines are fitted for 1946 to 1962, 1963 to 1995, and 1995 to 2023, respectively. Each period's yield increase and relative yield variability is also included on the graph.

In these examples, both counties appear to have relatively low levels of variability, with Phelps, NE exhibiting very low variability. This may be in part due to the benefits of irrigation in moderating weather-based yield swings. Corn production in Phelps County, NE, is largely under irrigation, while Washington County, IA, is mostly rainfed.

YEAR-OVER-YEAR YIELD GROWTH

Over the full time period of 1946 to 2023, the greatest year-over-year yield increases occurred in central Illinois and the upper west parts of the Corn Belt (northwest half of Iowa, southern Minnesota, and eastern South and North Dakota), along with irrigated areas of Nebraska and southwestern Kansas (Figure 3).

During the double cross era of 1946 to 1962, yield growth was very slow in the Dakotas due to poorly matched or adapted genetics. Pockets of Iowa, Illinois, and Indiana saw large yield jumps in this period. Kansas is not included due to lack of complete county-level data. Central and northwestern Nebraska also saw major gains due to growth in acreage under irrigation.

The single cross era of 1963 to 1995 saw major yield increases in Nebraska, southwestern Kansas, and the Missouri bootheel, presumably due to the introduction of large-scale irrigation management. Yield growth languished in southern and eastern Iowa and eastern Illinois. Upon deeper examination this was due to highly variable yields during this period for those counties. For example, Washington County, IA (eastern part of the state), had a yield increase of 0.84 bushels per

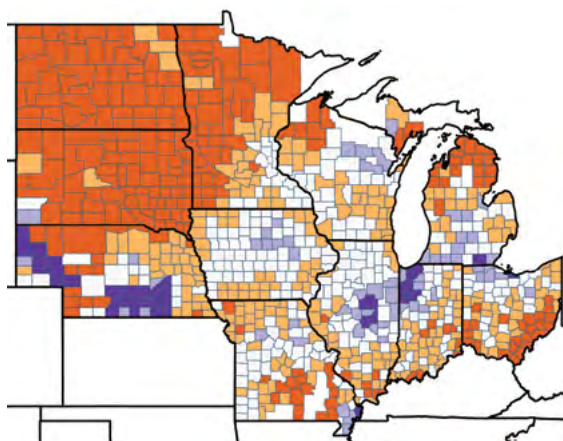
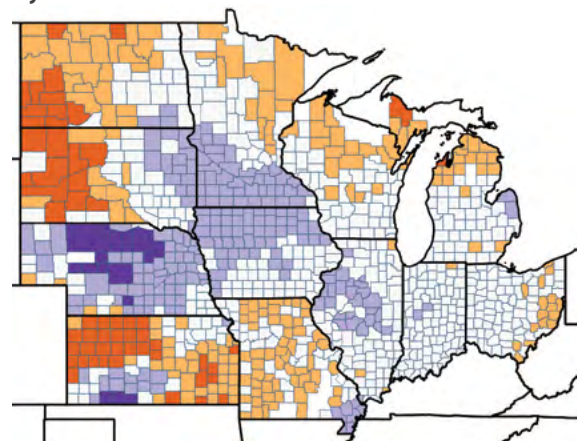
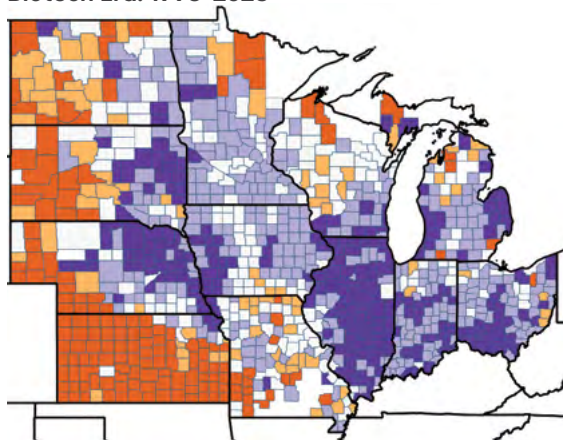
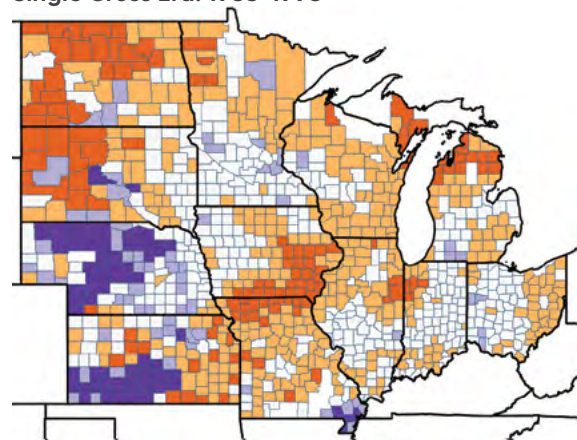
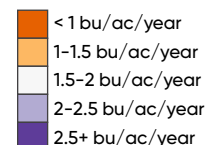
Hybrid Corn Era: 1946–2023**Double Cross Era: 1946–1962****Single Cross Era: 1963–1995****Biotech Era: 1996–2023****Yearly Yield****Growth**

Figure 3. Yearly yield growth (bu/acre) by county over the full hybrid corn era (1946 to 2023), double cross era (1946 to 1962), single cross era (1963 to 1995), and biotech era (1996 to 2023).

acre per year during this period with a coefficient of variation of 16.6%. Drought years of 1983 and 1988 pulled down the generally increasing yield trend. See the Washington County, IA, graph above for more details.

In the biotech era of 1996 to 2023, major yield growth occurred throughout the Midwest, primarily in Illinois but also in Indiana, Ohio, Michigan, Nebraska, and the Dakotas. Despite the benefit of irrigation, Kansas yield growth stagnated during this time to less than 1 bu/acre/year. This may be due to more acres of lower yielding dryland corn coming into production during this time, utilizing newly developed drought-tolerant genetics. Curiously, muted yield growth was exhibited in a band of counties running north-south through central Iowa. The drought of 2012 and wet conditions in 2013 played a part in this reduction of yield growth for that area.

RELATIVE YIELD VARIABILITY

The relative yield variability is a useful statistic to illustrate the relative variability of yield that a period and county has compared to its yield levels during that period.

Any reduction in relative yield variability can be due to improvements in genetics, both increasing overall yields and reducing losses during stressful environments. This also may

be due to technological improvements, such as irrigation, pest control (weeds, insects, and disease), and operations timeliness due to larger and faster planting and harvesting equipment.

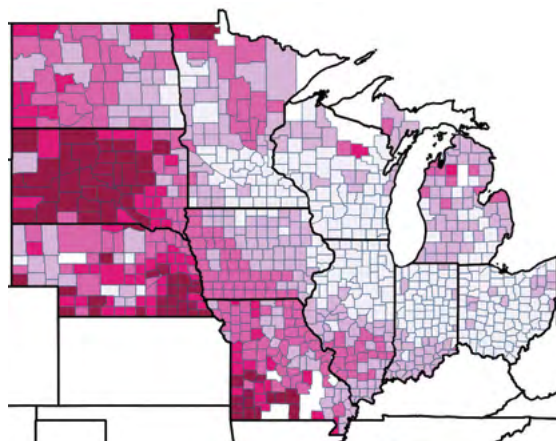
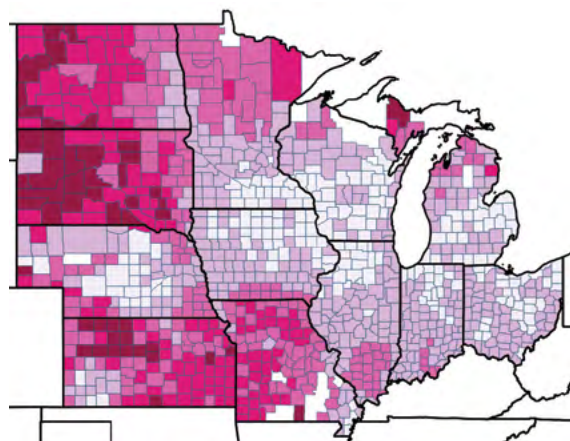
The relative yield variability map for 1946–2023 provides guidance to the overall variation of corn production across the Midwest. The irrigated areas of Nebraska and southwestern Kansas, northern Iowa, southern Minnesota and Wisconsin, and northern Illinois have lower relative yield variability than other parts of the Midwest, such as the Dakotas, Kansas, and Missouri.

During the double cross era of 1946–1962, parts of Illinois, Indiana, Wisconsin, and southern Minnesota exhibited lower relative yield variation. However, this variation increased into western Iowa, Nebraska, Missouri, and the Dakotas, likely due to genetics that were not as tolerant of the variable environments found in those regions. The benefits of irrigation are visible in central Nebraska, reflected in reduced relative yield variability compared to eastern Nebraska where irrigation was not in place at the time.

Variation is reduced during the single cross era of 1963–1995 in the central Nebraska and southwestern Kansas regions, again due to the implementation of irrigation during that

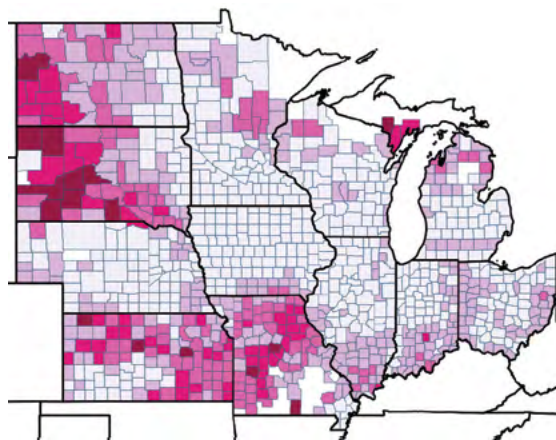
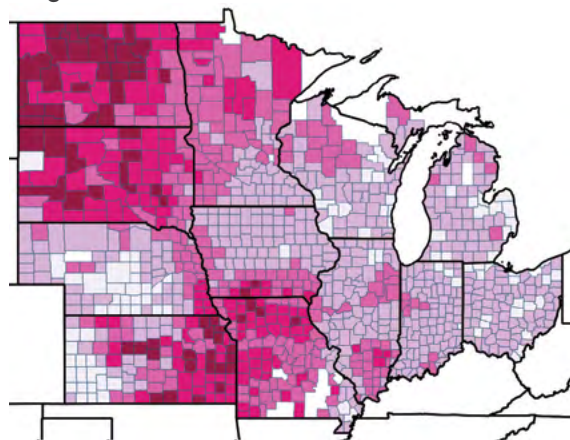
Hybrid Corn Era: 1946–2023

Double Cross Era: 1946–1962



Single Cross Era: 1963–1995

Biotech Era: 1996–2023



Relative Yield Variability

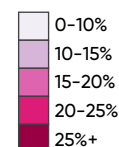


Figure 4. Relative yield variability (%) by county over the full hybrid corn era (1946 to 2023), double cross era (1946 to 1962), single cross era (1963 to 1995), and biotech era (1996 to 2023).

time. The Dakotas, eastern Kansas, Missouri, and southern Iowa still exhibit higher variation due to the environment and genetics matched in those areas.

However, during the biotech era of 1996–2023 there was a great reduction in variation across large areas of the Midwest, including previously variable regions like the eastern Dakotas. Improvements in genetics and traits, including weed and insect control, are likely contributors to the reduction in variation. A few areas of southern Iowa, Missouri, eastern and northern Kansas, and west of the Missouri River in the Dakotas still show relatively high levels of variation compared to the main Corn Belt region. Improvements in genetics helped to bring down the overall variation in many areas, but environmental conditions still have greater influence in others.

YIELD LEVELS IN ENVIRONMENTAL STRESS YEARS

1983, 1988, and 2012 were years in which widespread severe drought sharply reduced corn yields and in 1993, extensive flooding and below average temperatures reduced yields and delayed maturity (Figure 5). These four years are selected to illustrate the effects that localized droughts and flooding have on yield performance in particular regions. These depressed yields generated higher variability in yield and

reduced the year-over-year yield growth during those periods for those affected counties. The yield loss was due in part to the environment (weather and soils), but also due to the way the genetics at that time responded to the environment. Advances in genetics – particularly, improvements in drought tolerance – have reduced the impact of environmental extremes over time. Corn yields in 1983, 1998, and 2012 were all sharply below the trendline average for their respective time periods; however, yields were considerably higher in 2012 compared to 1983 and 1988 in most areas.

TAKING A REGIONAL VIEW

Focusing on the compiled results from the 12 states, there was a 1.88 bu/acre/year yield increase from 1946 to 2023 (Figure 6). During the double cross era of 1946 to 1962, the yield increase was 1.66 bu/acre/year. Interestingly, the yield increase was about the same during the single cross era of 1963 to 1995 with 1.59 bu/acre/year, along with an increase of relative yield variability from 7.5 to 9.4%. However, during the biotech era of 1996 to 2023, both the yearly yield rate of increase improved to 1.90 bu/acre/year and a reduction of variation occurred, with the relative yield variability dropping to 3.8%. The one year with a great deviation from the trend line was the drought year of 2012 with a mean yield of 122.5 bu/acre for the region.

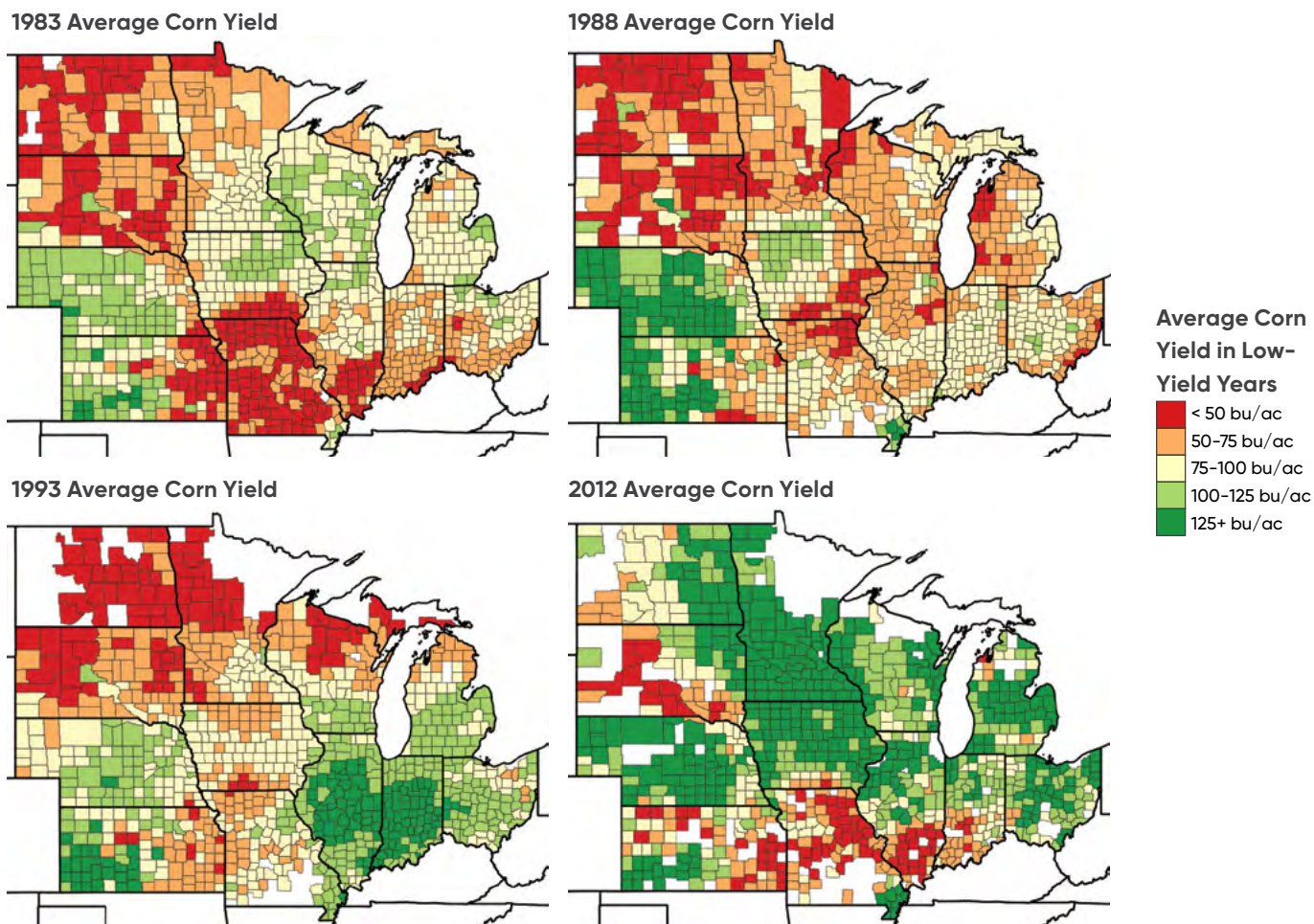


Figure 5. Average county level corn yields (bu/acre) in years when corn yield was sharply reduced by widespread environmental stress: 1983 (drought), 1988 (drought), 1993 (flooding and low temperatures), and 2012 (drought).

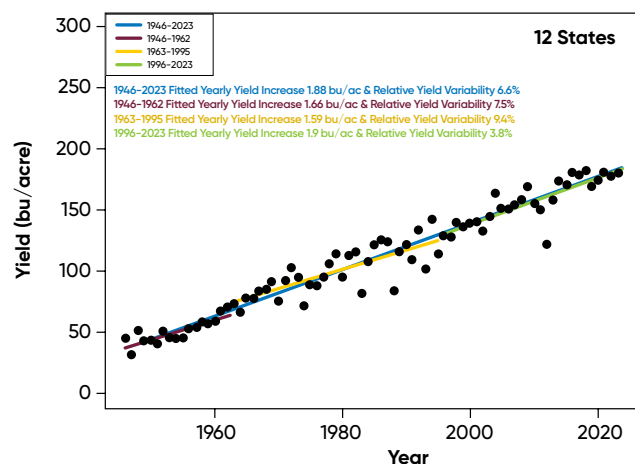


Figure 6. Average corn yield (bu/acre) by year (1946-2023) and line fits for 4 time periods across 12 Midwestern states.

WHAT CAN BE LEARNED FROM THIS?

Corn yields in the Midwestern United States have increased over time, primarily due to improved genetics, traits, and management. However, the improvement has not been

uniform spatially or temporally. Some periods show more improvement in yield growth rate than others. Some periods show a greater reduction in variation than others. Areas like Illinois and central Nebraska show strong yield growth and reduced variation, while “fringe” areas like the Dakotas, Missouri, and southern Iowa still have relatively high levels of variation and less yield growth.

These maps and graphs help to show where growth has occurred and where it can still take place with focused genetics and management. While the soils and weather in the “fringe” areas cannot be easily changed, the selection of proper genetics, along with improved management (variable rate seeding, cover crops, and trait selection) may provide an opportunity to drive greater yield gains and reduce year-to-year variation.

These maps and graphs can also provide useful context as to how far the seed corn industry has come over 78 years. Improvements in breeding, testing, and trait integration are showing their effects, especially in recent years. Environments that caused large yield reductions in the past are now increasingly muted due to the improvements made in the industry.



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Mark Jeschke, Ph.D.,
Agronomy Manager

COMPARING MATURITY OF PIONEER® BRAND CORN PRODUCTS

KEY POINTS

- Comparative relative maturity (CRM) ratings are values that allow maturity comparisons between corn products.
- There is no industry standard for maturity ratings, which can make it challenging to compare corn product maturities across seed brands.
- CRM rating is based on expected grain moisture at harvest – each additional in point in CRM reflects an additional ½ point of moisture at the same harvest timing.
- Hybrids with the same CRM rating may differ in their time to silking and physiological maturity.
- Understanding the time to silking and physiological maturity is important for mitigating stress risk, managing irrigation timing, and ensuring hybrids can reach maturity before the first frost.

COMPARATIVE RELATIVE MATURITY (CRM)

Corn maturity ratings help growers compare and select corn products, manage risk, and spread out their harvest period. However, because there is no industry standard for these ratings, comparing corn product maturities across seed brands is not necessarily straightforward. This article explains corn maturation and the comparative relative maturity (CRM) rating system for Pioneer® brand corn products.

By rating its corn products for silking, physiological maturity and harvest moisture, Corteva Agriscience provides information needed to accurately compare corn product differences and help make sound decisions. CRM ratings for Pioneer brand corn products are values that allow maturity comparisons between corn products. However, they do not represent actual days from planting or emergence. Because growers tend to talk in calendar days, the guidelines provided here will allow you to convert CRM or growing degree unit (GDU) differences between corn products to approximate calendar days. Varied climates or extreme conditions may alter some corn maturity comparisons.

GROWING DEGREE UNITS (GDU)

Growing degree unit ratings assigned to Pioneer brand corn products are based on the amount of heat unit accumulation measured from planting date to silk and physiological maturity (or zero kernel milk line), using the 50°F minimum / 86°F maximum accumulation method. The GDU formula to calculate daily accumulation is:

$$\text{GDUs} = [(\text{min. temp.} \geq 50^{\circ}\text{F} + \text{max. temp.} \leq 86^{\circ}\text{F}) / 2] - 50$$

GDUs, like relative maturity ratings, have no industry standard. Companies use different formulas or methods to calculate GDUs and evaluate their corn products in different locations, so comparisons between companies are usually difficult.

GDUs to physiological maturity (zero kernel milk line), is the best indicator to determine if a corn product can normally mature in an area based on comparison with long-term GDU accumulation records for the area.

Example: Similar harvest moisture w/ different silking dates:

Hybrid	GDUs to Silk	CRM
Hybrid A	1240	100
Hybrid B	1190	100
Difference	50 GDUs	0 CRM
Guideline	25 GDU = ~1 day	1 CRM = ~1 day
Calendar Day Difference	2 days	0 days

Hybrid B will silk around two days earlier than Hybrid A.

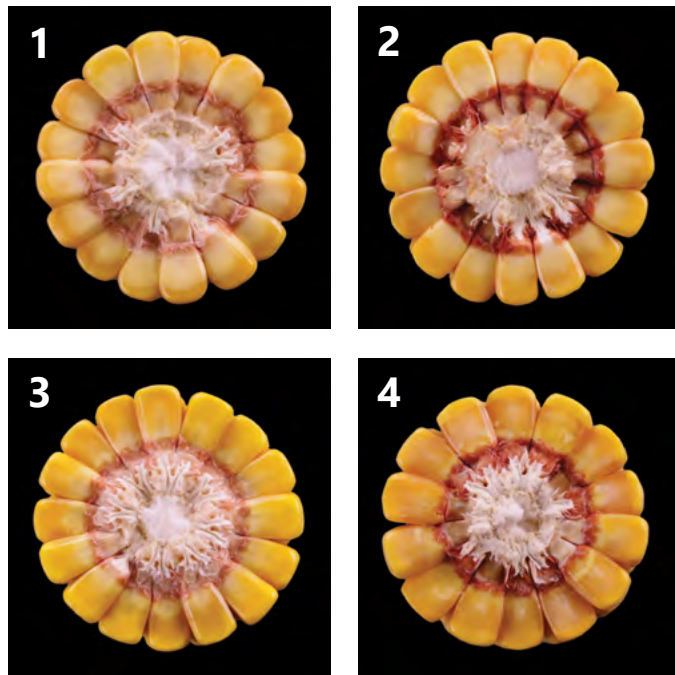


Figure 1. Progression of the milk line down the kernels as corn ears approach physiological maturity.

COMPARING MATURITY DIFFERENCES AT SILKING

Some growers like to spread the pollination period to help reduce risk of yield loss associated with stress events during this time, but planting corn products with different harvest moisture ratings (different maturities) may not always provide the desired difference. These general guidelines can help:

- At silking, a difference between corn product ratings of 25 GDUs equals approximately one calendar day.
- Under normal planting conditions, a 5-day delay in planting date equals only a 2-day delay in silking date.

Research has documented that corn can adjust its growth and development, requiring fewer GDUs to reach maturity

Example: Different harvest moisture but similar silking dates:

Hybrid	GDUs to Silk	CRM
Hybrid C	1340	109
Hybrid D	1340	111
Difference	0 GDUs	2 CRM
Calendar Day Difference	0 days	2 days

Even though Hybrid D is two days later to harvest moisture, Hybrid C and Hybrid D will silk at about the same time.

when planted later. For example, if Hybrid C were planted on May 1 and again on May 20, instead of an 8- to 10-day delay in silking, you may observe only a 4- to 5-day difference.

Area Adaptation – To help determine if a new corn product fits your area, compare its silk rating to a corn product you know and consider these general guidelines:

- Earlier silking corn products generally move north of their adapted zone and more readily adapt to higher elevations.
- If moved too far north or up in elevation, late silking corn products may not reach physiological maturity before frost or may have reduced yield potential if abnormally late silking exposes the crop to cooler temperatures during grain fill.

Early Irrigation Timing – Corn products that silk early should receive irrigation earlier than those that silk late. The first in-season irrigation of early corn products, planted south of their normal adapted zone for early harvest, should be based on their stage of development rather than traditional calendar dates that may be used for full-season corn products.

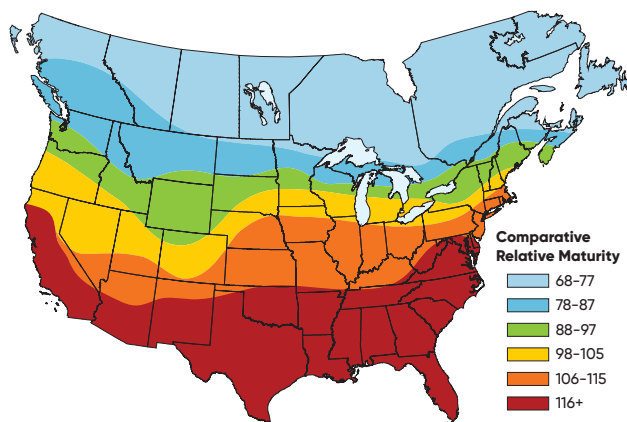


Figure 2. Dominant corn maturity zones.

Stress during the period spanning two weeks before until two weeks after silking can result in large yield reductions since kernel number is determined during this stage. Severe moisture stress can delay silk emergence, reduce kernel set and cause incomplete pollination.

COMPARING DIFFERENCES AT PHYSIOLOGICAL MATURITY

A hard killing frost before physiological maturity will cause premature black layer, halt grain fill, and may result in poor grain quality and test weight. Frost-damaged corn is usually slower drying and additional losses may result due to delayed harvest. It is critical to select corn products that can normally mature before the first average killing frost date in your area.

The GDUs to physiological maturity rating is the best indicator to determine whether a corn product can safely be planted in an area. Compare the ratings of a new or unfamiliar corn product to one you are currently planting or one that is used successfully in your area.

Example: Corn products with similar harvest moisture or CRM in the fall can reach physiological maturity at different times:

Hybrid	GDUs to Phys. Maturity	CRM
Hybrid E	2580	111
Hybrid F	2730	111
Difference	150 GDUs	0 CRM
Guideline	25 GDU = ~1 day	1 CRM = ~1 day
Calendar Day Difference	10 days	0 days

Hybrid E will reach physiological maturity about 10 days earlier than Hybrid F.

General Guidelines:

- At physiological maturity (zero milk line), a difference between corn product ratings of 15 GDUs equals approximately one calendar day.
- At physiological maturity (zero milk line), the grain moisture content will be approximately 30% for most corn products.

Final Irrigation Timing – Late season stress can reduce yields due to premature death by reducing kernel weight and inviting stalk rot problems. Grain quality and test weight can also be significantly affected.

Several different methods or models exist to calculate final irrigation needs. Comparing GDU differences between corn products for physiological maturity and checking for zero milk line development in the field can be helpful general indicators of final water requirements.

Example: A corn product that reaches physiological maturity early shows that its kernel milk line is almost completely down and approaching black layer. If your field water-holding capacity is at 60%, further irrigation may not be required. However, a corn product that is 5 to 10 days later to physiological maturity may require an additional watering to mature properly, depending on field capacity or daily water use.

COMPARING MATURITY DIFFERENCES AT HARVEST

By comparing harvest moisture (CRM) ratings, you can estimate the difference in moisture content between corn products and help plan a harvest schedule. A corn product with a CRM difference of 10 would be approximately 10 days later to reach a similar harvest moisture level (normally in the low 20s) if planted on the same date as the earlier corn product.

By using the general guideline that one CRM equals ½ point of moisture, a corn product that is rated 10 CRM later would be approximately 5 points wetter if both corn products were planted and harvested the same day. In the field, however, this relationship can change depending on harvest timing, moisture at harvest, and environmental conditions.



Paul Hermans,
Sales Agronomist

James D'Aoust,
Sales Agronomist

Mark Jeschke, Ph.D.,
Agronomy Manager

CORN YIELD RESPONSE TO PLANT POPULATION IN CENTRAL AND EASTERN ONTARIO – 2023

KEY FINDINGS

- Optimum plant population was greater in higher yielding environments than in lower yielding environments.
- Pioneer® P9026^{AM}™ and P9466^{AML}™ brand corn differed in their response to plant population, and optimum population for maximum yield.
- Kernel weight declined with increasing population. Kernel weight was similar between the two hybrids at lower population but diverged slightly at higher populations.

HYBRID RESPONSE TO POPULATION – 2023 TRIALS

- On-farm trials evaluating corn hybrid response to plant population were conducted at 14 locations across Central/Eastern Ontario in 2023.
- Hybrids were planted at 4 different populations at each location. Most locations included four populations: 26,000, 30,000, 34,000, and 38,000 plants/acre.
- A total of eight different Pioneer® brand corn products were included in the study, with Pioneer P9026^{AM}™ (AM,LL,RR2) and P9466^{AML}™ (AML,LL,RR2) brand corn included at most locations (Table 1).
- Each location had either 1 or 2 replications.
- Average kernel weight was measured at 10 locations in 2023 for Pioneer® P9026^{AM}™ and P9466^{AML}™ brand corn.

Table 1. Pioneer brand corn products included in 2023 on-farm population trials and the number of locations for each.

Hybrid/Brand ¹	Number of Locations
P9026 ^{AM} ™ (AM,LL,RR2)	10
P9316 ^Q ™ (Q,LL,RR2)	1
P9466 ^{AML} ™ (AML,LL,RR2)	12
P9492 ^{AM} ™ (AM,LL,RR2)	1
P9624 ^Q ™ (Q,LL,RR2)	1
P9845 ^{PCE} ™ (PW,ENL,RIB)	1
P96760 ^Q ™ (Q,LL,RR2)	1
P97299 ^{AM} ™ (AM,LL,RR2)	1

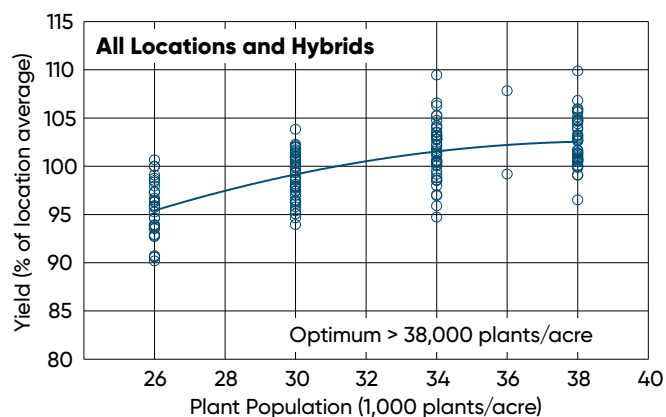


Figure 1. Corn yield response to population across all hybrids and locations. Corn yield is expressed as a percent of the location average.

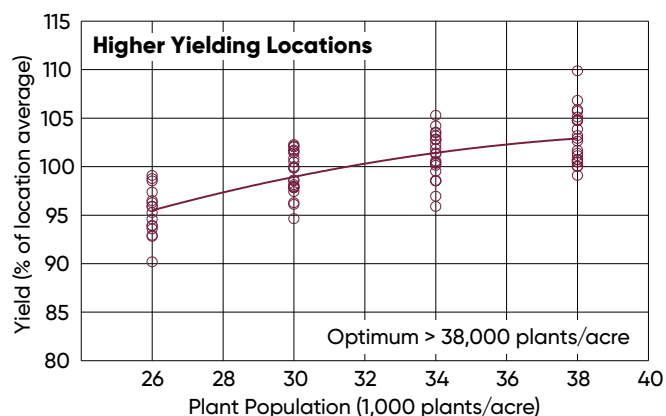


Figure 2. Corn yield response to plant population at seven higher yield level locations. (Location average >235 bu./acre.)

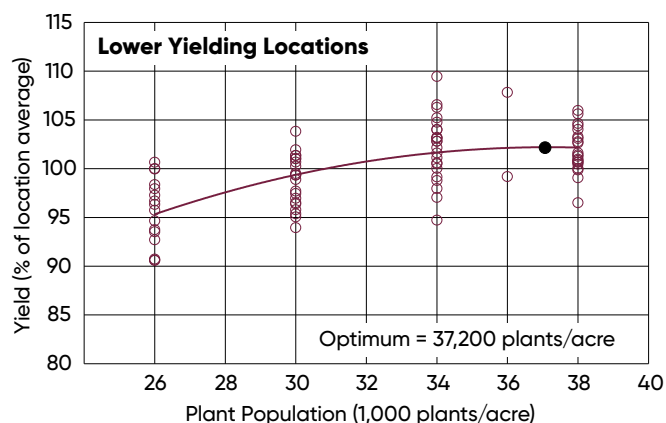


Figure 3. Corn yield response to plant population at seven lower yield level locations. (Location average < 235 bu./acre.)

RESULTS

2023 Population Trials

- The agronomic optimum plant population across all hybrids and locations was above the highest population in the study of 38,000 plants/acre (Figure 1).
- On-farm trial locations were separated out as higher or lower yielding based on the average yield of the location to determine if yield response to plant population differed by yield level.
- Seven locations were classified as lower yielding, with a location average yield of 215–235 bu/acre.
- Seven locations were classified as higher yielding, with a location average yield of 235–280 bu/acre.
- Higher yielding environments would be expected to have a higher optimum plant population and that proved to be the case in this study.
- As was the case across all locations, the optimum plant population for the higher yielding subset of locations was above the highest population in the study of 38,000 plants/acre (Figure 2).
- For lower yielding locations, the agronomic optimum plant population was slightly below the top end of the study range at 37,200 plants/acre. (Figure 3).

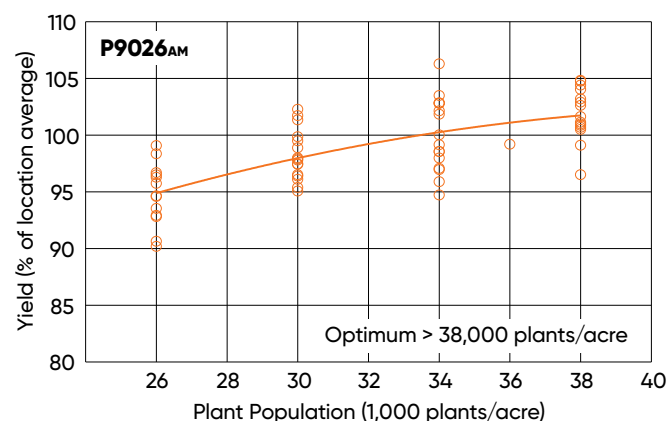


Figure 4. Yield response of Pioneer P9026_{AM} to plant population.

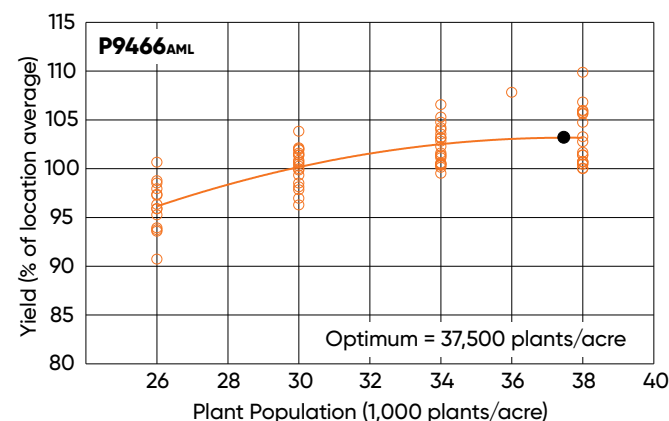


Figure 5. Yield response of Pioneer P9466_{AML} to plant population.

2023 Hybrid Comparison

- This study included two Pioneer® brand corn products, P9026_{AM}™ and P9466_{AML}™, that were planted at the majority of trial locations.
- The optimum plant population for P9026_{AM} was above the population range of the study (>38,000 plants/acre) (Figure 4).
- The optimum plant population for P9466_{AML} was 37,500 plants/acre (Figure 5).

Multiyear Results: 2021–2023

- 2023 was the third year that corn population trials were conducted across Central and Eastern Ontario.
- In 2021, population trials across 16 locations including populations of 28,000, 32,000, 36,000, and 40,000 found an agronomic optimum of 37,600 plants/acre.
- In 2022, population trials were conducted across 22 locations with a slightly lower population range of 26,000, 30,000, 34,000, and 38,000 and the agronomic optimum was above the range of the study.
- Across all 52 site-years of the study from 2021–2023, the agronomic optimum population was above the top end of the population range of 40,000 plants/acre (Figure 6).

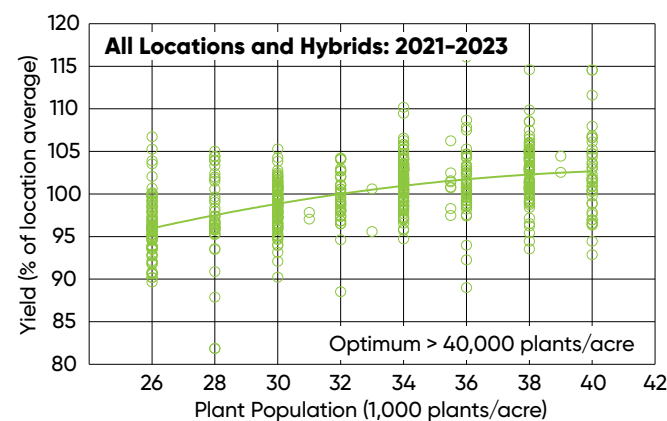


Figure 6. Yield response to plant population across all hybrids and locations from 2021–2023.

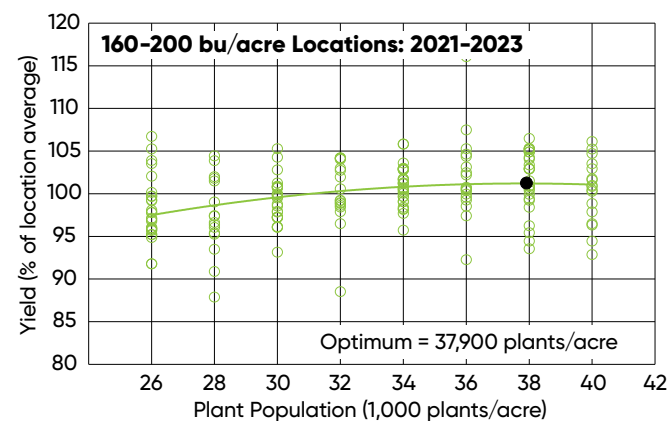


Figure 7. Yield response to plant population across 17 low yield locations (location average 160–200 bu/acre) from 2021–2023.

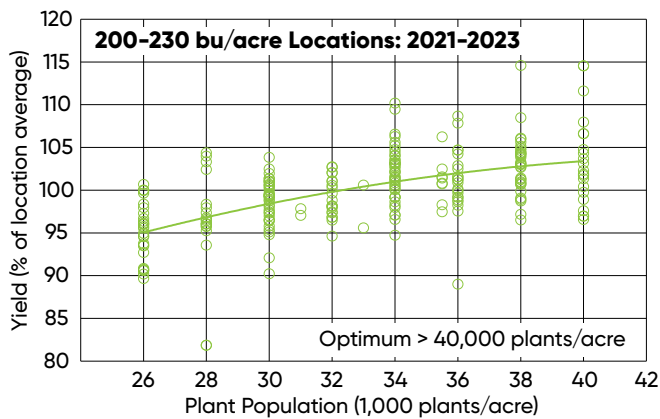


Figure 8. Yield response to plant population across 23 moderate yield locations (location average 200-230 bu/acre) from 2021-2023.

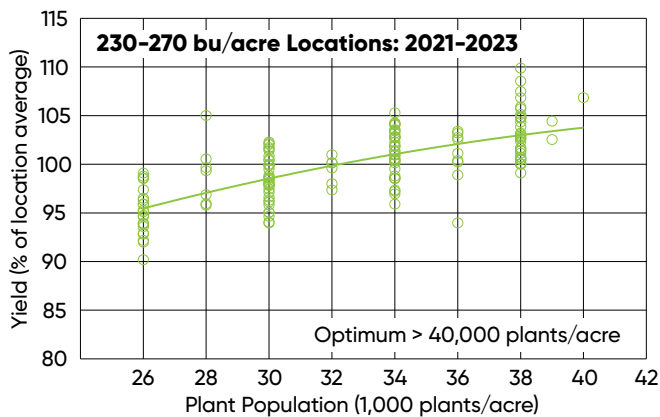


Figure 9. Yield response to plant population across 16 high yield locations (location average 230-280 bu/acre) from 2021-2023.

- All plant population trial site-years from 2021 to 2023 were separated into three yield classifications: low (160-200 bu/acre), moderate (200-230 bu/acre), and high (230-280 bu/acre).
- Only the lower yielding locations had an agronomic optimum plant population that fell within the population range of the study (Figure 7).
- For the moderate and high yielding locations, yield was greatest at the top end of the population range.

2023 Kernel Weight

- Average kernel weight was measured at 10 locations in 2023 for Pioneer® P9026AM™ and P9466AML™ brand corn (Figure 10).
- Kernel weight was relatively high in this study, with an average of 73,460 kernels/bushels. Even at the highest population, kernels/bushels did not exceed 80,000 (Figure 10).
- Kernel weight declined with increasing population. Kernel weight was similar between the two hybrids at lower population but diverged slightly at higher populations.
- A balance between kernels per bushels and kernels per acre is needed to maximize agronomic and economic returns.

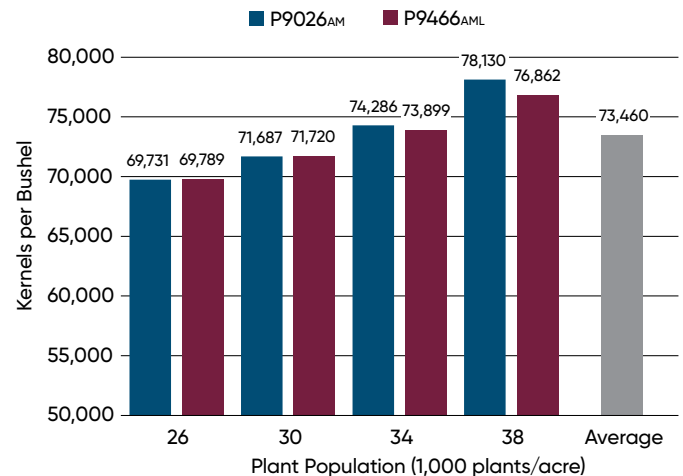


Figure 10. Kernels per bushel by hybrid and population across 10 study locations in 2023.

- For other hybrid population recommendations, please check out the Pioneer Planting Rate Estimator at: <https://www.pioneer.com/ca-en/tools-services/planting-rate-estimator.html>
- Local research is ideal for population setting. Talk to your Pioneer Sales Representative.

Special thanks to our cooperators and project supporters:

Eastern Ontario: Emerald Acres, J&H Nixon Farms, Hog Haven Inc., Golden Rail Farms, Vernon Valley Farms, Fife Agronomics, Dutchbern Farms, Jim Parks, David Renaud and Marc Heeney

Central Ontario: Reesor Seed & Grain, Parbro Farms Ltd., Ryan Svendsen, Ray Cann Farming Ltd., Glen Isle Farms Ltd., Jeff Harrison Farms Ltd., Hollowdale Cattle Company Ltd., Greydafton Farms Inc.



HYBRID AND PLANT POPULATION EFFECTS ON CORN KERNEL WEIGHT



Liam Bracken,
Associate Territory Manager

Paul Hermans,
Sales Agronomist

James D'Aoust,
Sales Agronomist

Mark Jeschke, Ph.D.,
Agronomy Manager

KEY FINDINGS

- A field study was conducted in 2023 to evaluate corn kernel weight, including differences among hybrids, and effects of plant population.
- Kernel weight was generally greater than normal in this study due to favorable grain fill conditions, with hybrid family averages ranging from 77,146 to 66,759 kernels/bu (32.9 to 38.0 g/100 kernels).
- An understanding of relative kernel weights for hybrids can help in calculating more accurate yield estimates.

IMPORTANCE OF KERNEL WEIGHT TO CORN YIELD

- Genetic gains and enhanced management are the main contributing factors to the approximately 2 bu/acre annual increase in average corn yields.
- Corn breeders have improved the genetic ability of hybrids to maintain kernels per ear at higher populations (Tollenaar and Lee, 2002), resulting in more kernels per acre and more yield.
- However, another key factor in the yield equation that has been receiving more attention recently from industry and university institutions is kernel weight.
- Genetic improvements in kernel weight have been associated with an extended kernel-fill period (Fernandez et al., 2022).
- Understanding the relative importance of kernel number and kernel weight in how an individual hybrid builds yield can improve the accuracy of pre-harvest yield estimates as well as help in evaluating the influence of late-season management or environmental conditions on kernel weight.
- When making pre-harvest yield estimates, the traditional 90,000 kernels/bu kernel weight factor used for calculating yield may underestimate the yield of the crop.

2023 KERNEL WEIGHT STUDY

- A field study was conducted in 2023 to evaluate corn kernel weight, including differences among hybrids, and effects of plant population.
- **Locations:** 9 locations in Eastern Ontario
- **Plot Layout:** 1-2 replications per location
- **Hybrids:** Several, range from 90 to 98 CRM
- **Plant Populations:** 26,000, 30,000, 34,000, and 38,000 plants/acre

Sampling Methods

- Three representative ears were collected from each hybrid and population and shelled to obtain moisture.
- 100 kernels from each sample were divided and weighed, and the weight corrected to 15.5% moisture.
- Kernel weights (expressed as kernels/bushel) were calculated based on 56 lbs in a bushel of corn.

RESULTS

- In 2023, growing conditions were above average through this geography with above average rainfall and an open fall.
- Locations in the study encompassed a large range of yield environments, with hybrid within location yields ranging from 161 to 293 bu/acre.

Table 1. Average kernel weight by hybrid family expressed as kernels/bu and g/100 kernels, relative kernel weight as a percentage of the location average and number of comparisons.

Hybrid Family	Kernel Weight (kernels/bu)	Kernel Weight (g/100 kernels)	Relative Kernel Weight (% of Loc. Mean)	# Comp.
P9026	73,475	34.6	100.7	20
P90630	72,623	35.0	101.9	11
P9233	70,868	35.8	104.4	19
P9316	77,035	33.0	96.1	18
P9466	73,066	34.8	101.3	25
P9492	70,410	36.1	105.1	16
P9535	69,869	36.4	105.9	11
P9624	73,190	34.7	101.1	7
P96760	73,269	34.7	101.0	20
P97299	74,576	34.1	99.2	7
P9823	66,759	38.0	110.8	3
P9845	68,883	36.9	107.4	10
DKC42-05	77,146	32.9	95.9	10
DKC46-40	74,342	34.2	99.5	5

- Kernel weight was generally larger than average in this study with hybrid family averages ranging from 77,146 to 66,759 kernels/bu (32.9 to 38.0 g/100 kernels) (Table 1).
- The total range of kernel weights observed in the study was large, ranging from 104,000 to 59,000 kernels/bu (24.4 to 43.1 g/100 kernels).
- To account for environmental differences between locations, a relative kernel weight for each hybrid within a location was calculated as a percentage of the location average. Those percentages were then averaged by hybrid family over all plot locations, as shown in Table 1.
- Kernel weight decreased as plant population increased. Figure 1 shows average kernel weights for two Pioneer® brand corn products that declined from an average kernel weight of 36.4 g/100 kernels at 26,000 plants/acre to 32.8 g/100 kernels at 38,000 plants/acre.
- Kernel weight of the two corn products was similar at lower populations, but P9026^{AM}™ brand corn lost more kernel weight at higher populations than P9466^{AML}™ brand corn did.

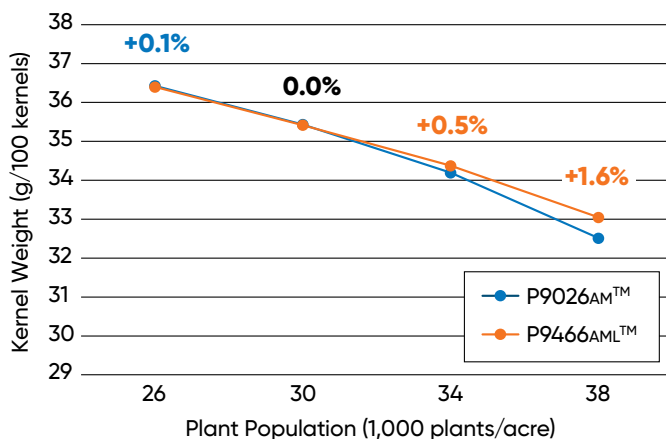


Figure 1. Kernel weight (g/100 kernels) of Pioneer® P9026^{AM}™ (AM, LL, RR2) and P9466^{AML}™ (AML, LL, RR2) brand corn by plant population.

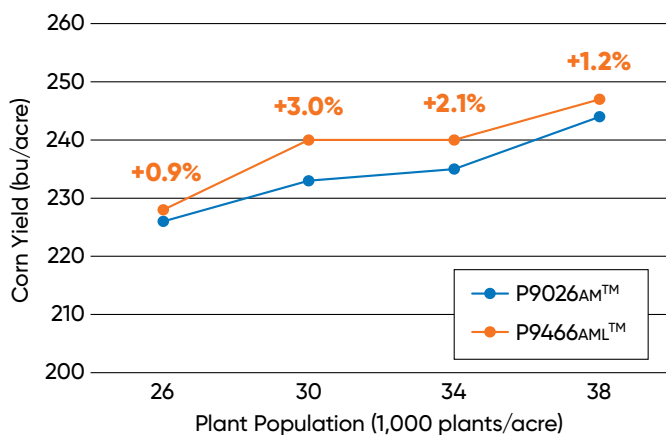


Figure 2. Yield (bu/acre) of Pioneer® P9026^{AM}™ (AM, LL, RR2) and P9466^{AML}™ (AML, LL, RR2) brand corn by plant population.

- Yield of both corn products was maximized at the highest population, as the greater number of kernels per unit area more than compensated for lower kernel weight (Figure 2).
- The drop in kernel weight at high population for P9026^{AM}™ was not reflected in yield, which was less than that of P9466^{AML}™ but not much more so than at the lowest population.
- Results of the study showed that high kernel weight does not necessarily correlate to higher test weight (Figure 3).
- Test weight is a measure of the density of bulk grain, which is the weight of grain that can be packed in a specific volume. Factors such as kernel size, slipperiness of seed coat, and seed integrity all contribute to the test weight grade.

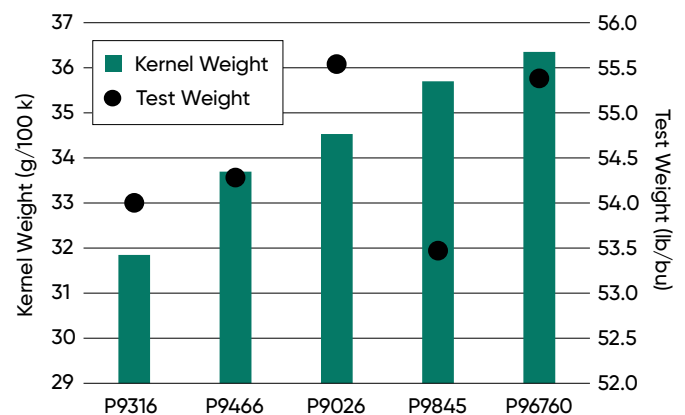


Figure 3. Average kernel weight and test weight of several Pioneer hybrid families in the 2023 study in Eastern Ontario.

KERNEL WEIGHT AND YIELD ESTIMATES

- Kernel weight is influenced by many factors including hybrid genetic profile, management, and environmental conditions, all of which can impact how the hybrid maintains the full kernel weight potential. Any conditions such as lack of water, disease pressure, or nutrient deficiencies can impact the late season grain fill period and kernel weight.
- An understanding of relative kernel weights for hybrids can help in calculating more accurate yield estimates. In addition, understanding how hybrids make yield provides a reference point for making management decisions and can aid in diagnosing product performance.
- When estimating yields, consider using 80,000 kernels per bushel as your standardized kernel weight estimate for most hybrids. For a hybrid family such as P96760, a lower kernels/bu (~70,000) may be more appropriate. Conversely, hybrids in the P90630 family, having a factor of 90,000 kernels/bu may be more suitable. If late-season growing conditions are conducive, a lower kernel/bu number may be assigned (~70,000 kernels/bu), compared to 90,000 kernels/bu if late season conditions are poor.

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Mark Jeschke, Ph.D.,
Agronomy Manager

MANAGING CORN FOR GREATER YIELD POTENTIAL:

Insights from the 2023 NCGA National Corn Yield Contest

KEY POINTS

- Improved hybrids and production practices are helping corn growers increase yields. Over the past 20 years, U.S. yields have increased by an average of 1.6 bu/acre/year.
- The NCGA National Corn Yield Contest provides a benchmark for yields that are attainable when conditions and management are optimized.
- The 2023 contest had 431 entries that exceeded 300 bu/acre, the most ever to attain that yield level.
- Pioneer® brand products were used in 176 NCGA National Corn Yield Contest entries that topped 300 bu/acre in 2023, as well as 205 state-level winners.
- Plant populations in high-yield entries were generally above average but not extraordinarily high, with most falling between 34,000 and 38,000 plants/acre.
- High-yield entries tended to be planted relatively early; however, there were numerous instances where 300 bu/acre yields were achieved with late May or early June planting.
- The vast majority of high-yield entries were planted in 30-inch rows, reflecting overall industry trends.
- Nearly 75% of 300 bu/acre entries included some form of in-season nitrogen application.

BENCHMARKING CORN YIELD

Since the introduction of hybrid corn nearly a century ago, corn productivity improvements have continued through the present day. Over the last 20 years, U.S. corn yield has increased by an average of 1.6 bu/acre per year. These gains have resulted from breeding for increased yield potential, introducing transgenic traits to help protect yield, and agronomic management that has allowed yield potential to be more fully realized.

As growers strive for greater corn yields, the National Corn Growers Association (NCGA) National Corn Yield Contest provides a benchmark for yields that are attainable when environmental conditions and agronomic management are optimized.



2023 NCGA National Corn Yield Contest Trends

The 2023 growing season was overall a good but not great year for corn yields. The USDA estimated average yield was 174.9 bu/acre, which was up slightly from 2022 but still below the long-term trendline. Corn yields were flat or down compared to 2022 in Minnesota, Wisconsin, Illinois, Iowa, Missouri, and Virginia but up in most other states. Indiana, Ohio, and New York set new record highs, as did a cluster of southern states including Tennessee, Alabama, Georgia, and South Carolina.

Drought was the major yield-limiting factor in 2023 with much of the central and northern Corn Belt under some degree of drought stress throughout much of the season. However, high corn yields were still achieved in the NCGA National Corn Yield Contest across many states, including those most affected by drought. The number of contest entries yielding over 300 bu/acre hit a new record high in 2023 with 431, topping the previous high of 418 entries set in 2021 and up sharply from 282 in 2022 (Figure 1).

Thirteen states set new records for 300 bu/acre entries, including Minnesota, Iowa, and Wisconsin, where corn yields overall were flat or down due to drought (Table 1). One of the biggest changes compared to 2022 was in Nebraska, where the number of 300 bu/acre entries was down sharply following two consecutive years of very strong performance.

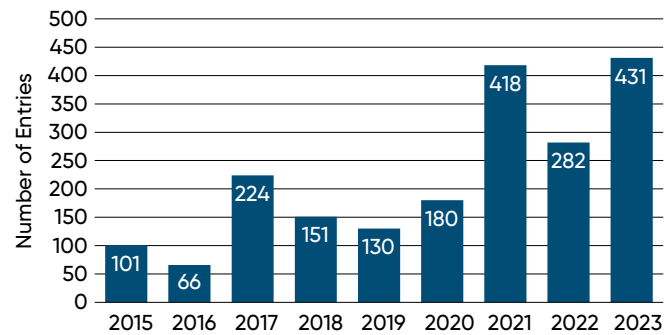


Figure 1. Total entries in the NCGA National Corn Yield Contest exceeding 300 bu/acre by year from 2015 to 2023.

Table 1. Number of NCGA National Corn Yield Contest entries over 300 bu/acre by state, 2019–2023.

State	2019	2020	2021	2022	2023
	number of entries				
AL	5	4	2	3	4
AR	0	1	4	1	2
CA	3	2	1	0	0
CO	0	1	13	6	2
DE	6	0	7	7	10*
GA	7	5	7	7	12*
IA	3	6	33	11	50*
ID	1	3	5	1	2
IL	6	19	37	28	34
IN	8	23	34	26	46*
KS	2	6	13	9	11
KY	3	3	24	1	8
MA	4	1	0	0	3
MD	5	3	8	13	11
MI	4	3	14	2	14*
MN	0	5	3	4	13*
MO	3	11	15	9	9
MT	0	0	0	0	1*
NC	3	0	4	1	2
ND	0	0	0	0	6*
NE	7	37	96	95	57
NH	0	0	0	1	0
NJ	9	9	10	4	12*
NM	1	0	0	0	0
NY	0	0	1	0	0
OH	2	6	25	15	24
OK	0	2	7	2	3
OR	7	0	0	4	1
PA	15	0	2	2	7
SC	4	3	5	0	3
SD	0	2	3	1	4*
TN	3	3	8	1	17*
TX	1	2	5	3	3
UT	0	2	6	4	5
VA	9	0	12	5	19*
WA	7	3	4	3	2
WI	1	13	8	12	29*
WV	1	2	1	1	5
WY	0	0	1	0	0

* New record

Also, of note in the 2023 contest was the continued increase in high yields in northern geographies with shorter CRM hybrids. North Dakota and Montana both had their first-ever 300 bu/acre contest entries in 2023. A total of 13 entries topped 300 bu/acre using Pioneer® brand corn products with maturity under 100 CRM (Table 2).

Pioneer® brand products were used in 176 NCGA National Corn Yield Contest entries that topped 300 bu/acre in 2023, as well as 205 state-level winners. State-level winners included a total of 81 different Pioneer brand products from 62 different hybrid families ranging from 91 to 120 CRM (Appendix).

Yields exceeding 300 bu/acre have been achieved using Pioneer® brand products from 82 different hybrid families

Table 2. Pioneer hybrid families with entries over 300 bu/acre in the 2023 NCGA National Corn Yield Contest.

Hybrid Family	2019	2020	2021	2022	2023	2019-2023
number of entries						
P14830					24	24
P1742				8	20	28
P0953			11	10	17	38
P1170				5	17	22
P1027					13	13
P0924			4	6	10	20
P1718				9	10	19
P1185		10	29	20	5	64
P1136				4	5	9
P1383				3	5	8
P1278				2	5	7
P1366	9	3	6		4	22
P0529					4	4
P1828	4	6	5	4	3	22
P0035					3	3
P1563	1	11	22	15	2	51
P1506		1	4		2	7
P1222			5	6	2	13
P9998	3		2	1	2	8
P13476					2	2
P1608					2	2
P9492					2	2
P9540					2	2
P1197	11	6	8	2	1	28
P1572		6	7	4	1	18
P1108	1	3	10	2	1	17
P0720		3	3		1	7
P1370		2		2	1	5
P1359		1	6	4	1	12
P2042			5	10	1	16
P0817			1	2	1	4
P00177					1	1
P0404					1	1
P10811					1	1
P1413					1	1
P1457					1	1
P1511					1	1
P9193					1	1

over the past five years, ranging from 91 to 120 CRM. The top-performing Pioneer hybrid families in the National Corn Yield Contest are shown in Table 2. The Pioneer brand P14830 family of products had the most 300 bu/acre entries in the 2023 contest, supplanting the P1185 family, which was the top performer the previous two years. Pioneer brand P14830, P1742, P0953, P1170, P1027, P0924, P1718 families all had 10 or more entries over 300 bu/acre in 2023.

HYBRID SELECTION

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

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

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

HIGH-YIELD MANAGEMENT PRACTICES

Top performers in the NCGA yield contest not only have produced yields much higher than the current U.S. average, they have also achieved a higher rate of yield gain over time. Over the past 20 years, U.S. corn yields have increased at a rate of 1.6 bu/acre per year while winning yields in the non-irrigated yield contest classes have increased by 4.5 bu/acre per year (Figure 2). Contest fields are planted with the same corn hybrids

available to everyone and are subject to the same growing conditions, which suggests that management practices are playing a key role in capturing more yield potential. The following sections will discuss management practices employed in contest entries yielding above 300 bu/acre.

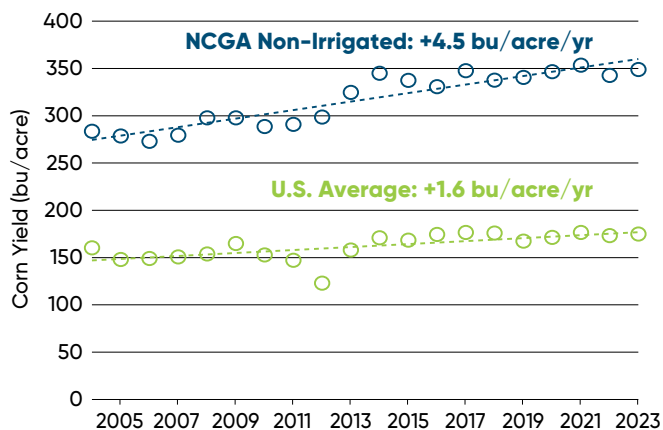


Figure 2. Average yields of NCGA National Corn Yield contest non-irrigated class national winners and U.S. average corn yields, 2004–2023.

PLANTING PRACTICES

Plant Population

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

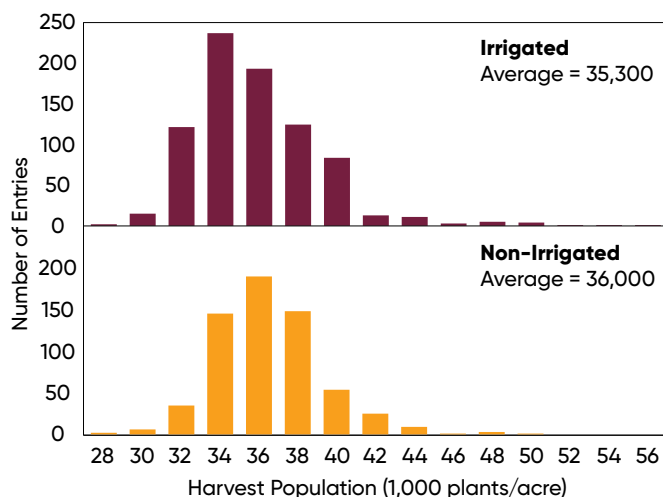


Figure 3. Harvest populations and corn yield of irrigated and non-irrigated NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2019–2023.

Harvest populations in irrigated and non-irrigated national corn yield contest entries over 300 bu/acre from 2019 through 2023 are shown in Figure 3. The average harvest population of non-irrigated entries (36,000 plants/acre) was slightly greater than that of irrigated entries (35,300 plants/acre) over five

years. Both are well above the USDA average plant population of 29,200 plants/acre, as would be expected for high-yielding environments. However, yields over 300 bu/acre were achieved over a wide range of populations, from 27,000 to 56,000 plants/acre, demonstrating that exceptionally high populations are not necessarily a prerequisite for high yields. Although population density is important in establishing the yield potential of a corn crop, it is just one of many factors that determine yield.

Planting Date

High-yielding contest plots are usually planted as early as practical for their geography. Early planting lengthens the growing season and, more importantly, moves pollination earlier. When silking, pollination, and early ear fill are accomplished in June or early July, heat and moisture stress effects can be reduced.

The range of planting dates for contest entries exceeding 300 bu/acre in several states is shown in Figure 4, as well as the mid-point of corn planting progress according to USDA NASS for reporting states. Average planting dates for 300 bu/acre entries in 2023 was generally mid-April for Southern and East Coast states and late April through early May for Corn Belt states. The 2023 contest had several high-yield entries planted in mid- to late May and even early June, demonstrating that high yields can still be achieved under favorable conditions if planting is not delayed for too long. However, the odds of achieving high yields are generally going to be better with earlier planting.

- 300 bu/acre Entries Planting Date (min - average - max)
- Corn Planting 50% Completed (USDA NASS)



Figure 4. Average planting date and planting date range of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2023 in select states.

Row Spacing

The vast majority of corn acres in the U.S. are currently planted in 30-inch rows, accounting for around 80% of corn production. A majority of 300 bu/acre contest entries over the past five years have been planted in 30-inch rows (Figure 5). This proportion has increased slightly in recent years as wider row configurations (most commonly 36-inch or 38-inch) have remained steady and narrower row configurations (15-inch, 20-inch, 22-inch, or 30-inch twin) have declined.

Row spacings narrower than the current standard of 30 inches have been a source of continuing interest as a way to achieve greater yields, particularly with continually increasing seeding rates. However, research has generally not shown a consistent yield benefit to narrower rows outside of the northern Corn Belt (Jeschke, 2018).

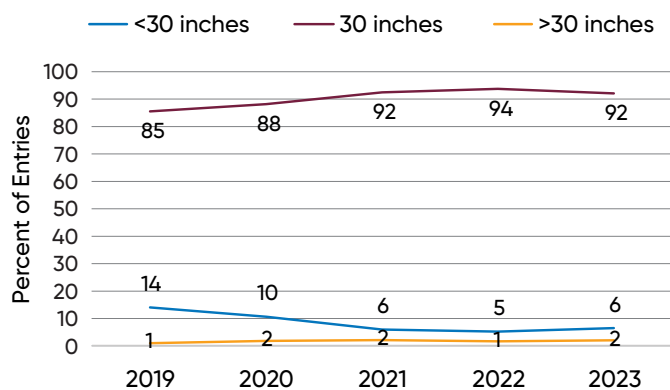


Figure 5. Row width used in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2019–2023.

CROP ROTATION

Rotating crops is one of the practices most often recommended to keep yields consistently high. Rotation can break damaging insect and disease cycles that lower crop yields. Including crops like soybean or alfalfa in the rotation can reduce the amount of nitrogen required in the following corn crop. A majority of the fields in the 300 bu/acre entries were planted to a crop other than corn the previous growing season (Figure 6).

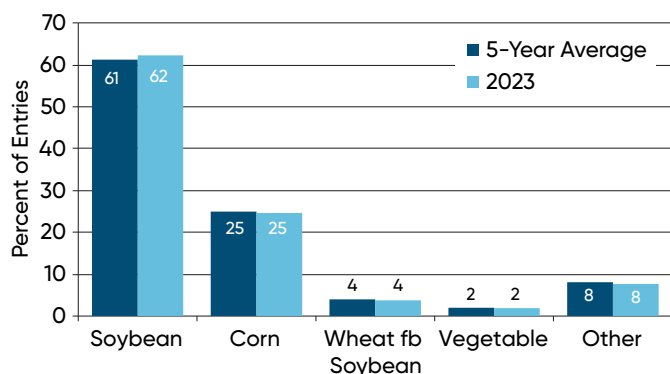


Figure 6. Previous crop in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2023 and 5-year averages.

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

TILLAGE

Over the past five years, around 40% of the high-yield entries in the NCGA contest have used conventional tillage, with the other half using no-tillage or some form of reduced tillage (Figure 7). Tillage practices in 2023 did not differ much from 5-year averages; however, over a longer timeframe, the proportion of high-yield entries using conventional tillage has declined, offset by increases in no-till and strip-till.

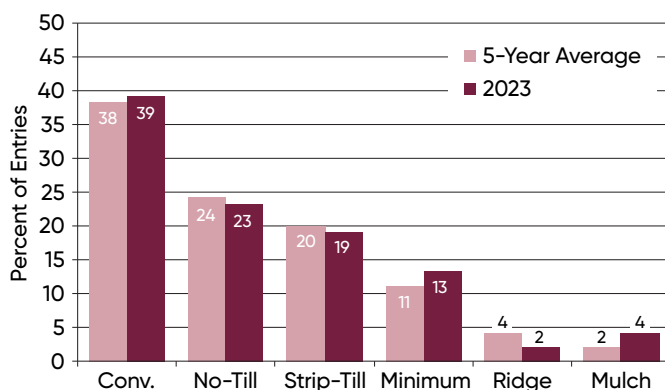


Figure 7. Tillage practices in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2023 and 5-year averages.

NUTRIENT MANAGEMENT

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

Nitrogen

Corn grain removes approximately 0.67 lbs of nitrogen per bushel harvested, and stover production requires about 0.45 lbs of nitrogen for each bushel of grain produced (IPNI, 2014). This means that the total N needed for a 300 bu/acre corn crop is around 336 lbs/acre. Only a portion of this amount needs to be supplied by N fertilizer; N is also supplied by the soil through mineralization of soil organic matter. On highly productive soils, N mineralization will often supply the majority of N needed by the crop. Credits can be taken for previous legume crop, manure application, and N in irrigation water. Nitrogen application rates of entries exceeding 300 bu/acre are shown in Figure 8. Numbers are based on 353 entries that reported N application rates and include fertilizer N as well as estimated N from reported manure applications.

Nitrogen Rates

The N application rates of 300 bu/acre entries varied greatly, but the majority were in the range of 200 to 300 lbs/acre (Figure 8). As corn yield increases, more N is removed from the soil; however, N application rates do not necessarily need to increase to support high yields. Climatic conditions that favor high-yield will also tend to increase the amount of N a corn crop obtains from the soil through increased mineralization of organic N and improved root growth. Total nitrogen applied in high-yield entries has trended downward in recent years. In the 2016 contest, over half of high-yield entries had over 300 lbs/acre of N applied, compared to one third of entries in 2023.

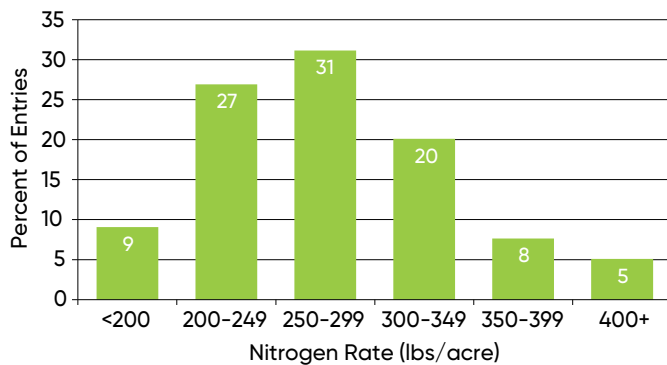


Figure 8. Nitrogen rates (total lbs/acre of fertilizer and manure N applied) of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2023.

Nitrogen Timing

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

Timing of N fertilizer applications in 300 bu/acre entries is shown in Figure 9. Very few included fall-applied N. Many applied N before or at planting. Nearly 75% of 300 bu/acre entries included some form of in-season nitrogen, either side dressed or applied with irrigation. Multiple nitrogen applications were used in over 75% of high-yield entries.

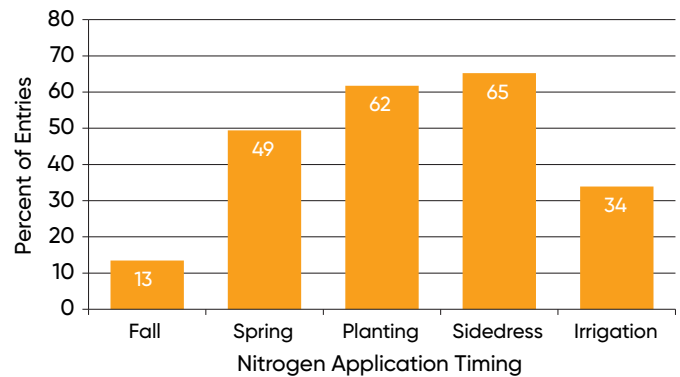


Figure 9. Nitrogen fertilizer application timing of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2023.

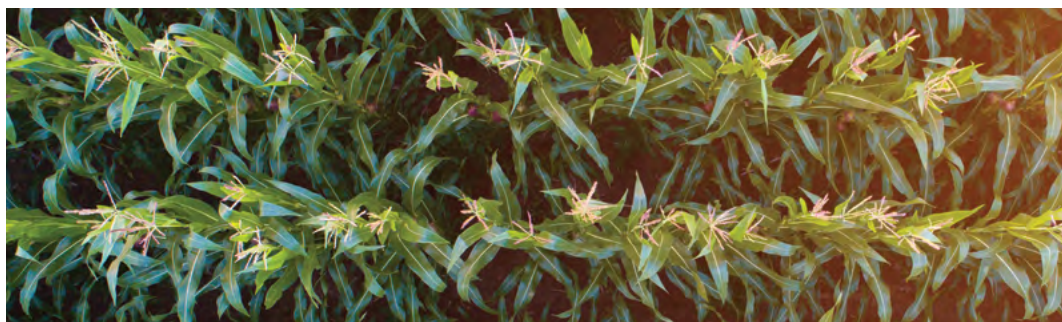
New Nitrogen Management Class

A new feature of the NCGA National Corn Yield Contest in 2023 was the addition of the Nitrogen Management Class (Class J). Entrants in this class were required to limit total nitrogen applications from non-field sources to 180 lbs/acre of actual nitrogen applied. For the initial year, this class was limited to 100 total entrants from select Corn Belt states. Rules for this class also placed limits based on previous crop, with only fields planted to corn, soybean, wheat, or a wheat followed by soybean double crop eligible for entry.

The Nitrogen Management Class had 15 entries reporting yield in 2023. Of these 15 entries, 3 were able to top 300 bu/acre while applying no more than 180 lbs/acre of N.

Secondary and Micronutrients

Around 40% of 300 bu/acre entries reported applying one or more secondary or micronutrients. Sulfur (S) was the most commonly applied nutrient, followed by zinc (Zn), and boron (B), and a smaller number of entries included magnesium (Mg), manganese (Mn), or copper (Cu). Micronutrients are sufficient in many soils to meet crop needs. However, some sandy soils and other low organic matter soils are naturally deficient in micronutrients, and high pH soils may reduce their availability (Butzen and Jeschke, 2022). Additionally, as yields increase, micronutrient removal increases as well, potentially causing deficiencies.



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Mark Jeschke, Ph.D.,
Agronomy Manager

C3 AND C4 PHOTOSYNTHESIS – IMPLICATIONS FOR CROP PRODUCTION

KEY POINTS

- C3 and C4 carbon fixation are two different pathways by which plants convert carbon dioxide (CO₂) from the atmosphere into organic compounds.
- The majority of plant species use C3 photosynthesis, which has a flaw that causes a loss of energy through a process known as photorespiration.
- A relatively small percentage of plant species, known as C4 plants, have evolved a modification to their carbon fixation pathway that allows them to greatly reduce energy lost to photorespiration.
- The improved efficiency of C4 plants comes with an added energy cost, so it is not always advantageous – which photosynthetic pathway is more energetically favorable depends on environmental conditions.
- The C4 pathway allows crops like corn and sugarcane to be more productive, but the overall efficiency with which plants convert light energy into biomass is still relatively low, for both C3 and C4 pathways.
- Current research is focused on using biotechnology tools to improve the efficiency of photosynthesis and increase the yield potential of important crops.

CONVERTING LIGHT INTO YIELD

Photosynthesis is the process by which plants transform light energy into chemical energy. In crop production, maximizing the rate and duration of photosynthesis over the course of growing season is critical to achieving the greatest possible yield potential because it determines the total amount of resources available to carry out biochemical processes and build plant components, including harvestable yield.

Not all plants carry out photosynthesis in exactly the same way though. Certain steps of the process differ in important ways among major crop species, which has implications for energy efficiency, stress tolerance, and yield potential. Scientific advances over the past couple of decades have increased our understanding of photosynthesis and fueled interest in modifying and improving it to increase yields of agricultural crops.



Carbon Fixation

The most important way that photosynthesis differs among crop species is in the carbon fixation pathway. Carbon fixation is the process in photosynthesis by which plants convert carbon dioxide (CO_2) from the atmosphere into organic compounds. This set of enzymatically regulated chemical reactions is commonly referred to as the “dark reactions,” although this term is something of a misnomer, as it only means that the reactions are not dependent on light to proceed, not that they exclusively occur at night. C3 and C4 carbon fixation (also written C3 and C4) are two different pathways used by plants in this process (Figure 1). The numbers in the names refer to the number of carbon atoms in the molecules produced in the first step of carbon fixation:

- In C3 plants, the product of the first step is 3-phosphoglycerate, a 3-carbon acid.
- In C4 plants, the first product is oxaloacetate, which has 4 carbon atoms.

The majority of plant species use C3 photosynthesis; however, a small number of species – including important crop species such as corn, sorghum, and sugarcane – use C4 photosynthesis. This distinction is important in crop production because the photosynthetic pathway used by a crop affects its photosynthetic efficiency, optimal environmental conditions, tolerance to stress, and yield potential.

C3 PHOTOSYNTHESIS

Of the more than 300,000 known plant species on earth, the vast majority (~90%) use the C3 photosynthetic pathway. C3 plants incorporate CO_2 into carbohydrates using the photosynthetic carbon reduction (PCR) cycle, also known as the Calvin cycle. The key enzyme responsible for carbon fixation in C3 plants is ribulose-1,5-bisphosphate carboxylase/oxygenase (commonly referred to as RuBisCO), which converts CO_2 and ribulose biphosphate (RuBP, a 5-carbon sugar) into two molecules of 3-phosphoglycerate (PGA).

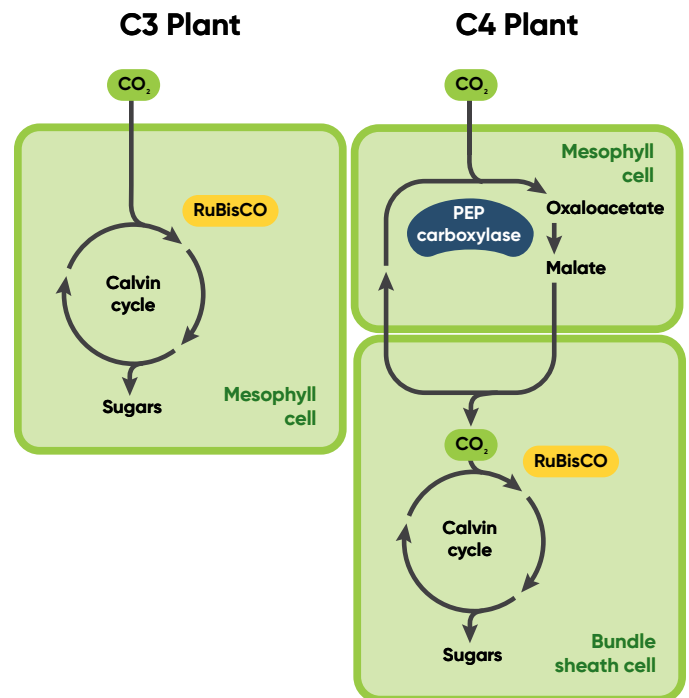


Figure 1. Comparison of major steps in the carbon fixation pathways of C3 and C4 plants.

The Problem With RuBisCO

The problem with C3 photosynthesis is that RuBisCO not only reacts with CO_2 (the desired reaction) but also with oxygen, which it does about 20-25% of the time. When RuBisCO reacts with oxygen, the combination of RuBP with O_2 produces one molecule of PGA and a 2-carbon molecule called 2-phosphoglycolate, a toxic compound that the plant must recycle through a process known as photorespiration. Photorespiration is a wasteful process that consumes energy and results in a portion of fixed carbon being re-released as CO_2 . The process also produces ammonia, which the plant must expend energy to detoxify.



Figure 2. Soybeans, wheat, and rice – as well as most other crop species – utilize the C3 carbon fixation pathway.

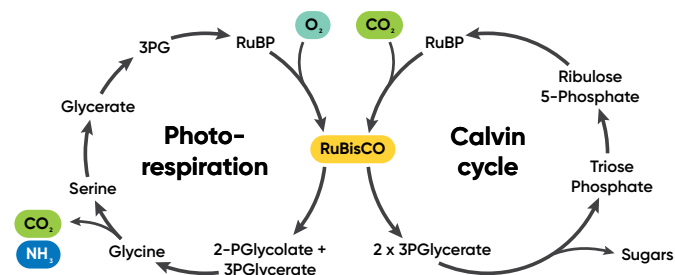


Figure 3. Calvin cycle and photorespiration pathways.

C4 PHOTOSYNTHESIS

A relatively small percentage of plant species (~3%) have evolved a modification to their carbon fixation pathway that allows them to greatly reduce energy lost to photorespiration by adding an additional step ahead of the Calvin cycle. C4 plants have a distinctive leaf anatomy (called Kranz anatomy) that allows them to physically separate the steps involved in carbon fixation between two types of cells: mesophyll cells and bundle-sheath cells (Figure 1).



Figure 4. Only a few major crops utilize the C4 carbon fixation pathway: corn, sorghum, sugarcane, and millet.

An Extra Step to Improve Carbon Fixation

In C4 plants, the initial step in carbon fixation is carried out by an enzyme called phosphoenolpyruvate carboxylase (PEPC) in the mesophyll cells, which are located close to the stomata where carbon dioxide and oxygen enter the plant. PEPC has a high affinity for CO₂ and is, therefore, much less likely to react with oxygen molecules than RuBisCO. PEPC fixes carbon dioxide into a 4-carbon molecule called oxaloacetate, which is then converted to other 4-carbon acids (malate or aspartate) that are transported into the bundle sheath cells that contain RuBisCO. Once in the bundle sheath cells, the C4 acids are decarboxylated to generate CO₂ – which reacts

with RuBisCO – as well as a C3 compound that returns to the mesophyll to repeat the cycle.

This process functions somewhat like a supercharger for carbon fixation – it increases the concentration of CO₂ in the bundle sheath cells to a level where the oxygenase reaction of RuBisCO is negligible, thus making carbon fixation much more efficient. This feature allows C4 plants to be far more productive. Although they comprise less than 3% of known plant species, their greater efficiency allows them to carry out 20-30% of global terrestrial carbon fixation (Lloyd and Farquhar, 1994).

Improved Efficiency Comes with a Cost

The greater efficiency and productivity of C4 carbon fixation does not come for free, however. There is an additional energy cost to the plant that comes with adding the CO₂-concentrating step ahead of the Calvin cycle. Consequently, C4 carbon fixation does not constitute an across-the-board advantage in all circumstances. Which photosynthetic pathway is more energetically favorable depends on environmental conditions.

ADVANTAGES AND TRADEOFFS

Cool Temperatures, High CO₂, Low Light = C3 Advantage

The energy cost associated with C4 carbon fixation means that C3 plants retain an advantage in overall efficiency under conditions where photorespiration is naturally suppressed, such as higher ambient CO₂ and cooler temperatures (Osborne and Beerling, 2006). As photorespiration increases with higher temperatures and lower CO₂ levels, the relative advantage of C4 carbon fixation increases (Figure 5).

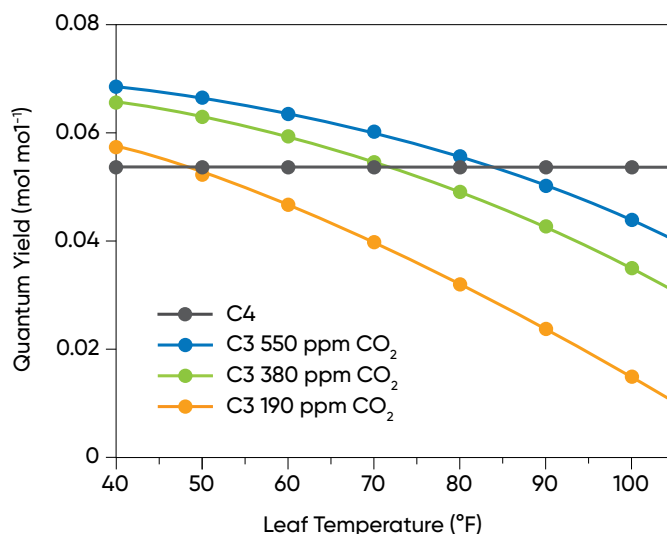


Figure 5. Modelled interaction between temperature and CO₂ level on the photosynthetic quantum yields of C3 and C4 plants (Osborne and Beerling, 2006).

There are a couple of reasons why photorespiration increases with temperature. As temperature increases, RuBisCO loses specificity for CO₂ and increasingly reacts with oxygen. Higher temperatures also increase atmospheric water demand on

the plant. When C3 plants close their stomata in response to water stress, RuBisCO will react more with oxygen as internal CO₂ concentrations are drawn down, increasing the rate of photorespiration.

Hot, Dry, Full Sunlight, Low N = C4 Advantage

C4 plants have an advantage in environments prone to drought stress, high temperatures, and nitrogen (N) deficiency. The CO₂ concentrating mechanism of C4 plants gives them a greater ability to close their stomata in response to heat and drought stress and pull internal CO₂ concentrations down to lower levels before photosynthesis slows and the stomata must be opened again.

Figure 6 shows generalized light response curves for C3 and C4 plants. At low temperatures, the C3 plant has a greater initial response to light and a higher light-saturated photosynthesis level, while the added energy cost of the CO₂ concentration mechanism puts C4 plants at a disadvantage. Most C3 species reach light saturation at levels well below full sunlight. At higher temperatures, C4 plants attain much higher photosynthetic output and do not reach light saturation, even at full sunlight.

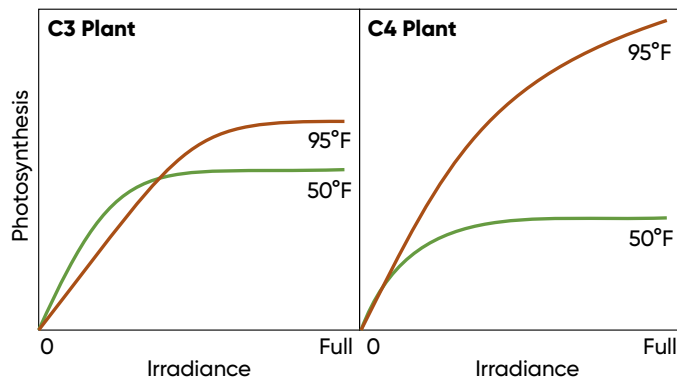


Figure 6. Generalized light response curves for C3 and C4 plants at low and high temperature.

(Reproduced from *Plants in Action*, published by the Australian Society of Plant Scientists.)

The greater nitrogen efficiency of C4 plants is primarily a function of the amount of N used in producing RuBisCO. Because RuBisCO operates with much greater efficiency in C4 plants, the plants can produce 60–80% less of it (Long 1999). Conversely, C3 plants must produce more RuBisCO, which uses more nitrogen; a not inconsequential investment, as RuBisCO accounts for nearly 50% of the total protein in leaf tissue of C3 plants (Cui, 2021).

Distribution of C3 and C4 Species

The global distribution of C3 and C4 species reflects their respective advantages. C4 species are most common in hot and dry environments such as tropical grasslands and savannas where their more efficient carbon fixation pathway provides the greatest advantage. C4 species also tend to thrive in ecosystems that experience frequent disturbance (such as wildfire), as their faster growth rate allows them to grow back more quickly. C3 plants tend to dominate in

environments with lower growing season temperatures – such as higher elevations – and places where light intensity is limited, such as the understory of forests.

EVOLUTION

The significant inefficiency that photorespiration creates in C3 plants raises the obvious question of why such a flawed pathway would evolve in the first place and why it persists in the majority of plant species today. The Calvin cycle first evolved in cyanobacteria over 2 billion years ago, at a point in Earth's history when atmospheric CO₂ concentrations were much higher than today, and oxygen levels were much lower. In that environment, the oxygenase activity of RuBisCO did not constitute a major inefficiency because there was very little oxygen in the atmosphere with which it could react (Erb and Zarzycki, 2018).

C4 carbon fixation is a much more recent evolutionary innovation, emerging between 25 and 32 million years ago at a point when lower CO₂ and higher oxygen levels in the atmosphere made the oxygenase activity of RuBisCO much more of a liability. Today, there are around 8,100 known C4 species, most of which are grasses (~5,000); however, C4 species exist in at least 61 distinct evolutionary lineages of plants, making it a notable example of convergent evolution.

IMPACT ON CROP PRODUCTIVITY

For crop species that utilize the C3 carbon fixation pathway, such as soybeans and wheat, the cost associated with photorespiration in terms of lost yield potential is substantial. Under current atmospheric CO₂ levels, it is estimated that the energy lost through photorespiration reduces total U.S. soybean production by 36% and wheat production by 20% (Walker et al., 2016). Yield impact varies by geography and climate, with greater impacts occurring in warmer regions where photorespiration is higher. For example, yield loss in soybean is estimated to be over 50% in warmer southern states compared to 30–40% in northern latitudes.

IMPROVING PHOTOSYNTHESIS

The substantial lost potential in global agricultural productivity attributable to photorespiration in C3 crops has led to considerable interest in the possibility of using biotechnology to reduce or eliminate photorespiration, which could dramatically increase yields of C3 crops.

Why Not Fix RuBisCO?

The most straightforward solution to the problem would be to simply fix RuBisCO – alter the enzyme in a way so that it reacts with CO₂ but not oxygen, thus eliminating the problem of photorespiration. However, this does not appear to be possible. Research has shown an inverse relationship between CO₂ specificity and catalytic rate – increasing the preference of the enzyme for CO₂ also slows it down. A lower catalytic rate could be overcome by increasing the amount of RuBisCO in the plant, but with RuBisCO already accounting

for nearly 50% of total protein in the leaf tissue of C3 plants, it is not clear that this would be feasible either (Zhu et al., 2004). The fact that no version of RuBisCO that lacks oxygenase activity has ever been found in nature suggests that this may be an intractable problem with RuBisCO. If this feature of RuBisCO were possible to eliminate without harming the carboxylation function of the enzyme, evolution would likely have already done so rather than (repeatedly) evolve the imperfect workaround of the C4 carbon fixation pathway.

Can We Convert C3 Plants to C4?

A more feasible option may be to just replicate evolution's solution to the problem by engineering a C4 carbon fixation pathway into C3 plants. This is not a simple proposition, given the specialized anatomy and biochemistry in leaves of C4 plants. However, the fact that C4 carbon fixation evolved independently numerous times in nature (with a few different biochemical variants of the pathway) offers hope that such a goal could be achievable. And the significant benefits that such an innovation could offer in terms of dramatically increased yields and greater resilience to drought stress has fueled considerable scientific interest in this area over the past 25 years.

C4 Rice Project

Efforts thus far to create a C4 version of a C3 crop have largely focused on rice due to its global importance as a major calorie source for around half of the world's population. What is today known as the C4 Rice Project originated at a workshop convened by the International Rice Research Institute (IRRI) in 1999 to assess the feasibility of engineering the C4 carbon fixation pathway into rice. Scientists identified the need to better understand the specific changes to the genome responsible for the biochemical and anatomical features of C4 plants. The C4 pathway was discovered and elucidated through research conducted in the 1960s, but by the 1990s research on C4 photosynthesis had waned. A resurgence of research in this area with modern genetic tools was deemed necessary to achieve such an ambitious goal.

The C4 Rice Consortium was created in 2006 to lay out a research plan and the project received financial backing from the Bill and Melinda Gates Foundation in 2008. Research in this area continues to progress, and with a far more formidable set of DNA sequencing and genetic transformation tools than were available at the time of the project's inception (Furbank et al., 2023).



Improving Radiation Use Efficiency

Improving photosynthetic efficiency of plants is often referred to as a "grand challenge" or "holy grail" of plant research in the 21st Century. Innovations that were at the core of the Green Revolution in the 20th Century – shortening the stems and increasing the harvest index in wheat and rice – involved changes to only a few genes. Photosynthesis, on the other hand, is a complex process involving numerous genes, making re-engineering it a challenging endeavor. Yet a growing sense that the strategies that enabled the Green Revolution have reached a plateau in yield improvement has led to greater focus on photosynthesis itself as the next frontier in crop improvement (Furbank et al., 2023).

There are four main factors that determine yield potential in crops (Covshoff and Hibberd 2012):

1. Total solar radiation over the growing season.
2. Efficiency of the plant in intercepting photosynthetically active radiation (PAR).
3. Radiation use efficiency – the efficiency with which PAR is converted by the plant into dry matter.
4. Harvest index – partitioning of dry matter to grain.

Yield improvements of the Green Revolution largely involved optimizing efficiency of light interception (though practices such as higher plant density) and increasing harvest index. Growers maximize seasonal solar radiation through timely planting and the use of full-season hybrids and varieties (to use as much of the growing season as possible). This leaves improving radiation use efficiency as the best opportunity for new genetic improvement (Covshoff and Hibberd 2012).

Room For Improvement

Engineering C4 photosynthesis into C3 crops is one way to work toward this goal, and a logical approach given that it involves utilizing a biochemical pathway that already exists in nature and offers the potential for dramatic yield gains in important crop species. Yet the fact is that neither photosynthetic pathway is particularly efficient. The efficiency with which plants convert light energy into biomass is relatively low, for both C3 and C4 pathways. The theoretical maximum for photosynthetic efficiency is 4.6% for C3 plants



and 6% for C₄ plants (at 30°C and 380 ppm atmospheric CO₂) (Figure 7). Efficiencies that are actually achievable in the field over the course of a growing season are even less (Zhu et al., 2008). By comparison, current commercially available solar panels are generally 15–20% efficient, with some advanced technologies reaching close to 40%.

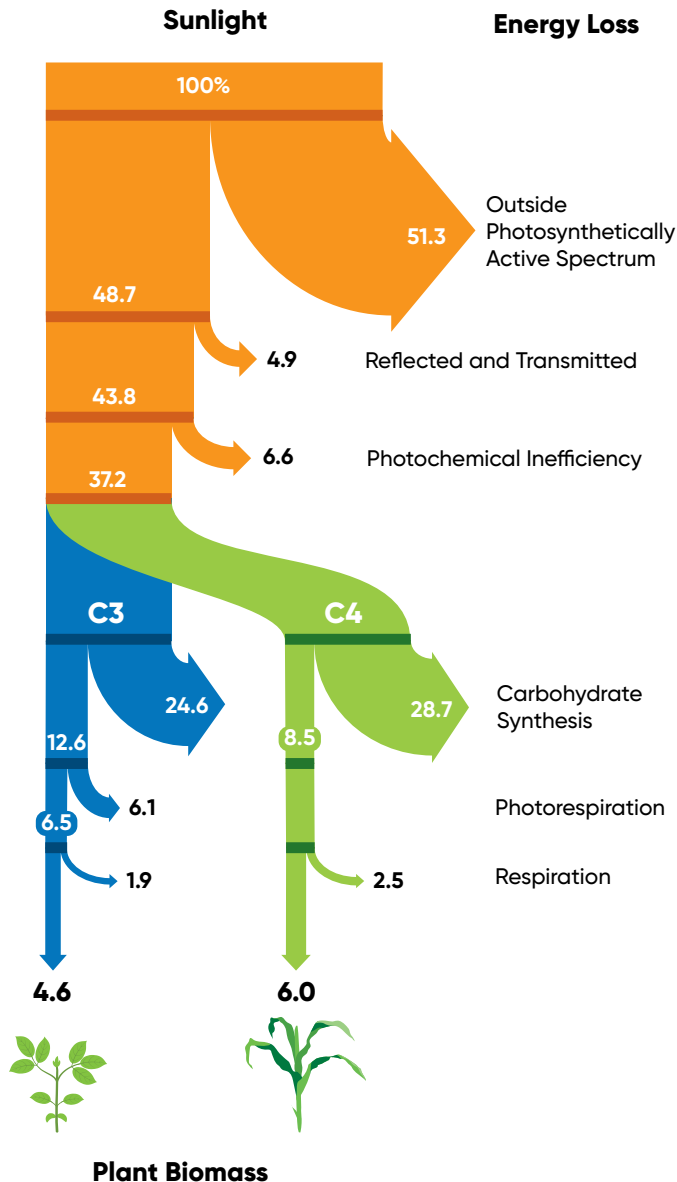


Figure 7. Minimum energy losses at each step of the plant photosynthetic process of C₃ and C₄ plants, from interception of radiation to the formation of stored chemical energy in biomass. Assumes a leaf temperature of 86°F and atmospheric CO₂ concentration of 380 ppm (Zhu et al., 2008).

Why is Photosynthesis So Inefficient?

One might expect that a biochemical pathway that has been ubiquitous in nature for hundreds of millions of years would be extremely optimized, given the countless generations of natural selection acting upon it. This makes the low efficiency of photosynthetic carbon fixation somewhat surprising. There are a couple of likely explanations for why this is the case.

First, evolution selects for survival, not maximum productivity. Photosynthetic rate is just one of many attributes that could be important in the life of a plant in determining its ability to successfully pass its genes on to the next generation. And which attributes are most important to the survival and successful reproduction of a given plant could vary considerably based on its environment.

Second, in the time since photosynthesis first evolved, Earth's climate and atmospheric composition have undergone significant changes, which means that the selection pressures imposed on plants have not been static over time. RuBisCO provides a very clear example of this – an attribute (oxygenase activity) that was not detrimental when it first evolved now is detrimental because of higher atmospheric oxygen.

Broader Efforts to Improve Photosynthesis

Considerable research has focused on RuBisCO as a limiting factor in photosynthetic efficiency; however, photosynthesis is a complex process with many steps and many possibilities for increasing efficiency and productivity. Realizing Increased Photosynthetic Efficiency (RIPE) is an international research project founded in 2012 focused on engineering crops to be more productive by improving photosynthesis. The development of sophisticated computer models has allowed scientists to simulate the process of photosynthesis and identify potential bottlenecks in the process (Zhu et al., 2016).

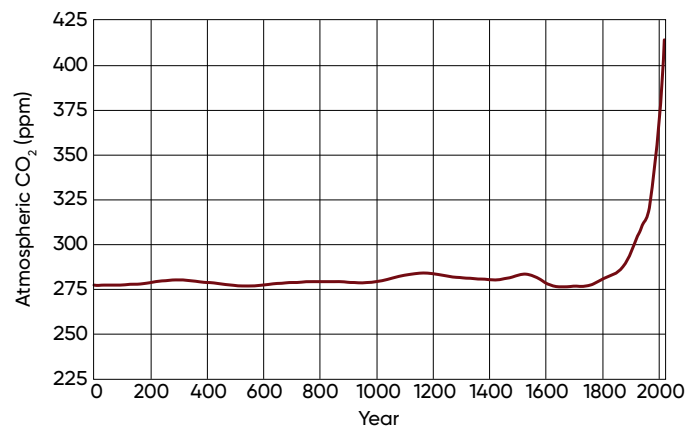


Figure 8. Atmospheric CO₂ concentration over the past 2,000 years based on ice core data (before 1958), and direct measurements taken at Mauna Loa and the South Pole (1958–present) (Keeling et al., 2001; MacFarling Meure et al., 2006).

One such bottleneck identified by RIPE Project scientists involves the process by which plant photosynthetic systems respond to fluctuations in light level, as occurs when clouds pass overhead or a leaf within a crop canopy transitions into and out of shade as the angle of incoming sunlight changes throughout the day. These adjustments are slow, taking several minutes and costing field crops up to 20% of their potential yield (Kromdijk et al., 2016). Scientists identified three proteins that, when increased, allowed plant leaves to adapt more quickly to fluctuations in light.

IMPACT OF RISING CARBON DIOXIDE

Research focused on improving photosynthetic efficiency and yield of crop plants is being conducted against a backdrop of rapidly increasing atmospheric CO₂. The recent increase in atmospheric CO₂ levels to over 420 ppm during the past 150 years, after fluctuating between 180 and 300 ppm over the prior million years, means that all plant life now exists in a world that is different from the one to which it is adapted (Figure 8). And continued CO₂ emissions from fossil fuel burning mean that this concentration will continue to rise in coming decades. What does rising CO₂ mean for productivity of C3 and C4 crop species and efforts to optimize photosynthetic efficiency?



Impact on C3 Plants

Numerous research studies have examined the effects of elevated CO₂ concentrations on crop growth and yield. In general, yields of C3 crops significantly increase at higher CO₂ levels, although responses vary by crop and growing conditions (Toreti et al., 2020). Higher CO₂ reduces the rate of photorespiration in C3 plants, increasing their photosynthetic efficiency.

In general, rising CO₂ is expected to boost yields of C3 crops; however, it is not necessarily as simple as more CO₂ = more yield. A multiyear study on the effects of elevated CO₂ (550 ppm) on soybeans found that total aboveground biomass increased by 22% but seed yield only increased by 9% due to a reduction in biomass partitioning to the seed (Bishop et al., 2015). Research has shown that C3 plants are not able to fully take advantage of higher atmospheric CO₂ because their biochemical processes are optimized for CO₂ levels that existed during the 20 million years preceding the industrial era (<300 ppm) and not the levels of today (>420 ppm) (Pearson and Palmer, 2000; Zhu et al., 2010).

Additionally, the CO₂ fertilization effect in C3 plants can disappear under drought stress. A multiyear field study showed that the stimulation of soybean yield by elevated CO₂ diminished to zero as drought intensified. Higher CO₂ did not counteract the effect of severe drought stress on photosynthesis and yield because elevated CO₂ interacted with drought to modify stomatal function and canopy energy balance (Gray et al., 2016).

Impact on C4 Plants

Yield of C4 crops generally would not be expected to respond to higher CO₂ in the same way as C3 crops because photorespiration is already suppressed in the C4 carbon fixation pathway. Research has shown this to be the case, with no significant change in yield of C4 crops such as corn and sorghum under elevated CO₂ when water supply was adequate. Under drought stress, however, elevated CO₂ can confer an advantage in C4 plants. Higher CO₂ leads to lower stomatal conductance (i.e., plants do not need to have their stomata open as much to take in adequate CO₂), which reduces transpiration and increases water use efficiency (Toreti et al., 2020).

CO₂ Effects vs. Climate Change Effects

Higher CO₂ concentrations can benefit yields of both C3 and C4 crops under certain conditions; however, changes to Earth's climate caused by higher CO₂ will affect crop yields as well. Projected changes for the U.S. Corn Belt include increased frequency of drought stress during the summer due to higher temperatures and evapotranspiration, with precipitation concentrated into less frequent and more intense events (Angel et al., 2018). Globally, the net effect of higher CO₂ levels and climate change on crop productivity is expected to be close to zero over the coming decades as positive and negative effects roughly cancel each other out, although important changes could occur at regional and local scales (Lobell and Gourdji, 2012).

POLLINATION IN CORN: TIMELINE OF KEY STEPS

KEY POINTS

- One can determine successful ovule fertilization shortly after pollination by gently shaking the ear and estimating the number of detached silks.
- Silks detach from developing, fertilized ovules on the second day after pollination.
- The number of detached silks two days or more after pollination corresponds with the number of kernels on the harvested ear.
- When scouting a field, it is more efficient to observe wilted silks and to feel for reduced silk elasticity to qualitatively estimate pollination success than to harvest ears and estimate the number of detached silks.
- The greater value of harvesting ears and estimating detached silks shortly after pollination is to quantitatively estimate ovule fertilization or to demonstrate the success rate of ovule fertilization to others.

POLLINATION TIMELINE IN CORN

One method to determine successful ovule fertilization following pollination in corn is to harvest the ear, remove the husk, gently shake the ear, and observe the number of detached silks that fall from the ear (Figure 1). Silks detach from all fertilized ovules while silks remain attached to unfertilized ovules. How soon after fertilization do silks detach from fertilized ovules? A field study was conducted to examine the timeline from pollen shed through ovule fertilization, silk detachment, and eventual kernel set.

FIELD STUDY

Corn ears were covered before silks emerged. Silks of selected ears were exposed to pollen for one day only on July 17, 18, 19, or 20, the third, fourth, fifth, or sixth day after the field was at 50% silk and the second, third, fourth, or fifth day after the field was at 50% anthesis, respectively. After this single day of exposure, silks were again covered with shoot bags to eliminate further pollination.

Selected ears were harvested at 1, 2, 3, 4, or 5 days after silk exposure to pollen, husks were carefully removed, the ears were shaken gently to allow detached silks to fall, and the number of detached silks per ear were estimated. Pollen density was heavy and silk growth was rapid on July 17 and 18. Pollen density was lighter and silk growth was slower on July 19, and both were dramatically reduced on July 20.



Figure 1. Successful pollination can be demonstrated by gently shaking the silks from an ear and estimating the number of detached silks.

Corresponding ears for each day of exposure were harvested at corn maturity, and the number of kernels on each ear were counted. There was a minimum of six replications for each sample timing for each exposure treatment.

SILKS DETACH TWO DAYS AFTER POLLINATION

For all four exposure dates, no silks detached the first day after exposure (Figure 2). Silks started to detach the second day after exposure for all four exposure dates. The number of detached silks remained constant (within one standard deviation unit of the mean) at 2, 3, 4, and 5 days after exposure. Kernel counts per ear at maturity corresponded closely to the estimated number of detached silks at 2, 3, 4, and 5 days after exposure. Figure 4 shows representative ears with no silks attached to fertilized, developing kernels at 2 to 5 days after exposure to pollen and kernel set of corresponding ears at maturity. Many silks originating from ovules that were not fertilized during pollination are still attached to the cob at grain maturity.

TIMELINE: POLLINATION TO SILK DETACHMENT

Results from this study indicate that silks detach from fertilized ovules on the second day after these silks are exposed to pollen. This time interval is consistent with previous research that describes and documents with photomicrographs the growth and development of the corn embryo during the fertilization process (Kiesselbach, 1999).

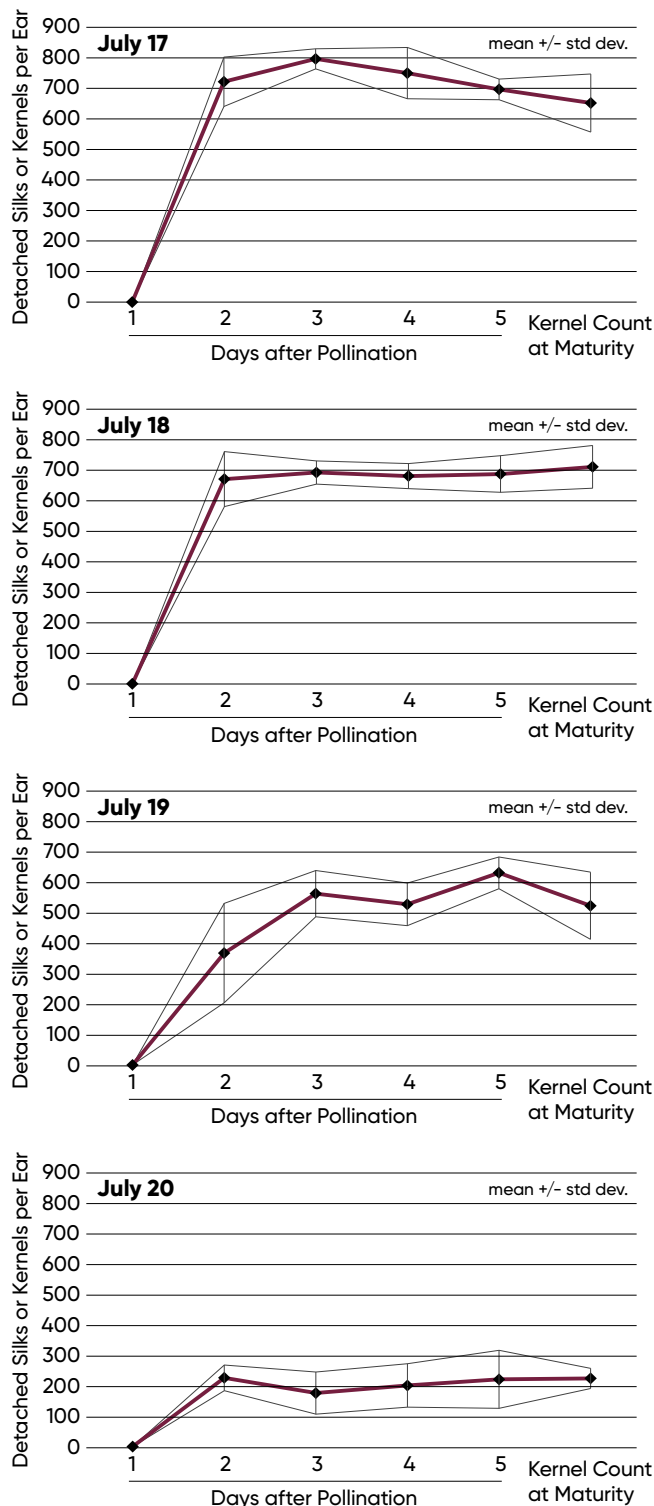


Figure 2. Estimated number of detached silks at 1, 2, 3, 4, and 5 days after pollination and corresponding kernel counts for ears exposed to pollination for one day only at 3, 4, 5, or 6 days after the field was at 50% silk.

Pollen shed starts when mature pollen grains fall through open pores of dehiscent anthers. Gravity and wind influence pollen movement as pollen grains fall. If no wind is present, pollen falls at a rate of about 8 inches per second. It would

therefore require just a few seconds for a pollen grain to fall the few feet from the tassel to receptive silks on the same corn plant if the pollen grain fell straight down. The flight time for the vast majority of pollen grains to land on receptive silks would very probably be less than one minute.

Very shortly after pollen grains land on receptive silks, pollen grains start to extrude pollen tubes. Pollen tubes begin to penetrate silk trichomes within about 15 minutes after capturing the fallen pollen. The purpose of the pollen tube is to create a channel within the silk to move the male genetic material from the pollen grain to the receptive female embryo. If corn plants have ample water, pollen tubes complete their growth process within 12 to 18 hours. This time interval depends on where pollen grains land on silks; time intervals increase if pollen tubes must penetrate longer silk lengths. If corn plants are under moisture stress, more than 24 hours may be required to complete pollen tube growth.

After the pollen tube penetrates the embryo sac, one male nucleus fertilizes the egg nucleus to create a fertile zygote that eventually becomes the seed embryo in the mature grain. A second male nucleus fertilizes two polar nuclei to create what eventually becomes the starch in harvested grain. The time required for this double fertilization is not known, but the time interval is probably very short because the male genetic material exits the pollen tube in very close proximity to the female gametes. Kiesselbach showed that a fertilized embryo and the genesis of starch formation are present by 40 hours after pollination.

As soon as the fertile embryo has formed, cells connecting the silk to the embryo sac begin to desiccate. As these cells dry, the silk no longer has access to food and water. The silk detaches from the embryo sac, dries, and turns brown. The point at which this silk detaches creates a silk scar on the mature grain. Seeds of some hybrids have visible silk scars while silk scars on seeds of other hybrids are barely visible (Figure 3).



Figure 3. Some hybrids have visible scars on the kernels where the silk was attached.

This desiccation and silk detachment process does not happen instantaneously. Time must elapse before this process is complete. Apparently, this desiccation and detachment process takes just a few hours because, based on the results of this study, all silks originating from fertilized embryos detach from these fertilized embryos during the second day after pollination. This result is also consistent with Kiesselbach's research. Kiesselbach showed that silk scars are present on the developing seed five days after pollination. Figure 5 briefly summarizes this pollination, fertilization, desiccation, and detachment timeline.



Figure 4. Representative ears showing fertilized ovules with no attached silks two or more days after pollination and kernel set at maturity. The field was at 50% silk on July 14. Each date shown in the figure is the single day of silk exposure to available pollen for each treatment date.

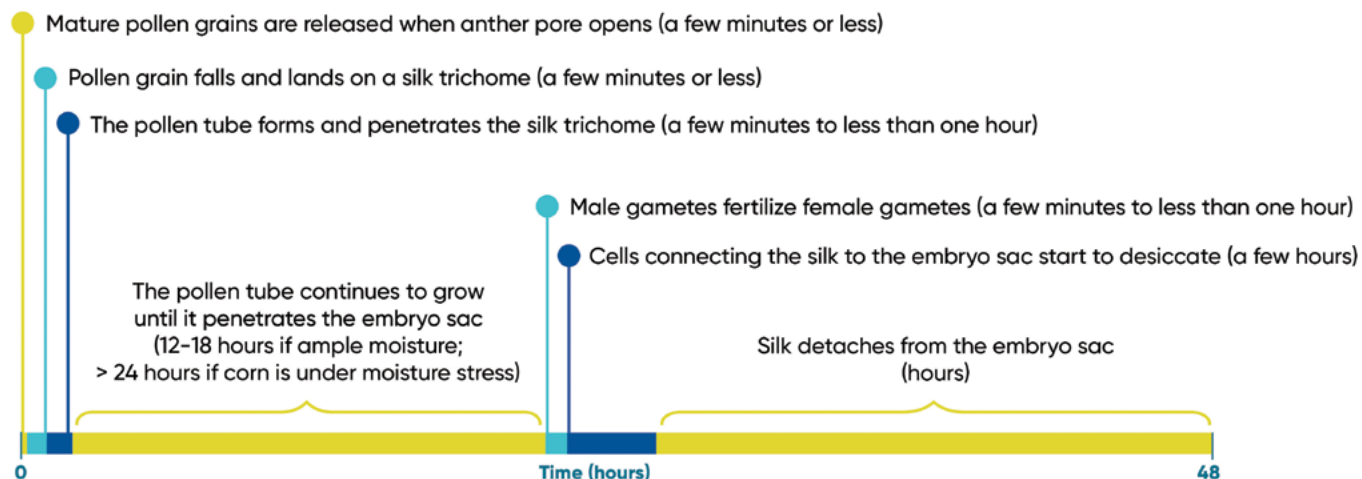


Figure 5. Timeline for pollination, ovule fertilization, and eventual silk detachment.

SILK DETACHMENT AS A SCOUTING TECHNIQUE

Silk detachment confirms successful fertilization of the corn embryo and occurs on the second day after pollination of exposed silks. It takes quite a bit of time to harvest an ear, carefully peel back the husks, and gently shake the ear to estimate the number of detached silks. From an efficiency perspective, it is faster to estimate fertilization success by observing the turgor of exposed silks. Silks in the early process of detachment or that are recently detached appear wilted and lose some of their elasticity when they are touched. The silk detachment method has value when the observer wants to quantify successful fertilization or the observer desires

to show how far the fertilization process has progressed to another who is less familiar or less knowledgeable of the corn pollination process. In these studies, the number of detached silks two or more days after successful fertilization correlated well with the number of kernels at maturity. The silk detachment method therefore also has value if one wants to estimate the number of potential kernels per ear at harvest.

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Rebecca Hensley, M.S.,
Sr. Research Associate
Windfall, Indiana, USA

Andrea Salinas,
Research Scientist
Viluco, Chile

Andres Reyes, Ph.D.,
Research Scientist
Woodland, California, USA

Christian Michel Navarro,
Sr. Research Associate
Woodland, California, USA

Logan Anderson,
Sr. Research Associate
Johnston, Iowa, USA

Jason DeBruin, Ph.D.,
Global Biotech Trait
Characterization Project Scientist
Johnston, Iowa, USA

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CORN BIOMASS ALLOCATION AND NITROGEN UPTAKE:

Insights from 13 Years of Field Research

KEY POINTS

- Plant biomass and nitrogen content were measured from a series of Corteva Agriscience field experiments conducted over a period of 13 years from 2011 to 2023.
- Plant biomass and N traits were categorized based on the associated yield for each test plot and split into four yield classes: <150, 150–200, 200–250, and >250 bu/acre.
- Leaf area index increased with each successively higher yield class, from an average of 4.4 in the <150 bu/acre class up to an average of 6.1 in >250 bu/acre yield class.
- At yield levels above 200 bu/acre, kernel number was maximized, with essentially all expressed silks resulting in successful kernel set. Below 200 bu/acre, incomplete kernel set resulted in lost yield potential.
- Kernel weight was the yield component with the greatest degree of differentiation among yield classes, increasing with each successively higher yield class.
- The percentage of total grain nitrogen that came from remobilization decreased with higher yield classes, indicating that higher-yielding crops rely more on nitrogen uptake during the grain-filling period.

INTRODUCTION

As corn yield potential continues to increase, it is important that management practices keep pace with the changes, ensuring that yield potential is fully realized. Crops producing more grain also produce more non-harvestable biomass, both of which require more nutrient uptake from the soil. Nitrogen (N) is one of the most important inputs for corn production, as well as one of the most challenging to manage efficiently.

Plant biomass and nitrogen content were measured from a series of Corteva Agriscience field experiments conducted over a period of 13 years from 2011 to 2023. The purpose of this research was to better understand corn biomass partitioning and N utilization at different yield levels. Yield outcomes in a given environment are shaped by numerous factors, including soil characteristics, growing season conditions, and agronomic management. The purpose of this study was not to test the impact of any specific environmental or management factor on corn yield, but rather to understand how corn plants function at different yield levels in terms of taking up and allocating nitrogen and building grain yield.

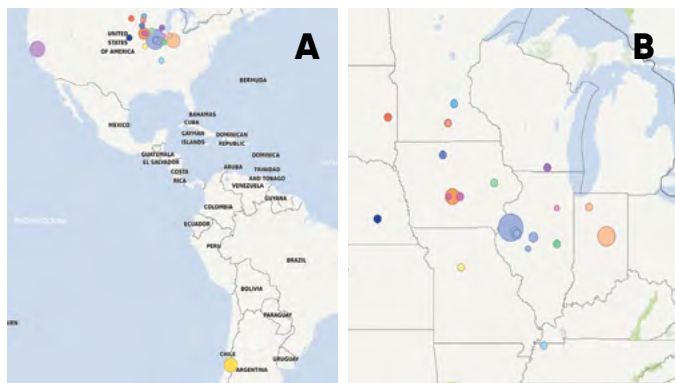


Figure 1. Locations in the U.S. and Chile (A) and more specifically in the Midwest U.S. (B) where trials were conducted between 2011 and 2023. The size of the circle indicates the number of data points collected at each location. Locations contributing the majority of data points were Johnston, IA, Macomb, IL, Windfall, IN, Woodland, CA, and Viluco, Chile.

METHODS

Plant biomass, N content, and corn yield measurements were collected from 6,092 research plots grown in fully irrigated and rainfed locations in the Midwestern U.S., Woodland, CA, and Viluco, Chile between 2011 and 2023 (Figure 1). Soil samples were taken prior to planting at each research location to measure soil texture, organic matter, and nitrate content. Whole plant samples were collected at flowering (R1) and maturity (R6) and separated into individual plant parts to determine biomass and N content. Plant samples were processed at Corteva research facilities and nitrogen analysis was conducted in Johnston, IA.



Research plots represented a range of different growing environments and management practices. Table 1 lists research locations by year, with previous crop, irrigation status, and soil organic matter level at each site. Organic matter ranged between 1.8 and 6.7% with an average of 3.8%. Trials conducted in Woodland, CA and Viluco, Chile were fully irrigated while trials in the Midwestern U.S. were mostly rainfed, with irrigation at the San Jose, IL, Mazon, IL, Johnston, IA, Union City, TN, and York, NE locations.

Plant densities of research plots ranged between 26,000 and 50,000 plants per acre and nitrogen fertilizer application rates up to 600 lbs N/acre (Table 2). Several experiments in the Midwest included a zero N treatment to determine the potential of the soil to contribute N via mineralization.

Plant biomass and N traits were categorized based on the associated yield for each test plot and split into four yield classes: <150, 150–200, 200–250, and >250 bu/acre. Measurements derived from plant samples included:

- Total N removed from field at harvest
- Total N remaining in the residue at harvest
- N uptake before and after flowering
- Amount of stored N remobilized to support grain filling
- Yield components (ovules, silks, kernels, and kernel weight)

RESULTS

Leaf Area Index

Leaf area index (LAI) is a measure of the total surface area of leaves per unit of ground area. Leaf area index increased with each successively higher yield class, from an average of 4.4 in the <150 bu/acre class up to an average of 6.1 in >250 bu/acre yield class. Observed leaf area index in the study

ranged from 1.85 to 9.08. Greater leaf area is an indicator of improved growth and canopy expansion and increases the potential for light interception. Additionally, leaf area is a storage warehouse for nitrogen which can contribute to remobilization for grain filling.

Table 1. Year, location, previous crop, irrigation status, and soil organic matter for field trials conducted between 2011 and 2023 to evaluate corn yield and associated yield components, plant biomass, and nitrogen uptake.

Year	Location	Previous Crop	Irrigated/ Rainfed	Soil OM	Year	Location	Previous Crop	Irrigated/ Rainfed	Soil OM
2011	Sciota, IL	Soybean	Rainfed	5.8	2018	Sciota, IL	Soybean	Rainfed	4.5
2012	San Jose, IL	Corn	Irrigated	2.5	2018	Sciota, IL	Soybean	Rainfed	3.8
2012	Sciota, IL	Corn	Rainfed	5.8	2018	Union City, TN	Corn	Irrigated	1.8
2012	Viluco, Chile	Corn	Irrigated	2.7	2018	Windfall, IN	Soybean	Rainfed	4.2
2013	Adair, IL	Corn	Rainfed	3.9	2018	Woodland, CA	Corn	Irrigated	2.6
2013	Viluco, Chile	Corn	Irrigated	2.1	2018	York, NE	Soybean	Irrigated	3
2014	Sciota, IL	Corn	Rainfed	5.4	2019	Algona, IA	Corn	Rainfed	3.9
2016	Johnston, IA	Corn	Irrigated	3.5	2019	Brookings, SD	Soybean	Rainfed	4.4
2016	Marion, IA	Corn	Rainfed	3.7	2019	Champaign, IL	Corn	Rainfed	4.1
2016	Sciota, IL	Corn	Rainfed	5.6	2019	Dallas Center, IA	Soybean	Rainfed	4.5
2016	Viluco, Chile	Corn	Irrigated	4	2019	Eau Claire, WI	Soybean	Rainfed	3.9
2017	Johnston, IA	Corn	Irrigated	3.6	2019	Janesville, WI	Soybean	Rainfed	4.5
2017	Marion, IA	Corn	Rainfed	3.6	2019	Macomb, IL	Soybean	Rainfed	4
2017	Marion, IA	Soybean	Rainfed	3.6	2019	Mankato, MN	Soybean	Rainfed	5.3
2017	San Jose, IL	Corn	Irrigated	2.7	2019	Marion, IA	Soybean	Rainfed	2.9
2017	Sciota, IL	Corn	Rainfed	3.6	2019	Mazon, IL	Soybean	Irrigated	5.3
2017	Viluco, Chile	Corn	Irrigated	3.6	2019	Miami, MO	Soybean	Rainfed	3.5
2017	Windfall, IN	Soybean	Rainfed	4.5	2019	Pleasant Plains, IL	Soybean	Rainfed	3.9
2017	Woodland, CA	Corn	Irrigated	2.6	2019	Union City, TN	Corn	Irrigated	2
2018	Champaign, IL	Corn	Rainfed	3.5	2019	Windfall, IN	Soybean	Rainfed	4.8
2018	Dallas Center, IA	Soybean	Rainfed	3.9	2019	York, NE	Soybean	Irrigated	3.4
2018	Janesville, WI	Soybean	Rainfed	2.9	2020	Adair, IL	Soybean	Rainfed	4.1
2018	Johnston, IA	Corn	Irrigated	3	2020	Windfall, IN	Soybean	Rainfed	4.1
2018	La Crosse, IN	Soybean	Rainfed	2.1	2021	Windfall, IN	Soybean	Rainfed	5.6
2018	Mankato, MN	Soybean	Rainfed	4.6	2022	Adair, IL	Soybean	Rainfed	3.9
2018	Marion, IA	Corn	Rainfed	3.1	2022	Johnston, IA	Soybean	Irrigated	4.4
2018	Mazon, IL	Soybean	Irrigated	3.1	2022	Pleasant Plains, IL	Soybean	Rainfed	4.9
2018	Miami, MO	Soybean	Rainfed	3.1	2022	Windfall, IN	Soybean	Rainfed	6.7
2018	San Jose, IL	Corn	Irrigated	2.8	2023	Adair, IL	Soybean	Rainfed	4.3
2018	San Jose, IL	Soybean	Irrigated	2	2023	Windfall, IN	Soybean	Rainfed	5.8

Table 2. Minimum, maximum, and average N rate and plant density for experimental plots that were grown between 2011 and 2023 in the Midwestern U.S., Woodland, CA, and Viluco Chile to measure yield, plant biomass, and N uptake.

Plant Density			
Yield Level	Minimum	Maximum	Average
bu/acre	plants/acre		
<150	26,000	50,000	35,000
150-200	26,000	50,000	34,000
200-250	26,000	55,000	35,000
>250	26,000	55,000	40,000

Nitrogen Application Rate			
Yield Level	Minimum	Maximum	Average
bu/acre	lbs N/acre		
<150	0	300	29
150-200	0	600	105
200-250	0	600	170
>250	0	600	370

Yield Components

The total number of ovules produced on the primary ear sets the yield potential of the plant. Ovule number is a product of the number of kernel rows around the ear, which is set at approximately the V7 growth stage, and the length of the ear (kernels per row) which is set during late vegetative growth. Ovule number in this study was relatively consistent across the higher yield classes (150-200, 200-250, >250 bu/acre), at around 680 ovules per ear. Only the lowest yield class (<150 bu/acre) had a lower ovule number, with around a 7% reduction compared to the higher yield classes.

Ideally, each ovule would produce a silk, but that did not prove to be the case. The number of silks expressed was around 20% less than the total number of ovules, an outcome that was relatively consistent across all yield classes. Leading into pollination, yield classes above 150 bu/acre had no loss in potential yield; only the lowest yield class already had lower yield potential locked in due to lower ovule number and silk expression.

Table 3. Leaf area index of the canopy at R1, yield components at R1 (ovule and silk number), yield components at R6 (kernel number and kernel mass), and grain yield for the four yield classes. The columns following the yield trait class indicate the number of observations that were used to calculate the mean.

Trait	<150 bu/acre		150-200 bu/acre		200-250 bu/acre		>250 bu/acre	
	n		n		n		n	
Leaf area index at R1 (m²/m²)	4.4	484	5.0	613	5.7	1,202	6.1	505
Ovule number (count)	632	208	684	102	680	234	680	103
Silk number (count)	502	122	543	96	562	164	517	90
Kernel number (count)	400	245	492	161	561	339	549	918
Kernel mass (dry basis, mg/kernel)	222	448	261	661	293	1,357	327	1,047
Kernels/bushel @ 56 lb test weight	~100K		~85K		~75K		~67K	
Yield (bu/acre)	112	617	180	1,166	225	2,386	287	1,923

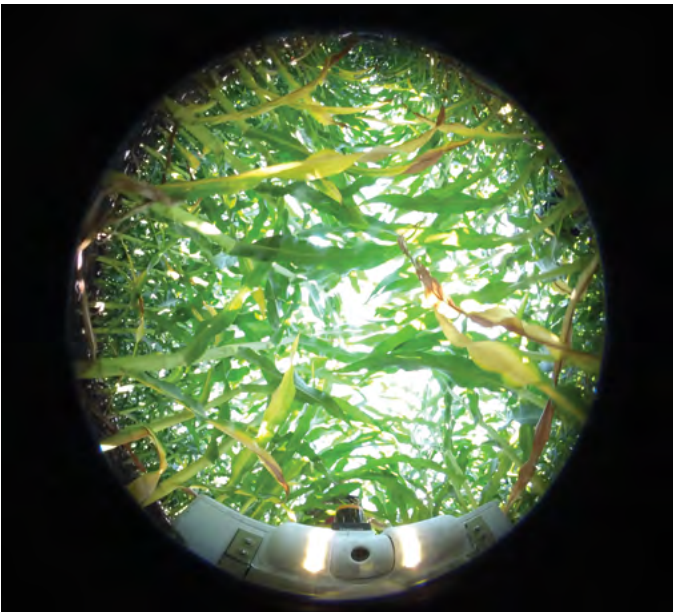


Figure 2. Leaf area index measurement at R1 in a field experiment near Windfall, Indiana in 2018. Leaf area index represents the amount of leaf area (m²) (vertically stacked) per m² of land area and corresponds to light interception, nitrogen storage, and water use.

Kernel number is set by the R2 growth stage, which occurs approximately 2 weeks after flowering, and can be negatively impacted by stress to the plant during this period. At yield levels above 200 bu/acre, kernel number was maximized, with essentially all expressed silks resulting in successful kernel set. Below 200 bu/acre, incomplete kernel set resulted in lost yield potential. At 150-200 bu/acre the number of kernels set was around 10% less than the number of silks expressed. Below 150 bu/acre, this gap grew to 20%.

Based on kernel number, yield classes above 200 bu/acre had no loss in yield potential at the R2 stage, while yield potential was reduced by 11% in the 150-200 bu/acre class, and by 28% in the <150 bu/acre class. Kernel weight was the yield component with the greatest degree of differentiation among yield classes, with kernel weight increasing with each successively higher yield class. Kernel weight increased 18%, 12% and 11% from the lowest yield class to the >250 bu/acre class. Kernel weight was the main component that separated good yield (200-250) from great yield (>250).



Figure 3. Image of a small ear at the time silks appear from the husk. From this picture the number of potential ovules can be counted by manually counting the rings and rows to get total ovule counts.

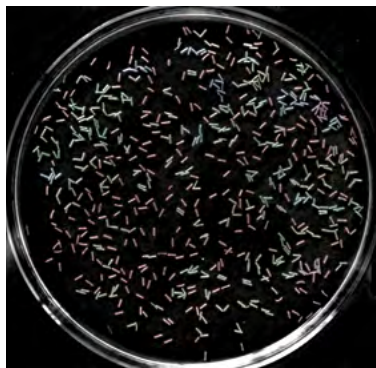


Figure 4. A technique was developed to take a cross section of the emerged silks from an ear in the field and store in a vial containing ethanol. Silks are spread apart on a petri dish and an image is collected. Image analysis software is used to count the number of silks.



Figure 5. At maturity, ears were harvested and a digital image was collected. Image analysis software was used to determine the total number of kernels per ear.

Because kernel weight increased with yield, the number of kernels required to reach one bushel (i.e. 56 lbs) decreased. When estimating yield from kernel number per ear and plant density select a number of kernels per bushel that is appropriate for the likely yield level.

Nitrogen Uptake

Total nitrogen uptake, measured at both the R1 and R6 growth stages, increased with each yield class (Table 4). N uptake post-flowering ranged from 43 lbs N/acre for the <150

bu/acre yield class to over 100 lbs N/acre in the >250 bu/acre yield class. The amount of N remobilized to grain increased with each yield class; however, the percentage of total grain nitrogen that came from remobilization decreased with higher yield classes, indicating that higher-yielding crops rely more on nitrogen uptake during the grain-filling period rather than remobilization.

Measurements of total plant N and grain N at R6 indicate that a corn crop taken for silage would remove between 106 and 302 lbs N/acre depending on the yield level. Corn taken for grain would remove between 66 and 209 lbs N/acre depending on the yield level. Residue remaining in the field following grain harvest ranged between 40 and 93 lbs N/acre depending on the yield level.

Both leaves and stems are major sinks for nitrogen prior to R1. After R1 leaves and stems begin to remobilize stored N to the grain to help with grain filling. At low yield levels, the leaves contribute the majority (>50%) of N contained in the grain, with the stem contributing another 10%. At the highest yield levels, the leaves contribute a smaller portion of the grain N via remobilization (<30%).

Biomass Partitioning (R1)

At flowering (R1), stalk tissue accounted for around 60% of total aboveground biomass, with approximately 30% of the biomass in green leaves, a ratio that was stable across yield levels. Stalk biomass and green leaf biomass both increased with each successively greater yield class. The amount of biomass comprised of senesced leaves decreased with higher yield levels, even as total leaf biomass increased, indicating that plants in higher yield classes retained more green leaf tissue post-flowering.

Despite accounting for only 30% of total aboveground biomass at R1, green leaf tissue contained around 50% of total N due to a greater concentration of N in the leaf tissue compared to stalk tissue. Leaf N concentration at R1 was 2.8% for high yield classes and 2.0% for low yield classes, providing a potential sufficiency level when tissue sampling.

Biomass Partitioning (R6)

Total plant biomass increased dramatically for all yield classes between R1 and R6, with the grain accounting for around half of total aboveground biomass at maturity (Table 6). Total plant biomass (vegetative + grain) for the highest yield class was over 31,000 lbs/acre and contained over 330 lbs N/acre, both of which were more than double the averages of the lowest yield class. At maturity, over 60% of the total plant N was in the grain, with 11-15% in the stalk and another 11-16% in green and senesced leaves.

Average N concentration in the vegetative material was 0.38, 0.54, 0.65, and 0.81% for the <150, 150-200, 200-250, and >250, respectively. When the grain and cob are removed, for earlage, the N concentration in the material is 0.9, 1.0, 1.1, and 1.2% for the low to high yield categories, respectively.

Table 4. Nitrogen uptake by a corn crop at R1 and R6, the amount of N contained in the grain at R6, the amount of N taken up post-flowering, the amount of N remobilized from the vegetative tissue to support grain N on a lbs/acre and percent basis for four yield classes based on bu/acre. The columns following the yield trait class indicate the number of observations that were used to calculate the mean.

Trait	<150 bu/acre		150-200 bu/acre		200-250 bu/acre		>250 bu/acre	
	n		n		n		n	
N uptake at R1 (lbs/acre)	78	287	126	582	146	1,163	161	572
N uptake at R6 (lbs/acre)	106	375	166	615	226	1,312	302	923
Grain N (lbs/acre)	66	446	114	681	155	1,452	209	980
Post Flower N uptake (lbs/acre)	43	283	59	427	86	1,018	103	562
Remobilization N to grain (lbs/acre)	43	266	66	482	74	1,055	77	552
Grain N from remobilization (%)	59	261	57	467	47	1,043	45	553

Table 5. Plant biomass and nitrogen content for corn at flowering (R1) for four yield classes. The percent N concentration for each plant part and the plant part contribution to total plant biomass and N content are included. Count represents the number of observations included in the mean.

	Yield Class	Biomass	N Content	N Concentration	Contribution to Total Biomass	Contribution to Total N Content	Count
		lbs/acre		%			n
Plant	<150	6,893	59	1.1	-	-	275
	150-200	8,485	124	1.4	-	-	532
	200-250	9,114	142	1.6	-	-	1,068
	>250	9,133	150	1.7	-	-	515
Stalk	<150	4,140	22	0.5	56.6	26.2	257
	150-200	5,612	44	0.8	60.1	33.6	410
	200-250	5,960	56	1	60	35.6	791
	>250	5,826	60	1	59.4	36.8	328
Green Leaves	<150	2,248	45	2	30.7	52.4	257
	150-200	2,650	66	2.5	28.3	50.8	398
	200-250	2,971	79	2.7	29.9	50.3	778
	>250	3,007	83	2.8	30.7	51.1	324
Husk	<150	296	5	1.6	4.1	5.3	200
	150-200	423	6	1.7	4.5	4.8	143
	200-250	402	7	1.8	4.1	4.5	351
	>250	401	6	1.6	4.1	4	198
Senesced Leaves	<150	299	5	1.1	4.1	6	161
	150-200	223	4	1.3	2.4	2.7	165
	200-250	201	4	1.4	2	2.7	290
	>250	159	2	1.2	1.6	1.4	178
Tassel	<150	204	5	1.9	2.8	5.5	30
	150-200	195	4	1.8	2.1	3	67
	200-250	218	5	2.2	2.2	3.4	112
	>250	222	5	2.1	2.3	2.8	21
Ear	<150	95	3	3.4	1.3	3.7	228
	150-200	159	5	3.4	1.7	4	206
	200-250	131	4	3.6	1.3	2.8	399
	>250	137	5	3.6	1.4	3.1	215
Shank	<150	37	1	2.4	0.5	1.1	190
	150-200	77	2	2.3	0.8	1.2	67
	200-250	54	1	2.7	0.5	0.8	217
	>250	57	1	2.7	0.6	0.8	42

Table 6. Plant biomass and nitrogen content for corn at maturity (R6) for four yield classes. The percent N concentration for each plant part and the plant part contribution to total plant biomass and N content are included. Count represents the number of observations included in the mean.

	Yield Class	Biomass	N Content	N Concentration	Contribution to Total Biomass	Contribution to Total N Content	Count
	bu/acre	lbs/acre		%			n
Plant	<150	15,889	106	0.7	-	-	375
	150-200	19,960	170	0.8	-	-	622
	200-250	23,509	226	1	-	-	1,367
	>250	31,631	331	1	-	-	1,511
Grain	<150	7,534	66	1	44.9	61.1	460
	150-200	10,478	114	1.1	50.6	65.1	691
	200-250	13,064	155	1.2	53.4	67.3	1,536
	>250	16,339	209	1.3	56.8	73.7	1,619
Stalk	<150	4,973	17	0.3	29.6	15.4	229
	150-200	5,482	24	0.4	26.4	13.4	348
	200-250	6,218	30	0.5	25.4	13	821
	>250	7,101	34	0.5	24.7	11.8	527
Senesced Leaves	<150	1853	9	0.5	11.1	8.7	192
	150-200	1758	15	0.9	8.5	8.4	255
	200-250	1887	19	1	7.7	8.2	641
	>250	1774	18	1	6.1	6.3	222
Cob	<150	991	5	0.5	5.9	4.9	382
	150-200	1,217	6	0.5	5.9	3.4	522
	200-250	1,431	8	0.5	5.9	3.4	1,277
	>250	1,560	6	0.4	5.4	2.1	773
Green Leaves	<150	661	6	0.9	3.9	5.6	100
	150-200	989	13	1.3	4.7	7.4	109
	200-250	965	14	1.4	3.9	6	508
	>250	904	13	1.4	3.1	4.7	244
Husk	<150	642	4	0.6	3.8	3.5	141
	150-200	682	3	0.5	3.2	1.7	182
	200-250	751	4	0.6	3.1	1.6	412
	>250	863	3	0.5	3	1	270
Shank	<150	122	1	0.8	0.7	0.9	130
	150-200	130	1	0.8	0.6	0.6	108
	200-250	162	1	0.8	0.7	0.5	279
	>250	222	1	0.9	0.8	0.5	119

Nitrogen Uptake

Prior to R1, N uptake (i.e. soil N contribution) ranged between 75 and 119 lbs of N per acre (Table 7). In the <150 bu/acre category, N uptake post flowering was 24 lbs/acre and increased to 38 lbs per acre in the 150-200 bu/acre category. While the number of observations is lower in the 200-250 bu/acre and >250 bu/acre categories N uptake was 68 and 122 lbs/acre, respectively. This finding would indicate that field

or locations within fields that can continue to mineralize N throughout the season to deliver N for grain filling will support increased grain yield. In the <150 bu/acre category, 76% of nitrogen contribution from the soil occurred by R1 with little N uptake up post flowering. In the higher yield potential classes 56% nitrogen contribution from the soil occurred by R1 with significant N accumulation still occurring after flowering.

Table 7. Nitrogen uptake in corn biomass at R1 and R6 when zero N was applied, and all N was supplied by residual NO₃-N and mineralization, for four yield classes. Count represents the number of observations that were used to calculate the mean. All measurements occurred at Midwestern U.S. locations and does not include Woodland, CA or Viluco, Chile.

					Location Soil Organic Matter		
Yield Class	N uptake R1		N uptake R6		Minimum	Maximum	Average
bu/acre	lbs/acre	n	lbs/acre	n			
<150	75	211	99	261	2.1	6.7	4.1
150-200	98	138	136	155	1.8	6.7	3.8
200-250	119	58	187	64	1.8	6.7	3.4
>250	116	3	238	5	2.8	4.6	3.4

Harvest Index

The harvest index (HI) is a measure of how efficiently a plant converts its total biomass into grain yield. Historically, the harvest index for corn has been around 0.5, meaning that around half of the total aboveground biomass at maturity is contained within the grain. Some studies have shown an increase in harvest index associated with genetic yield gain in corn. Results of this study showed that harvest index increased with yield level, from 0.45 at yields below 150 bu/acre, to 0.53 at 150–200 bu/acre yields, and leveling off at 0.56 for yields above 200 bu/acre (Table 8).

The nitrogen harvest index (NHI) measures how efficiently a plant converts the total nitrogen uptake into grain nitrogen. Nitrogen Harvest Index was lower for the lowest yield class in the study, averaging 0.61 and was around 0.70 for all other yield classes.

Table 8. Harvest index (ratio of grain and total biomass) and nitrogen harvest index (ratio of N contained in the grain and total N in all plant biomass) at R6 for four yield classes. Count indicated the number of observations that were used in calculating the mean.

Yield Class (bu/acre)	Harvest Index	Count	Nitrogen Harvest Index	Count
<150	0.45	587	0.61	432
150-200	0.53	647	0.69	466
200-250	0.56	1,353	0.71	961
>250	0.56	830	0.70	665



CONCLUSIONS

- Production of plant biomass and the accumulation of N are strongly correlated to grain yield.
- Management that removes growth limitations prior to R1 is critical in the attempt to maximize kernel number and limit yield reductions.
- Late season N uptake from the soil rather than a dependency on remobilization is a noticeable feature of high-yield locations, contributing to kernel weight increase.

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Lucas Borrás, Ph.D.,
Senior Research Scientist

Brian Dahlke,
Research Scientist

Jose Rotundo, Ph.D.,
Research Scientist

Alejo Ruiz, Ph.D.,
Research Scientist

Linda Byrum,
Associate Investigator



MANAGEMENT OPTIONS TO MAXIMIZE THE QUALITY OF FOOD GRADE CORN

KEY POINTS

- Maintaining grain quality demanded by dry milling processors, while maximizing corn yield, is the greatest challenge dry milling supply chains currently face.
- Management practices and the environment in which corn is grown play a crucial role in meeting the quality standards demanded by processors.
- Corteva Agriscience conducted a series of field experiments to test how dry milling grain quality is affected by management practices.
- Kernel density was affected by crop management decisions such as hybrid selection, nitrogen (N) fertilization rate, plant population, and fungicide use.
- Research showed that maximizing kernel density required a higher N fertilization rate compared to what is needed to maximize grain yield.
- Crop management decisions that affected screen retention were hybrid selection, N fertilization rate, and plant population.
- Test weight was affected by hybrid selection, N fertilization rate, plant population, and planting date.

GRAIN QUALITY OF FOOD GRADE CORN

Food grade corn is a specialty ingredient used for various human consumption products. It is commonly dedicated to dry milling, an industry that produces a wide variety of yellow and white corn food ingredients. The main products from dry milling are degermed corn grits (endosperm pieces with embryo removed), corn meal, corn flour, and corn bran. These products are used in everyday foods, such as breakfast cereals, snacks, baked goods, and beer.

Grain quality in food grade corn is determined by kernel hardness and size. Increased kernel hardness improves the yield of the dry milling process to produce endosperm pieces and is typically estimated by different metrics such as test weight (a bulk grain density measurement), proportion of hard and soft endosperm (measured by visual inspections), kernel density (measured with a pycnometer), and/or flotation index (measured by the proportion of floating grains in a known solution) (Figure 1). Kernel size is relevant for dry milling because it reflects the grain capacity to yield large endosperm pieces, which are highly valued as a food ingredient. Currently, companies use screen retention to best estimate kernel size, with U.S. dry milling supply chains using 20/64 round-hole screens as the standard.

The ability to maintain the grain quality demanded by dry milling processors, while maximizing corn yield for growers, is the greatest challenge dry milling supply chains currently face (Borras et al., 2022). For the most part, specialty grain supply chains deal with this challenge by focusing entirely

on a genetic centered solution by providing genotype recommendations to farmers through preferred hybrid lists. Other relevant components that can impact grain quality for dry milling are commonly ignored, such as the interaction of genetics, environment, and management.

The few crop management practices commonly advised to farmers by food grade companies are hybrid selection and isolation for purity assurance. Besides these two practices, the farmer optimizes decisions related to other practices such as plant population, fertilization, and/or fungicide/insecticide usage with a focus on maximizing yield. Traits related to grain behavior during dry milling (test weight, kernel density, and screen retention) have a strong genetic component. However, management practices and the environment in which crops are grown also play a crucial role in meeting the quality standards demanded by processors (Duarte et al., 2005; Cirilo et al., 2011; Gerde et al., 2016; Tamagno et al., 2016; Cerrudo et al., 2017).

In recent years, Corteva Agriscience conducted a series of field experiments to test how dry milling grain quality is affected by management practices. For example, Figure 2 describes the results from two contrasting N fertilization rates over commercial hybrids on grain yield, kernel density, screen retention, and test weight. These individual trials demonstrated the significant impact of crop management on the quality of food grade corn, confirming previous academic studies and suggesting a comprehensive assessment on the effects of management and environmental factors on food-grade quality was needed. In the present article, we describe this comprehensive assessment, in which we evaluated what specific management and environmental factors affect corn dry milling quality traits across a wide range of growing conditions under rainfed production.

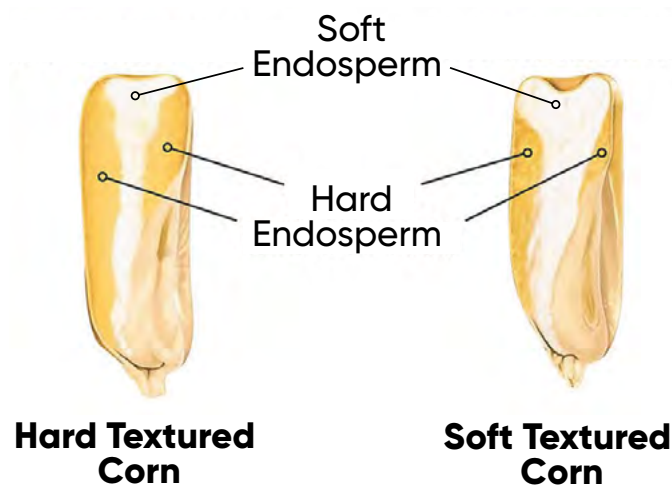


Figure 1. A main quality trait in food grade corn is kernel hardness and is related to the proportion of hard vs. soft endosperm. The kernel on the left is a hard textured corn with a higher proportion of hard endosperm. The kernel on the right has softer endosperm, with a smaller proportion of hard endosperm.

FOOD GRADE CORN FIELD TRIALS

A unique data set was compiled from field trials conducted across the central rainfed U.S. Midwest. Grain yield and dry-milling grain quality traits (kernel density, screen retention, and test weight) were measured from 97 current commercial

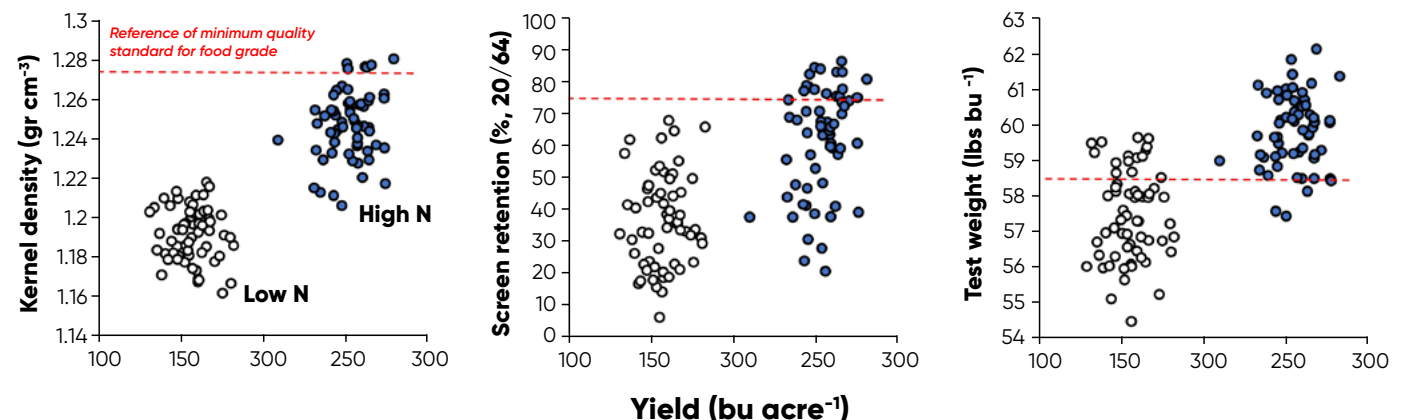


Figure 2. Nitrogen fertilization effects over grain yield, kernel density, screen retention, and test weight over a set of U.S. commercial hybrids with relative maturity from 105 to 115 CRM. Reference supply chain quality standards are shown (1.275 g/cm³ for kernel density, 75% for 20/64 screen retention, and 58.5 lbs/bu for test weight).

hybrids grown in 86 different environments. These 86 trials were conducted in Iowa, Illinois, and Indiana from 2019 through 2023 with no irrigation (Figure 3). The final dataset comprised around 3,300 observations for each trait. To determine the most important management and environmental factors affecting each grain quality trait we used mixed effects models following Gambin et al. (2016).

Grain yield was expressed at 15% moisture and measured with commercial or small plot research combines. Kernel hardness was estimated by kernel density using a gas pycnometer (Anton Paar, DMA 5001) and corrected by moisture content following Fox and Manley (2009). Test weight and kernel moisture concentration were measured with a Perten system (Perten AM5200). Kernel size was estimated as screen retention after shaking samples for 2 minutes in a 20/64 round holes screen and expressed as percentage (%) of the total sample that was retained above the screen.

RESULTS

All traits relevant to corn dry milling supply chain showed significant variability across field trials. Kernel density ranged from 1.115 to 1.345 g/cm³, screen retention ranged from 0 to 94%, and test weight ranged from 54.7 to 65.4 lbs/bu in the analyzed database. The most important management and environmental factors explaining each trait variability are described in Table 1.

Kernel density was affected by crop management decisions such as hybrid selection, N fertilization rate, plant population, and fungicide use. The environmental factors that affected kernel density included soil organic carbon, minimum temperatures during the vegetative period, and water balance during the vegetative period. Higher N fertilization,

higher soil organic carbon, fungicide application, and a better water balance during the vegetative period (less drought stress) had a positive impact on kernel density. On the other hand, higher plant populations and higher minimum temperatures during the vegetative period (common of later planting dates) had a negative impact on kernel density.

Table 1. Significant management and environmental factors affecting kernel density, screen retention, and test weight across hybrids and locations studied.

Significant predictor	Kernel Density	Screen Retention	Test Weight
Hybrid	X	X	X
Nitrogen fertilization rate	positive	positive	positive
Plant population	negative	negative	negative
Planting date			negative
Foliar fungicide	positive		
Soil organic carbon	positive	positive	positive
Minimum temperature vegetative	negative		
Maximum temperature vegetative			positive
Maximum temperature grain filling			negative
Water balance vegetative	positive		
Water balance grain filling		positive	

The crop management decisions that affected screen retention were hybrid selection, N fertilization rate, and plant population. Environmental factors like soil organic carbon and the water balance during the grain-filling period also affected screen retention. Higher N availability, soil organic carbon, and a positive water balance during grain filling (less drought stress during this period) positively affected screen retention. Plant population increases had detrimental effects on screen retention.

For test weight, the crop management options that significantly affected the trait were hybrid selection, N fertilization rate, plant population, and planting date. Significant environmental effects that influenced test weight were soil organic carbon and mean maximum temperatures during vegetative and reproductive periods.

Each one of the predictors described in Table 1 had a specific effect on the final trait of interest and were in agreement with management and environmental observations from previous academic studies on food grade corn production. Nitrogen fertilization and plant population also showed in previous studies they are important management options that need to be optimized when considering kernel hardness and size (Borras et al. 2003; Tamagno et al., 2016; Ruiz et al., 2022).

Figure 4 describes with more detail the response to N fertilization rate of kernel density and grain yield, and its interaction with plant population across all hybrids and

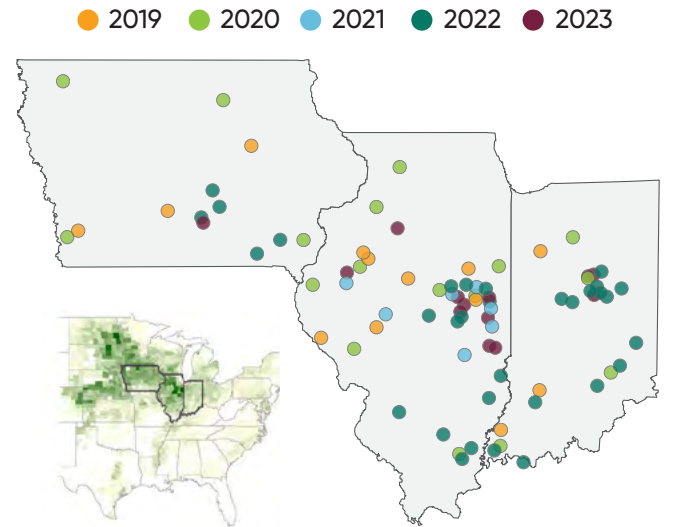


Figure 3. Location of the 75 on-farm strip experiments and 11 small plot field experiments conducted in Iowa, Illinois, and Indiana between 2019 and 2023. The experiments aimed to assess the impact of genotypes and management practices on grain yield, test weight, kernel density, and screen retention. The small U.S. map describes total acreage planted with corn by county, where a darker color indicates more acreage.

environments. Kernel density and yield increased as a function of N fertilization rate, but the response depended on the plant population used. In general, a lower plant population resulted in a higher kernel density across all N fertilization rates, and yield was lowest at low N rates and high plant populations and maximized at higher N rates with highest plant populations (as expected based on known

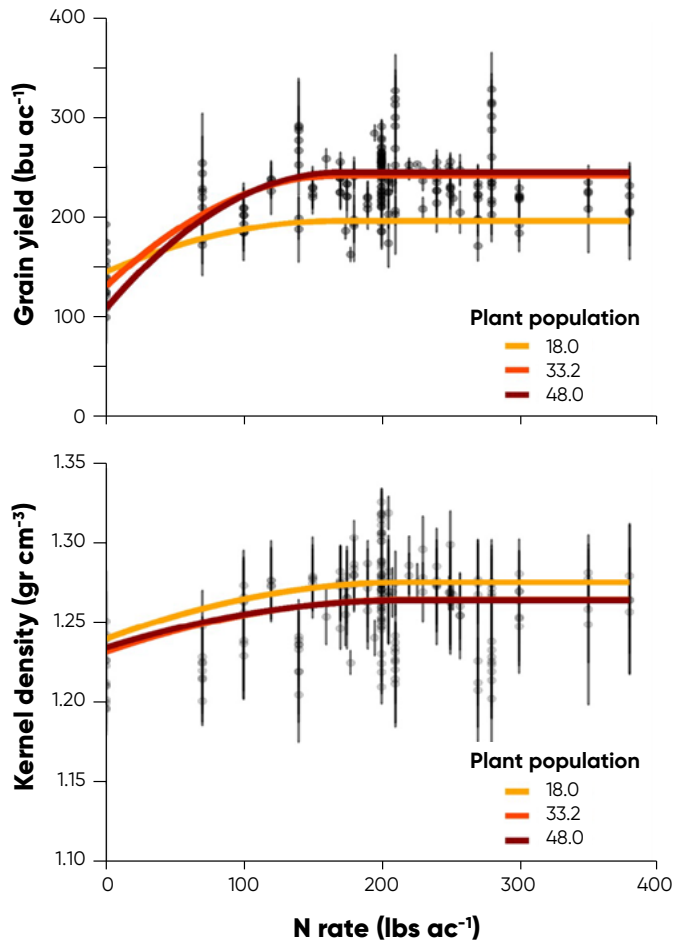


Figure 4. Grain yield and kernel density response to N fertilization rate in three plant populations (18, 33, and 48 thousand plants/acre). Curves are the fitted responses from the statistical analysis, and points are the average for each specific site x year combination.

interactions between plant population and N fertilization rate). Interestingly, the data showed that maximizing kernel density requires a higher N fertilization rate compared to what is needed to maximize grain yield (221 vs. 171 lbs N/acre). Lastly, we tested the effectiveness of the predictors listed in Table 1 in estimating each grain quality trait using an independent set of data from the region (leave-one-site-out cross-validation methodology). Figure 5 shows the accuracy of these predictions across the region, indicating that knowledge of the genetic, management, and environment factors (GxExM) at each site helped predict final grain quality with adequate accuracy.

When comparing the ability to predict kernel density, screen retention, and test weight using a GxExM model versus a traditional G model (what is traditionally done with hybrid preferred lists), the accuracies (measured as relative root mean square error) were 1.87, 26.7, and 2.0 versus 2.14, 28.9, and 2.2%, respectively. This shows that knowledge of how the crop was managed (in terms of N fertilization rate, planting date, plant population, and fungicide use) and a description of the environmental condition the crop was exposed to, helped explain the final grain quality with a better accuracy than only knowing the specific hybrid grown in a particular field.

CONCLUSIONS

When producing food grade corn, it is essential to select a suitable hybrid, as has been traditionally done. Additionally, other crop management decisions that are made by the farmer at each field are important. The amount of applied N and the plant population are relevant for all analyzed traits affecting grain quality for dry milling (kernel density, screen retention, and test weight). Fungicide use and planting date also significantly affected kernel density and test weight. These are all management practices that farmers can optimize in their operations to achieve maximum grain quality while still approaching maximum yields.

As a keynote, maximizing kernel density requires a larger N fertilization rate than the one needed to maximize grain yield. On average, 50 lbs N/acre more were needed across all hybrids and sites tested.

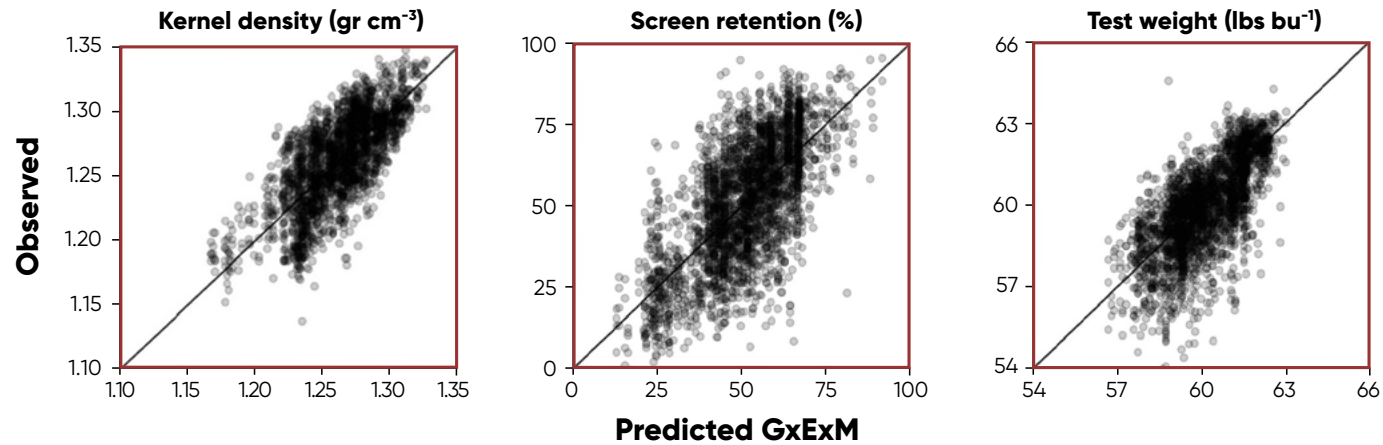


Figure 5. Observed and predicted kernel density, screen retention, and test weight from our GxExM models using leave-one-site-out cross-validation. Predictions were made using the management and environmental factors described in Table 1.

MECHANISMS OF NITROGEN LOSS FROM SOIL

KEY POINTS

- A central challenge in managing nitrogen fertility in corn production is the susceptibility of nitrogen to loss through leaching, denitrification, or volatilization.
- Nitrogen loss via volatilization can occur with manure and fertilizer products containing urea that are not incorporated into the soil by tillage or rainfall following application.
- Nitrogen in the nitrate (NO_3^-) form is susceptible to loss through leaching or denitrification.
- All three mechanisms of nitrogen loss can be influenced by weather and soil conditions.
- Nitrogen stabilizers can reduce the risk of nitrogen loss by slowing the rate of chemical reactions that occur in soil.

LEACHING

- Loss of nitrate (NO_3^-) that is carried by soil water downward below the crop root zone.

Situations at Risk of Nitrogen (N) Loss

- Leaching risk is typically greatest during April to June when intense rainfall events are most common and applied N is most susceptible to loss.

Processes and Reactions

- Nitrate is a negatively charged ion that is not attracted to soil particles and can move with soil water.
- Ammonium ions are converted to the nitrate form by the action of soil bacteria in a process known as nitrification.
- Nitrification is a two-step process: 1) oxidation of ammonia (NH_3) into nitrite (NO_2^-), and 2) oxidation of nitrite into nitrate (NO_3^-). Both steps are carried out by bacteria in the soil that use oxidation of chemical compounds as a source of energy.

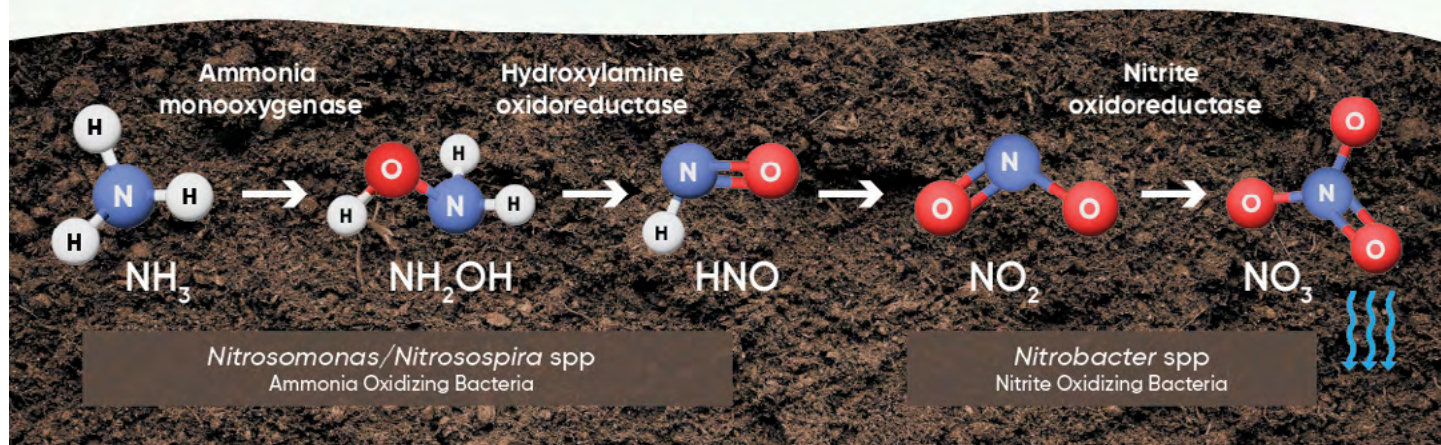
Important Factors

- **Rainfall** – The more water that moves through the root zone, the greater the potential for leaching.
- **Soil texture** – Coarse-textured soils have a lower water-holding capacity and more potential for leaching.

- **Rate of nitrification** – Multiple factors influence the rate of nitrification, which affects the susceptibility of N to leaching.
- **Soil temperature** – Nitrification is a biological process, so it is highly affected by temperature. It is maximized at soil temperatures above 75°F (24°C), slows at cooler temperatures, and essentially ceases below 40°F (4°C).
- **Soil moisture** – Both water and oxygen are required for nitrification, so it is favored by adequate but not excessive soil moisture. Nitrification is limited when saturation of soil pore space with water exceeds 60%.
- **Soil pH** – The optimal pH range for nitrification is between 6.5 and 8.8. Nitrification rates are reduced in more acidic soils.

Tactics to Reduce N Loss

- **Application timing** – Applying a portion of nitrogen in-season closer to the time of greatest crop demand reduces the opportunity for it to leach before being taken up.
- **Nitrification inhibitors** – Products such as N-Serve® and Instinct NXTGEN® slow the conversion of ammonium to nitrate, prolonging the period of time that nitrogen is in the ammonium form and reducing nitrogen loss from the soil.



DENITRIFICATION

- Loss of N to the atmosphere as N_2O or N_2 gas.

Situations at Risk of N Loss

- Denitrification occurs in saturated soils. The greatest nitrogen losses through denitrification generally occur in the spring when rainfall events are most frequent and crop uptake of nitrogen from the soil is relatively low.

Processes and Reactions

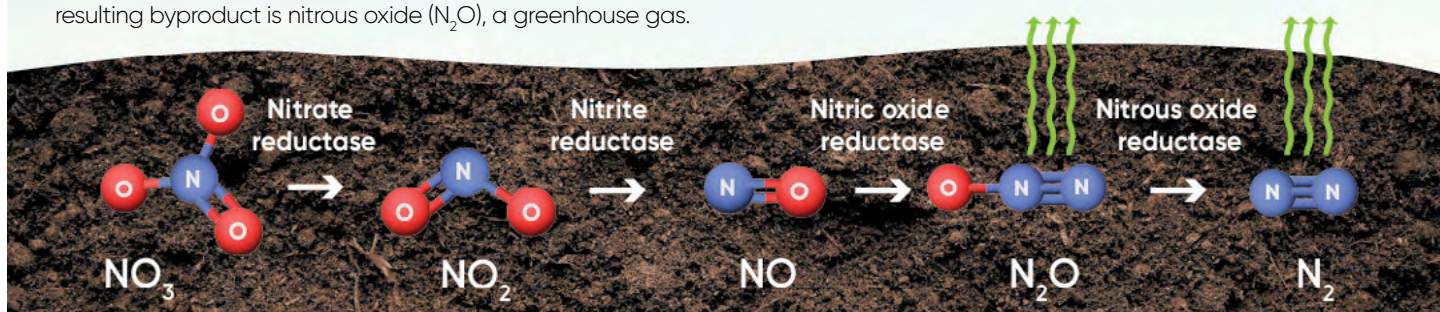
- Denitrification is a microbially facilitated process where nitrate (NO_3^-) is reduced and converted to N_2 gas through a series of intermediate steps.
- When oxygen in the soil is limited, a variety of bacteria will use the oxygen atoms from nitrate molecules for respiration.
- When nitrate is not completely converted to N_2 gas, the resulting byproduct is nitrous oxide (N_2O), a greenhouse gas.

Important Factors

- Soil water** – Denitrification is triggered by rainfall events of sufficient volume to saturate at least 60% of soil pore space. 2–3 days of saturation are required to begin denitrification.
- Nitrogen in the nitrate form** – Nitrogen in the ammonium form (NH_4^+) is not subject to denitrification.
- Soil temperature** – Denitrification is a biological process, so it increases with temperature.

Tactics to Reduce N Loss

- Keep nitrogen in the ammonium form** – The use of nitrification inhibitors has been shown to be highly effective at reducing N losses through denitrification.
- Reduce the potential for soil saturation** – Improving soil drainage can lower the risk of N loss from denitrification.



VOLATILIZATION

- Loss of surface-applied urea to the atmosphere as ammonia gas (NH_3).

Situations at Risk of N Loss

- Manure and fertilizer products containing urea that are not incorporated into the soil by tillage or rainfall within a short time following application.

Processes and Reactions

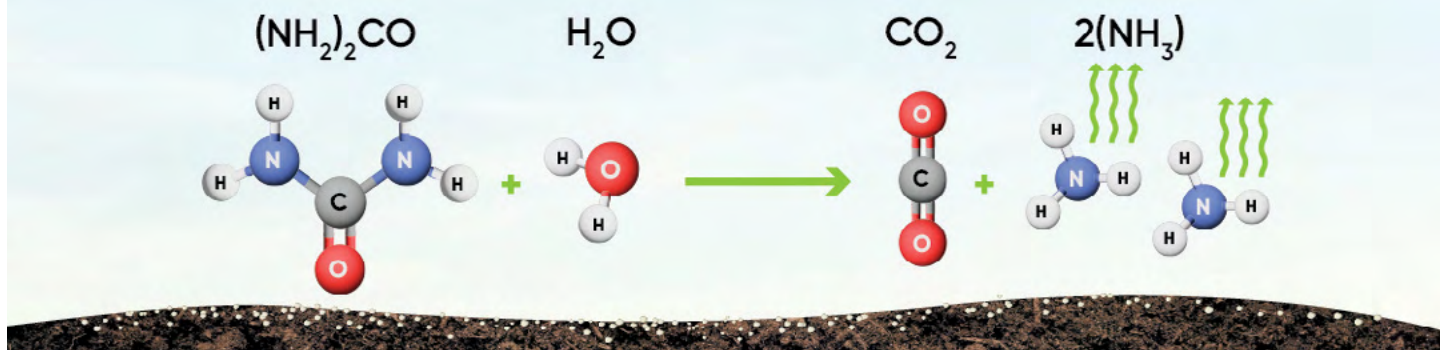
- Urea hydrolysis is catalyzed by urease, an enzyme that is produced by many types of common soil bacteria.
- Urea is hydrolyzed into one CO_2 and two NH_3 molecules.
- If this reaction occurs within the soil, the NH_3 reacts with soil water to form NH_4^+ , which is then bound to the soil.
- If it occurs on the soil surface, the NH_3 can be lost into the air.
- Most volatilization occurs within 2–3 weeks after application.

Important Factors

- Air temperature** – Urease activity increases as temperature increases. Hydrolysis is normally completed within ten days at $40^\circ F$ ($4^\circ C$) and within two days at $85^\circ F$ ($29^\circ C$).
- Soil surface moisture** – The hydrolysis reaction requires water, so volatilization increases with soil water content.
- Soil characteristics** – High soil pH, clay content, CEC, and/or organic matter are all associated with lower volatilization.
- Crop residue** – High levels of surface residue can increase soil surface moisture, prevent urea from reaching the soil, and harbor bacteria that hydrolyze urea.

Tactics to Reduce N Loss

- Incorporation by tillage**
- Incorporation by rainfall or irrigation**
- Urease inhibitors** – Urease inhibitors such as PinnitMax® TG slow down urea hydrolysis, which can reduce volatilization.





Jongwon Kang, M.S.,
Ph.D. Student

Department of Plant Agriculture,
University of Guelph
Guelph, Ontario, Canada

Jason DeBruin, Ph.D.,
*Global Biotech Trait
Characterization Project Scientist*

Rebecca Hensley, M.S.,
Sr. Research Associate

Joshua Nasielski, Ph.D.,
Assistant Professor
Department of Plant Agriculture,
University of Guelph
Guelph, Ontario, Canada



MINIMIZING VOLATILIZATION LOSS OF SIDEDRESSED NITROGEN IN CORN

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KEY POINTS

- This multi-year study in Illinois, Indiana, and Ontario measured the effect of nitrogen (N) fertilizer source, placement, and timing on N volatilization losses for in-season applications in corn.
- Urea and UAN, with and without a urease inhibitor were applied on the soil surface or injected into the soil mid-row at either V5 or V13.
- When no urease inhibitor was used, surface-applied urea generated significantly greater volatilization losses (average 35 lbs N/acre) than UAN (average 5 lbs N/acre).
- Urease inhibitors reduced volatilization losses for both UAN and urea; however, losses with UAN were already low even when applied on the surface.
- Application timing (V5 or V13) did not affect total NH_3 loss except with surface-applied urea, which had greater losses at V13 than at V5.
- Rainfall events impacted the total amount of N loss via volatilization. Soil moisture at application timing and subsequent rainfall interacted with soil texture to determine volatilization N losses.

IMPROVING NITROGEN USE EFFICIENCY OF IN-SEASON APPLICATIONS

One of the most challenging aspects of successfully managing nitrogen in corn is the fact that nitrogen from fertilizer can be lost from the soil before the crop is able to take it up. Nitrogen loss is not only a waste of resources, it also can have negative environmental impacts. Effective management practices can help reduce fertilizer N losses. This, in turn, increases the crop's access to applied N, enabling greater crop uptake and yield. Ammonia (NH₃) volatilization is a gaseous loss pathway that occurs when urea-containing fertilizers are used, especially when surface-applied. Following application, soil bacteria hydrolyze urea into one carbonic acid and two NH₃ molecules (Figure 1). If this reaction occurs within the soil, the NH₃ reacts with soil water to form NH₄⁺, which is then bound to the soil. If it occurs on the soil surface, the NH₃ can be lost into the air. Under the right conditions, a large fraction of surface-applied N can be lost to volatilization.



Nitrogen stabilizers are products applied or mixed into N fertilizers with the aim of reducing environmental N loss. These products work by slowing the rate of key chemical reactions that can make applied N susceptible to loss. There are two main types of stabilizers on the market.

Urease inhibitors are products that slow the rate of urea hydrolysis, which can reduce volatilization losses. These products contain the active ingredients NBPT and/or NPPT. Common trade names for urease inhibitors include Agrotain®, ANVOL™, and PinnitMax® TG.

Nitrification inhibitors limit the rate of nitrification, which can reduce N losses from leaching and denitrification. Examples include the active ingredient nitrapyrin (Instinct NXTGEN® and N-Serve®) or pronitradine (Centuro®).

Some products contain both urease and nitrification inhibitors, known as 'dual inhibitors'.

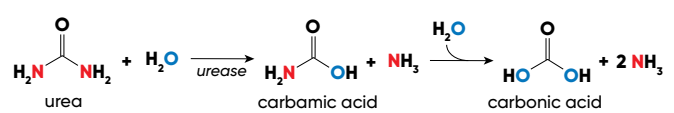


Figure 1. Reaction process once urea is applied to a field and is in contact with water that produces NH₃.

RESEARCH OBJECTIVES

A three-year field study at five locations was conducted to measure the amount of N volatilization (N lost as NH₃) from different N sources, placement, and application timings when N was applied in-season to corn. The goal of this study was to provide management recommendations for increasing N use efficiency and minimizing N losses from in-season applications.

MATERIALS AND METHODS

Replicated field studies were conducted in the U.S. near Adair, IL, and Windfall, IN, and in Canada near Elora, Ridgetown, and Winchester, Ontario over three years (2021–2023). In total, 15 site-years of data were collected. A total N rate application of 160 lbs N/acre was split-applied each year, with 30 lbs/acre N applied at planting followed by the remaining 130 lbs N/acre applied in-season. In-season treatments consisted of urea or liquid urea ammonium-nitrate (UAN; 50% urea, 25% NH₄⁺, 25% NO₃⁻) applied on the surface or injected 1–2 inches below the soil mid-row. Surface applied urea and UAN were either treated with a urease inhibitor (Agrotain® Dri-Maxx; Koch Agronomic Services) or left untreated (Table 1). These treatments were applied at all locations at the V13 growth stage. At the U.S. locations the same treatment was applied at the V5 growth stage in addition to the V13 growth stage.

Table 1. Nitrogen source and placement treatments applied at 130 lbs N/acre at V5 and/or V13 following 30 lbs N/acre applied at planting.

Treatment	Fertilizer type	Application method
Surface urea	Urea	Surface broadcast between rows
Surface urea + inhibitor	Urea, coated with Agrotain Dri-Maxx,	Surface broadcast between rows
Injected urea	Urea	Applied as a one-inch band injected into the soil between rows
Surface UAN	UAN	Surface application as two streams approximately 18 cm (7 inches) from the row
Surface UAN + inhibitor	UAN, with Agrotain Dri-Maxx,	Surface application as two streams approximately 18 cm (7 inches) from the row

Volatilization was measured up to 21 days following application using a method developed by Van Andel et al. (2017). Briefly, an ammonia dositube (#3D, Gastech Corporation; Japan) was placed in every plot and covered with a chamber (Figure 2a background and Figure 2b) that allowed for airflow around the dositube. The dositube passively recorded NH₃ volatilization and was checked daily for seven days post-application, then every two days for the remaining 14 days and replaced when necessary. Hourly wind speed data were collected using an anemometer placed within the crop canopy. Because the soil under the chamber stayed dry after

a rainfall, the dositube and chamber were moved to a new area after every rainfall to avoid bias (Figure 2a foreground). Combining wind speed data with dositube measurements allowed us to measure daily NH_3 loss.



Figure 2a. Overview of the various treatments with dositubes and buckets measuring volatilization. **Figure 2b.** A dositube connected to a wooden stake (foreground) and the bucket that is placed over the wooden stake to define the measurement area (background). Photo taken near Windfall, IN, in 2021 by Rebecca Hensley.

RESULTS

UAN Consistently Had Lower NH_3 Losses Compared to Urea

NH_3 losses were consistently lower with UAN than urea (Figures 3, 4, and 5). This was true regardless of whether an inhibitor was applied, whether injected or surface-applied, or when N was applied at V5 or V13 (Figure 4) and was consistent at U.S. and Canada locations (Figure 4 and 5). Among all N sources and placements tested, surface-applied urea without an inhibitor always had the greatest NH_3 loss (Figure 3).

NH_3 losses from urea could be incredibly rapid without an inhibitor. At Adair (2023), for example, 38 lbs N/acre was lost one day after application with an additional loss of 37 lbs/acre over the next four days. This represents nearly 58% of the application. (Figure 6). N losses, while not as sizeable as measured at Adair in 2023, occurred at Ridgetown during 2021, 2022, and 2023 following surface application of urea (Figure 7).

UAN N losses greater than 20 lbs N/acre (3rd Quartile) were uncommon, occurring only three times out of 15 site years for surface-applied UAN. The highest volatilization was observed at Ridgetown, ON, with a N loss of 35 lbs N/acre during 2023. This result is not surprising as UAN is 50% urea with the remaining 50% NH_3 and NH_4^+ . The urea component is the primary source of volatilization losses, so we would expect UAN losses to be around half those of urea. However, volatilization losses from UAN in this study were less than the theoretical 50% reduction.

Urease Inhibitors Reduced N Losses From Surface-Applied N, Especially With Urea

Urease inhibitors reduced NH_3 losses, especially during the first 8–13 days after N application. Time-course measurement of NH_3 losses at Ridgetown, ON during 2022 and 2023 indicated inhibitors were most effective for 8–13 days post-application (Figure 7). This is in line with previous research showing up to 14 days of activity for NBPT. Because N loss from untreated UAN was already quite low, the benefit of the urease inhibitor was much less. A good example of this effect occurred at Elora, ON, where the addition of the inhibitor to UAN reduced volatilization 65%; however, this resulted in a small 6 lb N/acre reduction in loss.

NH_3 Loss From Urea was Sensitive to Application Timing

Total NH_3 loss was not affected by N timing, except for the surface-applied urea. NH_3 losses from surface-applied urea (with or without an inhibitor) were greater at V13 compared to V5 (Figure 4). Warmer air temperatures at the V13 application timing may have driven larger volatilization losses. Since the breakdown of urea into NH_3 is a biological process, higher air temperatures increase the rate at which it occurs.

Soil Conditions and Rainfall After N Application Determine NH_3 Volatilization

While many factors under the farmer's control influence NH_3 losses, weather and soil properties are major determinants. For example, averaged across all N source and placement treatments, NH_3 loss from 130 lbs N/acre applied at V13 varied from 2.7 to 40.0 lbs N/acre depending on the location and year. Ideal weather conditions, in terms of minimizing NH_3 losses, would be for soil to be dry at application and then for a heavy rainfall to dissolve and move the N fertilizer a couple of inches below the soil surface as soon as possible after application.



Figure 3. Total NH_3 volatilization occurring 2 to 3 weeks following UAN or urea application to fields from 2021 to 2023 with application rates of 130 lbs N/acre at V13, across all 15 U.S. and Canadian site-years. Different letters denote significant differences based on a Tukey's test ($p \leq 0.05$). Values in the parenthesis indicate the cumulative NH_3 volatilization (lbs N/acre).

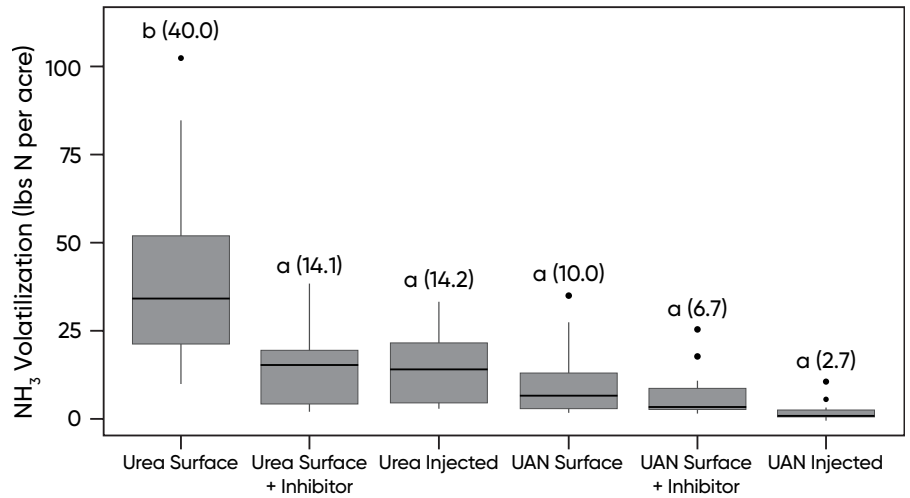


Figure 4. Total N loss via volatilization for six N treatments applied at V5 and V13 at locations near Adair, IL and Windfall, IN during 2021 to 2023. Lowercase letters are for comparison of N treatments within an application growth stage. Uppercase letters above the brackets compare UAN and Urea treatments.

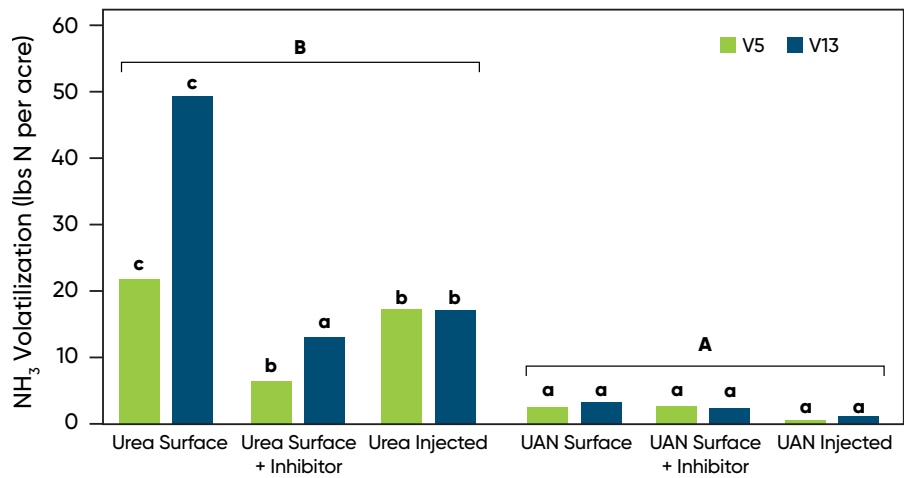
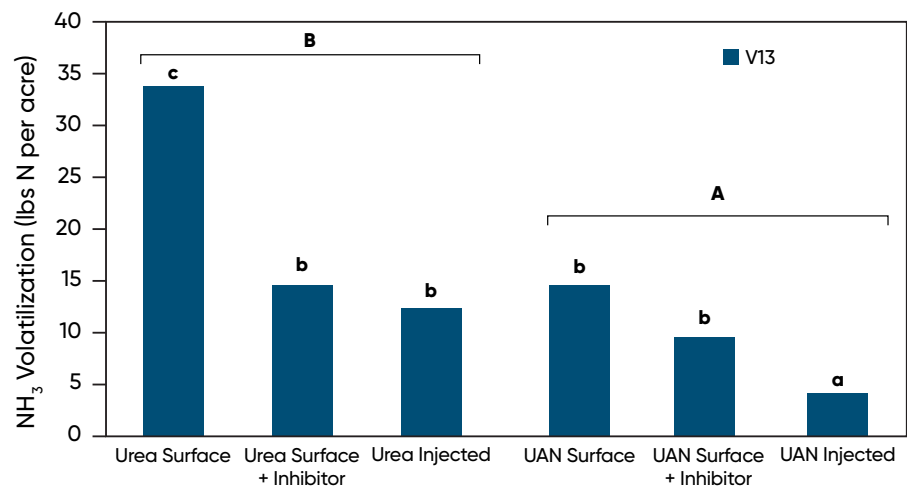


Figure 5. Total N loss via volatilization for six N treatments applied at V13 at locations in Ontario (Ridgetown, Elora, Winchester) during 2021 to 2023. Lowercase letters are for comparison of N treatments. Uppercase letters above the brackets compare UAN and urea treatments.



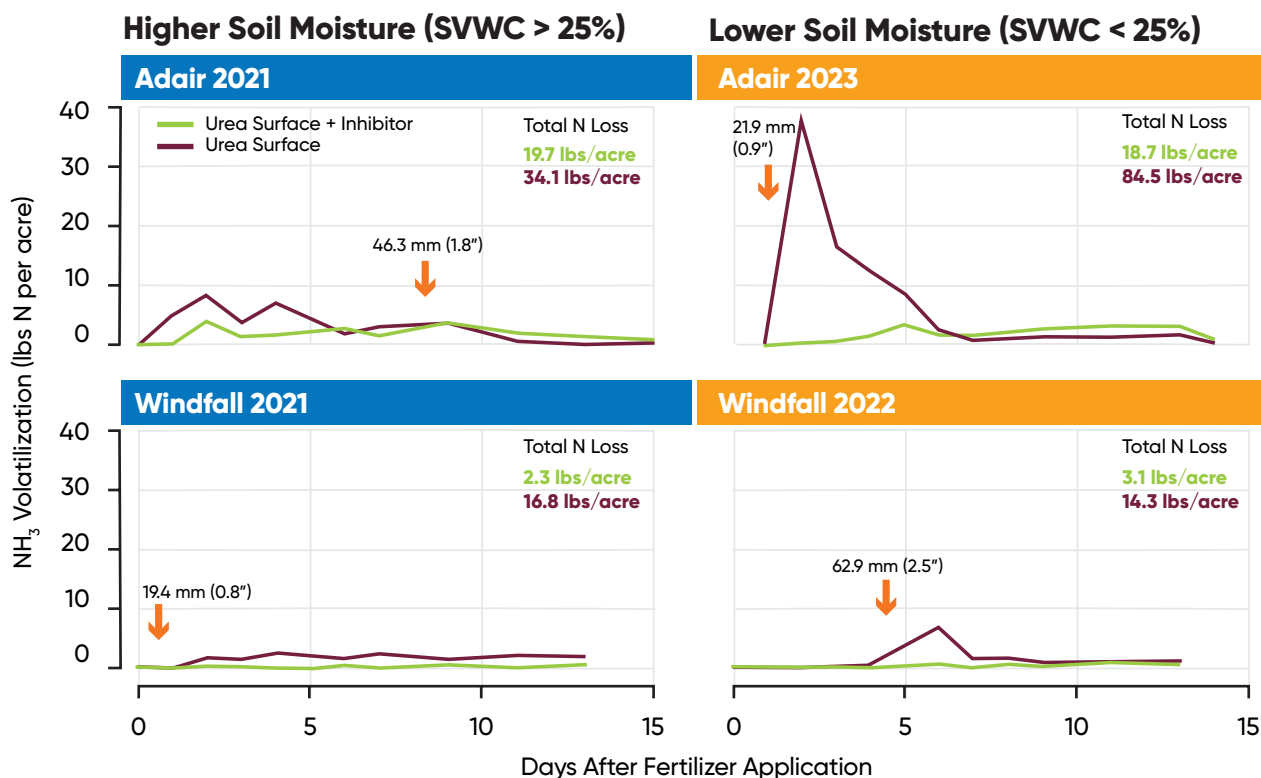


Figure 6. Daily NH₃ loss occurring two weeks following urea and urea + urease inhibitor surface application to fields at V13. Values in the charts indicate cumulative NH₃ volatilization (lbs N/acre) for urea with and without a urease inhibitor. Left panels (blue) are locations with soil volumetric water content (SVWC cm³/cm³) >25% moisture and panels on the right (orange) <25% soil moisture. Orange arrows indicate the largest rainfall event (mm) during the two-week sampling period of each growing season.

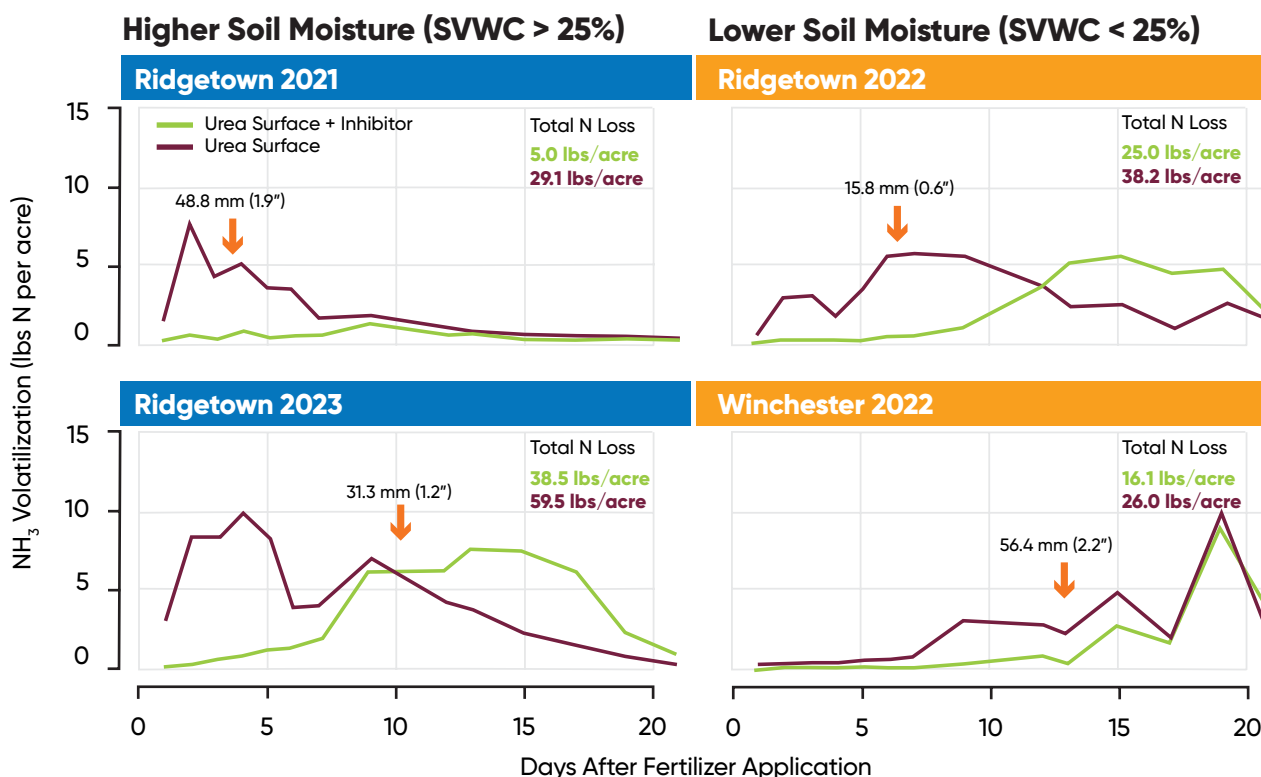


Figure 7. Daily NH₃ loss occurring two weeks following urea and urea + urease inhibitor surface application to fields at V13. Values in the charts indicate cumulative NH₃ volatilization (lbs N/acre) for urea with and without a urease inhibitor. Left panels (blue) are locations with soil volumetric water content (SVWC cm³/cm³) >25% moisture and panels on the right (orange) <25% soil moisture. Orange arrows indicate the largest rainfall event (mm) during the three-week sampling period of each growing season.

When applied to dry soil, NH_3 losses typically remained minimal for days until rainfall occurred. The urea hydrolysis reaction requires water to proceed, so the reaction rate will tend to be limited by dry soil at the surface. Application to moist soil resulted in immediate volatilization, specifically for surface-applied urea. Moist soil is defined as having a water content at 10 cm (4") depth greater than 29%. This would represent soil conditions that are borderline acceptable for field traffic. In moist soils, NH_3 losses would remain high until a rainfall event occurred to move the fertilizer N down into the soil.

Ideal weather conditions for minimizing NH_3 losses, would be for soil to be dry at application and then for a heavy rainfall to dissolve and move the N fertilizer below the soil surface as soon as possible after application.

Regardless of the initial soil moisture, a heavy rainfall would reduce but not eliminate subsequent NH_3 losses after an initial spike. Very large rainfall events (>2 inches/day [>50 mm/day]) were required to reduce NH_3 losses dramatically. Generally, the more rainfall, the less NH_3 loss. As a general rule, receiving 3 inches (76 mm) of rainfall over the 21-day measurement period was enough to limit NH_3 losses to 13 lbs N/acre on average (though losses from untreated urea were always high).

Adding a small amount of moisture, but not enough to drive the downward movement of N into the soil profile, favors volatilization.

Post-application, a light rainfall (<0.15 inches [<4 mm]) was possibly the worst situation regarding NH_3 losses, especially on dry soil with higher clay content (less sand) (Figure 8). It appears that adding a small amount of moisture, but

not enough to drive the downward movement of N into the soil profile, favors volatilization. Additionally, in a very dry year, disrupting the soil to inject the urea could cause more volatilization than leaving the urea on the surface because it exposed the urea to a small amount of soil moisture. For instance, at Adair, IL (2023) N was applied at the V5 growth stage to very dry soils followed by a cumulative rainfall of 0.1 inch (2.5 mm) during the 14-day measurement period. In this scenario the injected urea treatment had the greatest volatilization (26.5 lbs N/acre) compared to any other treatment (e.g., urea broadcast lost 4.9 lbs N/acre). Urease inhibitors demonstrated the most value in conditions where high volatilization losses were expected; applications onto wet soils, or after a light rainfall when applied onto dry soils.

Soil texture was an important feature that modified the interaction of volatilization and rainfall. The coarser the soil texture (i.e., as sand content increased), the less rainfall that was required to reduce NH_3 losses. This can be seen in Figure 7, comparing volatilization losses and rainfall at Winchester (20–26% sand) and Ridgetown (51–60% sand). Coarser soils

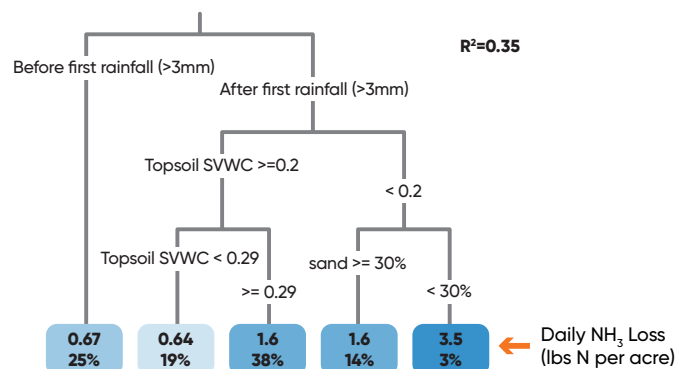


Figure 8. Flow diagram to describe the relationships between soil moisture, rainfall events, and soil texture to the potential and amount of volatilization using 15 site-years of data.

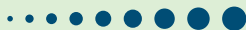
may allow for more rapid downward movement of dissolved N. NH_3 losses can remain minimal for days after application to dry soil until rainfall (>0.1 inch [>3 mm]) occurs (Figure 8). Heavy rainfall could reduce the N losses after an initial spike at Ridgetown (2021), whereas the highest NH_3 peak was observed after the large rainfall event at Winchester (2022). Additionally, at Adair (2022) where soil contains a similar sand content to Winchester (26% sand), heavy rainfall (>1.7 inches [>43 mm]) triggered the NH_3 losses, resulting in the highest peak. This difference arises because the field capacity at Ridgetown is around 20% of soil volumetric water content (SVWC), while that in Winchester and Adair is around 30% of SVWC. Thus, in Ridgetown, the dissolved N experienced rapid downward movement unlike in Adair or Winchester by heavy rainfall, preventing NH_3 from volatilizing.

CONCLUSIONS

N loss via volatilization can be measured in fields following N application using fairly simple tools. The outcomes from this work indicated that urea has a greater risk of N loss via volatilization compared to UAN, regardless of application timing. If urea is to be top-dressed or broadcast and incorporation via tillage is not possible, we recommend urease inhibitors, especially at later application timings.

If urea is to be top-dressed or broadcast and incorporation via tillage is not possible, we recommend urease inhibitors, especially at later application timings.

We also identify weather patterns that can work for or against you in terms of minimizing NH_3 loss. Ideally, soil is dry when surface-applying N and is followed by sufficient rainfall (3 inches [76 mm]) to dissolve and drive the N below the soil surface. When N is applied to wet soils or dry soils followed by small rainfall amounts, NH_3 losses will be large.



Jongwon Kang, M.S.,
Ph.D. Student

Joshua Nasielski, Ph.D.,
Assistant Professor

David Hooker, Ph.D.,
Associate Professor

Department of Plant Agriculture
University of Guelph
Guelph, Ontario, Canada

John Lauzon, Ph.D.,
Associate Professor

School of Environmental Sciences
University of Guelph
Guelph, Ontario, Canada

Craig Drury, Ph.D.,
Soil Biochemist

Agriculture and Agri-Food Canada

Jason DeBruin, Ph.D.,
*Global Biotech Trait
Characterization
Project Scientist*

Rebecca Hensley, M.S.,
Sr. Research Associate

MEASURING VOLATILIZATION LOSSES FROM NITROGEN FERTILIZER APPLICATIONS

KEY POINTS

- This article provides a step-by-step protocol that can be used for on-farm measurements of ammonia volatilization from nitrogen fertilizer applications.
- Ammonia (NH_3) volatilization is a gaseous loss pathway that occurs when urea-containing fertilizers are used, especially when surface-applied.
- Ammonia loss can be measured using dositubes, which are relatively inexpensive passive gas detection devices commonly used in industrial settings.
- Volatilization is usually greatest within a few days of nitrogen application, so dositube chambers should be installed as soon after application as possible.
- The measurement period should extend for at least 14 days after application and, ideally, up to 28 days.

MEASURING AMMONIA VOLATILIZATION

Ammonia (NH_3) volatilization is a gaseous loss pathway that occurs when urea-containing fertilizers are used, especially when surface-applied. This protocol provides all the necessary information to use the dositube method for measuring ammonia volatilization losses from nitrogen (N) fertilizer applications.

At the simplest level, this method involves placing a round chamber with a dositube inside of it on a representative part of the field after N application (Figure 1). The chamber must be checked at least every 3 days to record the dositube value to get an accurate measurement of N loss. The change in dositube values over time, combined with wind speed data, is used to calculate the amount of NH_3 lost. The dositube method was developed by John Lauzon and his research group at the University of Guelph to measure NH_3 emissions from manure (Van Andel et al., 2017), but it can be readily used for measuring NH_3 emissions from fertilizer.

MATERIALS

Dositubes are passive gas detection devices that measure the concentration of specific gases, such as ammonia. Commonly used in industrial settings, they operate based on a colorimetric principle where ammonia in the air reacts



Figure 1. Dositube chambers in a corn field for measuring ammonia volatilization loss from a sidedress nitrogen application.

with a reagent (sulfuric acid) inside the tube, causing a color change from purple to yellow. This application uses the GasTec 3D dositube manufactured by GasTec Corporation, based in Fukayanaka, Japan. Once the reagent is used up by the reaction, the dositube will need to be replaced with a new one. Expect to use 5-10 dositubes over a 21-day measurement period, depending on the amount of NH_3 loss.

Chambers for each dositube are required. A chamber is a white 4-gallon (15.4 L) bucket with an opening diameter of 10.8 inches (27.5 cm). Drill eight ½-inch holes at the bottom of the chamber and eight ½-inch holes about 1 inch from the lip of the chamber. These holes should be equally spaced. The holes act as chimneys for the chamber. With a plastic bucket, a standard ½-inch drill bit can be used. An example is shown in Figure 2. It is critical that the chamber used is as close as possible to the specified design. Altering the design of the chamber will result in large changes in measured dositube values (e.g., using different size chambers or changing hole configuration).

Wooden stakes and rubber bands keep the dositube centered in the middle of the chamber at a height 6 inches above the soil surface. Standard 12-inch wooden plot stakes can be used. Dositubes should be attached to the stake parallel to the soil surface, with the open tip slightly lower than the closed tip. This ensures that any moisture runs off the dositube (Figure 3).

An **anemometer** (wind speed recorder) is technically required as wind speed is needed to convert dositube readings to NH_3 loss in kg-N/ha, but workarounds using average estimated wind speed values can be used if an anemometer is not available. The anemometer should be installed at the height of the chamber in a representative area of the field.



Figure 2. Dositube chamber showing holes drilled through the bottom and around the lip of the bucket

SETTING UP

How many chambers are needed? We recommend at least four dositube chambers for every N fertilizer treatment being measured. For example, eight chambers would be needed to compare UAN with and without an N stabilizer. Comparing three different N fertilizer treatments would require 12 chambers.

When should the chambers be installed in the field?

Installation should occur as soon as possible after the N fertilizer application, as volatilization is normally greatest in the first few days after application.



Figure 3. Left: Dositubes used for measuring ammonia volatilization, showing where to break the dositube to begin measurement. Right: A dositube attached to a wooden stake with the open end angled slightly downward.

Field installation: In the field, break off the dositube end (Figure 3), attach the dositube to a stake, and push the stake securely into the ground. The dositube should be roughly 6 inches above the soil surface. To ensure consistency, draw two horizontal lines on each stake: one to indicate how deep to push the stake and the other to indicate where to attach the dositube. Then, place a chamber directly over the dositube. No plants should be under the chamber, just bare soil. The chamber should be pressed into the soil to make sure there are no large gaps between the chamber lip and the soil (Figure 4). It may be necessary to cut away some plants depending on crop row spacing.

Chamber placement: Place the chamber in a representative area to measure NH_3 loss appropriately. For broadcast urea, the chamber can be placed anywhere between the crop rows. For injected or surface-banded N, place the chamber directly over the band so that the band bisects the chamber in the middle (Figure 5). Cut away plants if necessary to accomplish this.



Figure 4. A correctly installed dositube chamber with no gaps between the bucket lip and the soil.



Figure 5. Left: Chambers placed in a field following a broadcast nitrogen application. **Right:** A field with banded nitrogen application in which the chambers are centered over the bands.

RECORDING DOSITUBE MEASUREMENTS

The dositube measures NH_3 loss in ppm/hr which stands for 'parts per million per hour.' The reading is equal to where the line is between the yellow and purple color (Figure 6). While easy to read, note that dositubes use the log scale, so the distance on the tube between 100 and 200 ppm/hr is much greater than the distance between 300 and 400 ppm/hr.

Ideally, data should be recorded from each chamber daily (or every two days) for at least 14 days and up to 28 days after N application. However, visiting the chamber every day may

not be feasible. Based on our data, the measurement interval for recording dositube measurements can be stretched to every three days without a large loss of accuracy. The more N loss there is, the more important it will be to record dositube readings frequently to get an accurate measurement.

If there is a heavy rain, move the chamber and dositube to a nearby spot to ensure soil conditions are representative. The chamber acts like an umbrella, keeping the soil beneath it dry. This is not representative of real-world conditions, so the chamber needs to be moved after every rainfall for accurate measurements.

Once the dositube reaches around 350 ppm/hr, we recommend that you replace it with a new dositube. This improves accuracy, especially if your measurement interval is greater than 2 days. Be sure to note the day the dositube is replaced. Depending on the severity of N loss, a 3-week measurement period will require 5 to 10 dositubes per chamber.

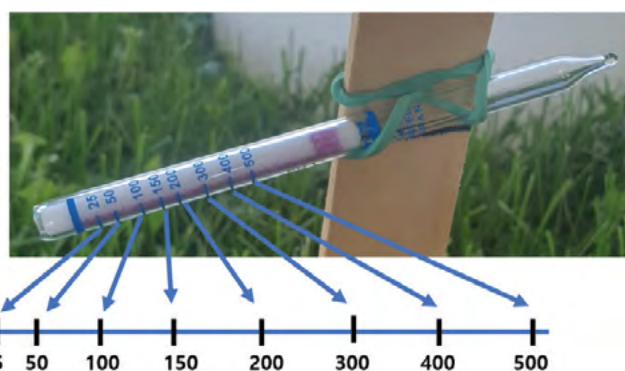


Figure 6. Top: Close-up view of a dositube showing the line between the purple and yellow color that indicates NH_3 loss in ppm/hr. **Above:** Expanded view of the measurement increments on the dositube.

Table 1. Average daily wind speeds in May, June, and July at 30 cm above the soil in corn fields (m/s) in at select locations in Ontario (Winchester, Elora, Ridgetown) and in the U.S. (Windfall, IN, and Macomb, IL). Data was collected over three seasons (2021–2023).

	Wind Speed 30 cm above the soil in corn field (m/s)				
Month	Ontario (Canada)			U.S.	
	Winchester	Elora	Ridgetown	Windfall	Macomb
May	1.69	1.06			
June	1.08	1.01	0.81	0.72	0.78
July	0.20	0.30	0.34	0.37	0.37

RECORDING WIND SPEED

Record the average daily wind speed at the height of the bucket. If an anemometer is not available, there are a couple of options for estimating wind speed. If a nearby weather station measures wind speed, those data can be used. Weather stations typically measure wind speed 2 meters above the soil surface, which is not representative of wind speed conditions closer to the soil surface. Wind speed is reduced the closer you are to the soil surface. Correction factors are available to convert wind speeds measured at one height to a different one. But once canopy closure is reached (when corn leaves cover up the inter-row area), wind speed data from local weather stations will not be representative. If you have no nearby wind speed data source, our research suggests that using average wind speed values as found in Table 1 do not result in major accuracy loss. You can use a daily average wind speed value of 0.88 m s⁻¹ before canopy closure and 0.39 m s⁻¹ after canopy closure if you do not have access to actual wind speed data.



CALCULATING NH₃ LOSS

The dositube method relies on the change in ppm/hr between two consecutive measurements. If the dositube reading is unchanged between two readings, then no NH₃ was lost. Change in the measurements between dates indicates N was lost as NH₃.

To convert the change in ppm/hr to a change in kg-N/ha of NH₃ loss, there are two steps. First, use a validated equation that uses the change in ppm/hr between measurements, as well as the average wind speed during the measurement interval, to convert ppm/hr to kg-N/ha. Next, use a scaling factor, based on the way N was applied, to properly scale the conversion of N loss measured from a round chamber to an area (hectare) basis. This second step helps account for things like skip-row applications where N is applied every second row. The equation and scaling factors are found below.

Equation:

$$\text{NH}_3 \text{ loss (kg-N/ha)} = (0.0378 \times \text{ppm/hr}) + (0.01 \times \text{ppm/hr} \times \text{wind}) + (0.000099 \times \text{ppm/hr}^2 \times \text{wind}) \times \text{scaling factor}$$

Where ppm/hr equals the change in dositube readings (in ppm/hr) between two measurements and wind equals average wind speed (in meters per second), and scaling factor is a number that depends on method of application.

Table 2. List of scaling factor values for the conversion equation, depended on the method of N application.

Method of application	Scaling factor
Broadcast or top-dress	1.0
One (1) N band/stream per row of corn (e.g., UAN injection side-dress)	0.30
Two (2) N bands/streams per row of corn (e.g., Y-Drop)	0.60

If N is applied skip-row, divide scaling factor by two.

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Mike Moechnig, Ph.D.,
Field Sciences Biology Team
Leader

Peter Baas, Ph.D.,
Biostimulant Biology
Characterization Leader

Greg Schulenberg,
Senior Technician –
Soil Microbiology

INSTINCT NXTGEN™ NITROGEN STABILIZER EFFECT ON NITROGEN LOSS

KEY FINDINGS:

- A field research study was conducted in 2023 to test the effect of Instinct NXTGEN™ nitrogen stabilizer on nitrogen loss through tile drainage.
- Instinct NXTGEN treatment reduced nitrogen concentration in tile drainage water by 24% following rainfall events after application.
- Results of this study show that nitrogen stabilizers can reduce nitrogen loss through tile drainage, even in years with minimal rainfall when nitrogen loss is relatively low.

REDUCING NITROGEN LOSS

- One of the most challenging aspects of successfully managing nitrogen is the fact that nitrogen from fertilizer can be lost from the soil before the corn crop is able to take it up.
- Under prolonged wet field conditions and warm temperatures, nitrogen can be lost either by leaching – the downward movement of nitrates below the root zone – or denitrification.
- Nitrification inhibitors are compounds that slow the conversion of ammonium to nitrate, prolonging the period of time that nitrogen is in the ammonium form and reducing nitrogen loss from the soil.
- A 2004 meta-analysis of hundreds of comparisons across a diversity of environments found that the use of nitrification inhibitors increased soil nitrogen retention by an average of 28% and reduced leaching by 16% (Wolt, 2004).
- Instinct NXTGEN™ nitrogen stabilizer is an encapsulated, water-based formulation of nitrapyrin that can be used with UAN, urea, and liquid manure.

RESEARCH OBJECTIVE

- A field research study was conducted in 2023 to test the effect of Instinct NXTGEN nitrogen stabilizer on nitrogen loss through tile drainage and corn yield when used with a spring UAN application.

STUDY DESCRIPTION

- The 2023 field study was conducted near Huntington, IN, at a research site with drainage infrastructure in place to allow sampling of nitrogen content in drainage water from treatment blocks (Figure 1).
- Treatment blocks were 40 x 300 ft, with 4 replications for each treatment.



Figure 1. Field research was conducted in 2023 to test the effect of Instinct NXTGEN nitrogen stabilizer on nitrogen loss through tile drainage at a field research site with drainage infrastructure in place to allow sampling of nitrogen content in drainage water.



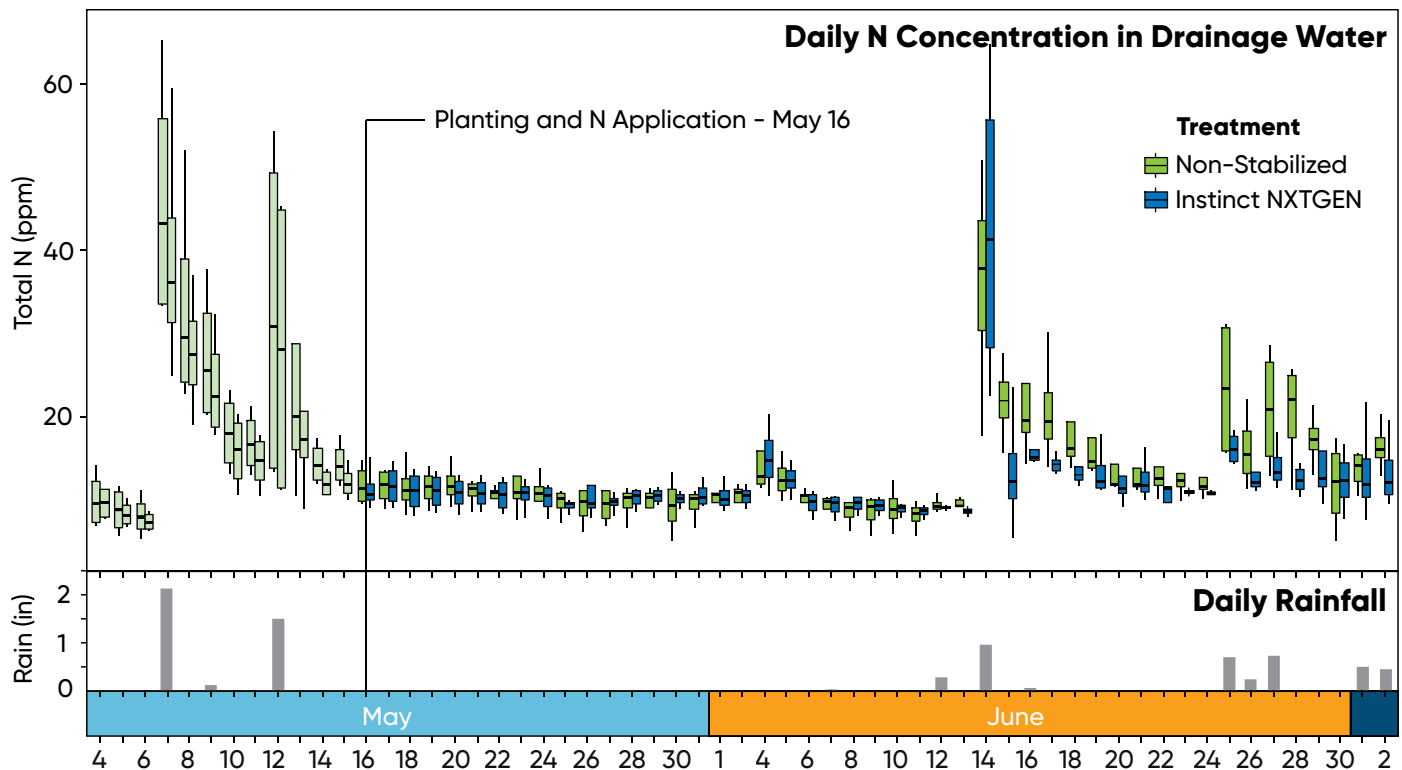


Figure 2. Daily rainfall totals and average nitrogen concentrations in tile drainage water from Instinct NXTGEN and non-stabilized UAN treatments.

- The study compared nitrogen loss and corn yield with 200 lbs/acre of nitrogen applied at planting as UAN in a sidedress band with and without Instinct NXTGEN at 24 fl oz/acre.
- Corn planting and nitrogen application were both done on May 16, 2023.
- Water samples were collected daily for an 8-week period that spanned 2 weeks before and 6 weeks after application and sent to a Corteva Agriscience lab for analysis.
- Water samples were analyzed for both ammonium and nitrate forms of nitrogen, although nearly 100% of nitrogen was in the nitrate form (data not shown), as would be expected.

RESULTS

- Sharp increases in drainage water nitrogen concentration followed rainfall events both before and after nitrogen application (Figure 2).
- Nitrogen concentration in drainage water from both the Instinct NXTGEN and non-stabilized treatments stayed relatively low for nearly a month following nitrogen application due to a lack of rainfall during this period.
- The first significant rainfall event following nitrogen application was on June 14, with subsequent rainfall during late June and early July.

- Differences in drainage water nitrogen concentration between the Instinct NXTGEN and non-stabilized treatments were observed during this period.
- Average drainage water nitrogen concentration between June 15 and July 3 was 24% lower in the Instinct NXTGEN treatment compared to the non-stabilized treatment (Figure 3).
- Corn yield did not significantly differ between the Instinct NXTGEN and non-stabilized treatments, suggesting that the additional nitrogen loss from non-stabilized treatment was not great enough to significantly impact yield (Figure 4).

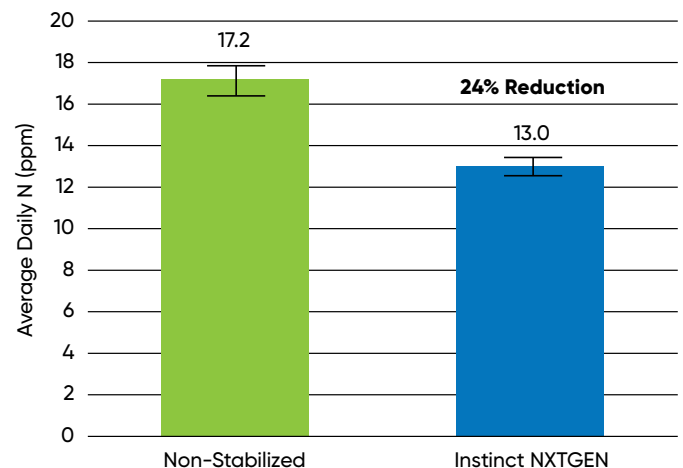
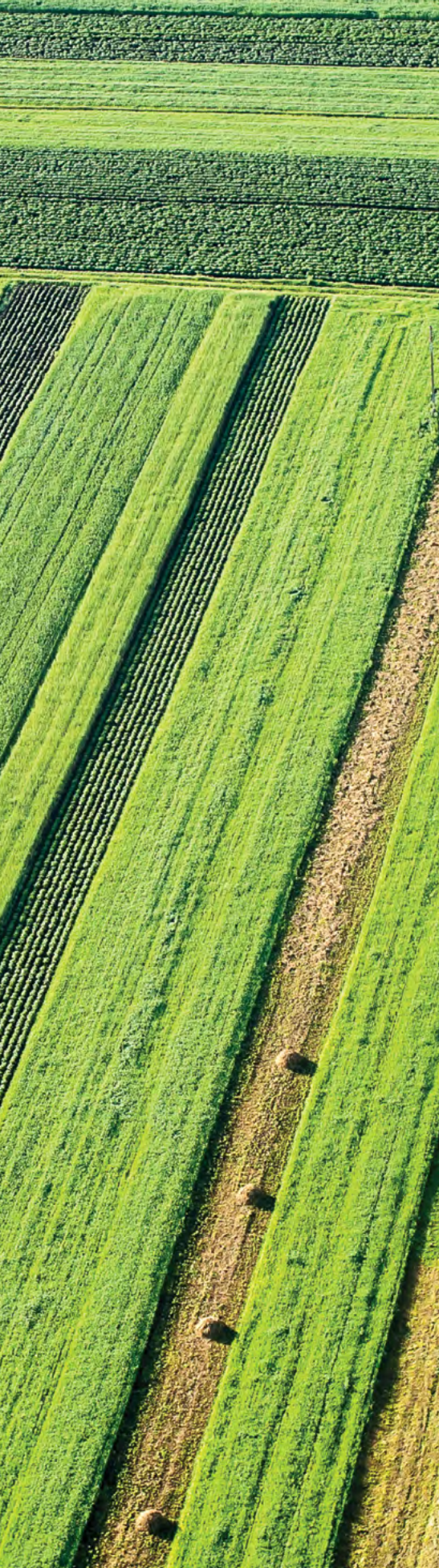


Figure 3. Average nitrogen concentrations in tile drainage water from June 15 to July 3 in Instinct NXTGEN and non-stabilized UAN treatments.



CONCLUSIONS

- Results of this study show that nitrogen stabilizers can reduce nitrogen loss through tile drainage, even in years with minimal rainfall when nitrogen loss is relatively low.
- Nitrapyrin generally has measurable activity in the soil for about six to eight weeks after application in warm soils conducive to crop growth (Trenkel, 2010).

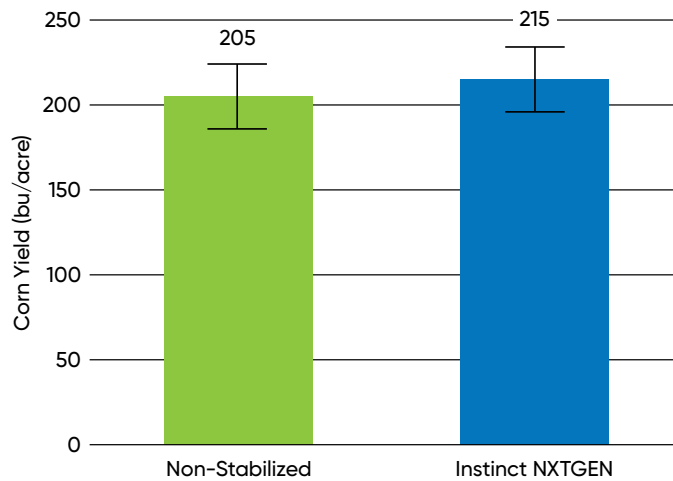


Figure 4. Average corn yield of Instinct NXTGEN and non-stabilized UAN treatments.

- Lack of rainfall kept nitrogen loss low for the first four weeks after application; the treatment differences observed during the June 15 – July 3 period would have been toward the end of the window of activity of the Instinct NXTGEN treatment in the soil.
- Corteva Agriscience field trials conducted over several years found that the use of nitrification inhibitors increased corn yield by an average of around 6 bu/acre.
- The highest value of nitrification inhibitors should be realized in scenarios with a high risk of nitrate losses from leaching or denitrification, including the following conditions (Ruark, 2012):
 - Tile-drained soils when leaching potential is high
 - Wet or poorly drained soils



Mary Gumz, Ph.D.,
Agronomy Innovation Leader

CORN ROOTWORM POPULATION MONITORING IN THE U.S. CORN BELT

KEY FINDINGS

- Corn rootworm (CRW) adult population levels and emergence associated with different CRW trait packages were measured at locations across the U.S. Corn Belt in 2024.
- Continuous corn fields (grain or silage) had heavier CRW pressure than rotated fields.
- There was a significant reduction in adult CRW beetles emerged in traps set over Vorceed® Enlist® products compared to traps set over Qrome® products

OBJECTIVES

- Monitor northern corn rootworm (NCRW) and western corn rootworm (WCRW) adult population levels across the Corn Belt.
- Assess CRW beetle emergence from hybrids with different CRW trait packages.

STUDY DESCRIPTION

Corn Rootworm Adult Population Levels

- Corn rootworm adult populations were quantified at 329 corn and soybean field locations in Iowa, Illinois, Wisconsin, Indiana, Kansas, Ohio, and New York in 2024.
- At each study location, six CRW sticky traps were placed along the length the field at the R2 corn growth stage (Figure 1). Traps were attached at ear height using a zip tie.
- In soybean fields, traps were placed on a stake at crop height when the surrounding corn fields were at R2.
- Each week, northern and western corn rootworms were counted and the average number of beetles per trap was recorded for each field. New traps were placed in the field for up to eight weeks.



Figure 1. Left: Arrangement of six sticky traps in a field. Right: A new Pherocon® AM/NB sticky trap was zip tied to plant at ear height each week of the study.

CRW Trait Effects on Adult Emergence

- Corn rootworm adult emergence was measured at 196 locations across northern Illinois and northern Iowa in 2024.
- At each plot location, emerging CRW beetles were counted in Vorceed® Enlist® corn products and Qrome® products using the emergence cage technique.
- Emergence cages are wood frames, approximately 24 x 48 x 6 inches. The top is covered in window screen and the bottom is open to the soil.
- In each plot, 4 to 6 corn plants were cut at ground level starting in late June. The emergence cage was placed over the stalks and a Trécé Pherocon No-Bait sticky trap was placed inside. CRW adults were counted, and traps were replaced once a week (Figure 2).

Figure 2. CRW emergence cage placed over cut corn plants. A new Pherocon® AM/NB sticky trap was placed in the trap each week of the study.



RESULTS

Corn Rootworm Adult Population Levels

- This study focused on the highest weekly count, i.e. the count from the week with the highest number of beetles trapped during the monitoring period, for each location. This is the number that is used to guide control practices for the following corn crop.
- Overall, more western than northern CRW were found in traps (Table 1).
- Highest average weekly counts for both species were found in Illinois and Wisconsin (Table 1). Pressure was highest for both species in northern Illinois and Wisconsin (Figures 3 and 4).
- The week with the highest weekly count was later in Wisconsin than other states and CRW beetles continued emerging later in Wisconsin as well (Table 1).
- CRW pressure was higher in corn fields than in soybean fields and was highest in corn fields that had corn as a previous crop (Tables 2 and 3).

- WCRW beetles were found in three soybean fields in Illinois, one in Indiana, and two in Ohio.
- WCRW was found in rotated corn fields in Illinois (10), Indiana (2), Ohio (2) and Wisconsin (6). NCRW beetles were found in rotated corn fields in Illinois (6), Ohio (1) and Wisconsin (5). Although further testing was not done, these observations could indicate the presence of variant western (soybean egg-laying) or variant northern (extended diapause) CRW (Table 4).

Table 1. Average highest weekly CRW beetle count and week of highest count (week of monitoring) by state.

State	Locations	Highest Weekly Count		Week of Highest Count	
		NCRW	WCRW	NCRW	WCRW
Illinois	33	3.3	18.0	2.1	2.4
Indiana	8	1.1	0.5	2.0	2.9
Kansas	1	0.0	2.0	1.0	1.0
New York	2	2.0	0.0	1.0	NA
Ohio	4	0.2	14.8	2.3	2.8
Wisconsin	282	2.2	18.3	2.4	3.7

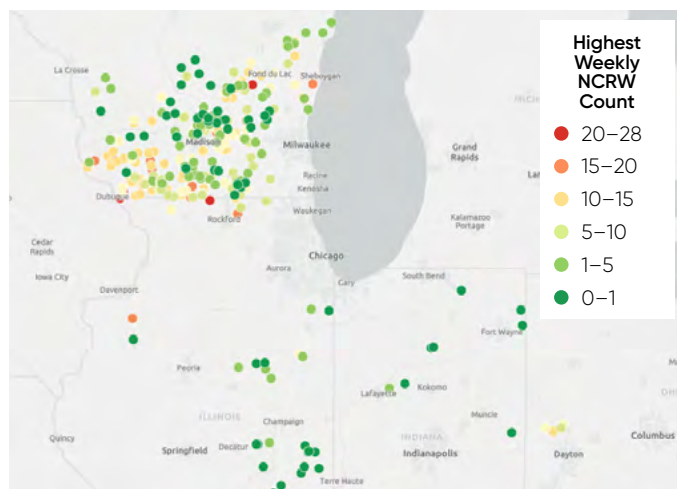


Figure 3. Highest weekly NCRW count by location.

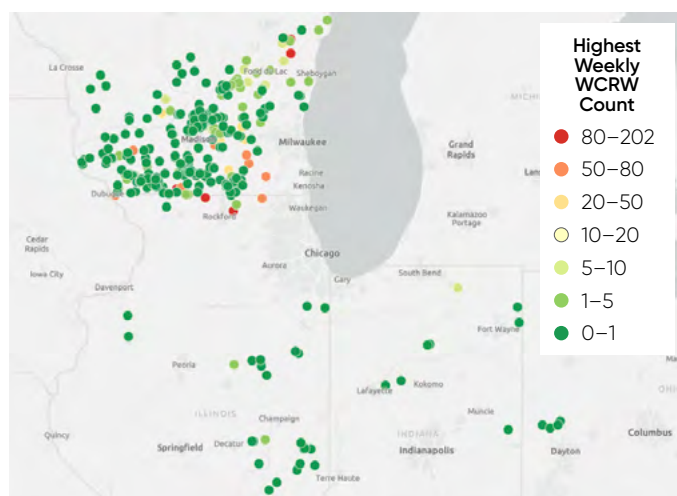


Figure 4. Highest weekly WCRW count by location.

Table 2. Average highest weekly CRW beetle count by crop.

2024 Crop	Average Highest Weekly NCRW Count	Average Highest Weekly WCRW Count
Corn	2.3	18.2
Soybean	0.1	2.8

Table 3. Average highest weekly CRW beetle count by previous crop.

Previous Crop	Average Highest Weekly NCRW Count	Average Highest Weekly WCRW Count
Alfalfa	0.0	0.0
Corn	1.3	18.9
Corn Silage	6.0	14.8
Soybeans	2.3	4.3
Wheat	2.0	3.0

Table 4. Number of rotated corn fields where CRW beetles were found by state.

State	Rotated Corn Fields with NCRW	Rotated Corn Fields with WCRW
Illinois	6	10
Indiana	0	2
Ohio	1	2
Wisconsin	5	6

CRW Trait Effects on Adult Emergence

- CRW beetle emergence levels were similar across northern Illinois and northern Iowa.
- In Illinois, only Western CRW were observed. Iowa locations observed both Western and Northern CRW adults.
- CRW beetle emergence peaked for most locations during Week 2. More locations had beetle emergence greater than zero that week and the maximum number of beetles emerged at any location spiked to 47 (Figure 5).
- By week 4, emergence numbers had dropped to week 1 levels.
- Vorceed® Enlist® and Qrome® products were compared to each other at 120 locations.
- There was a significant reduction in CRW beetles emerged in traps set over Vorceed Enlist products compared to traps set over Qrome products (Table 5).

Table 5. Weekly average CRW beetle emergence per cage by CRW trait.

CRW Protection	Sampling Week					
	1	2	3	4	5	6
Qrome®	0.8	2.8	3.2	1.4	0.9	1.3
Vorceed® Enlist®	0.1	0.5	0.6	0.4	0.3	0.6

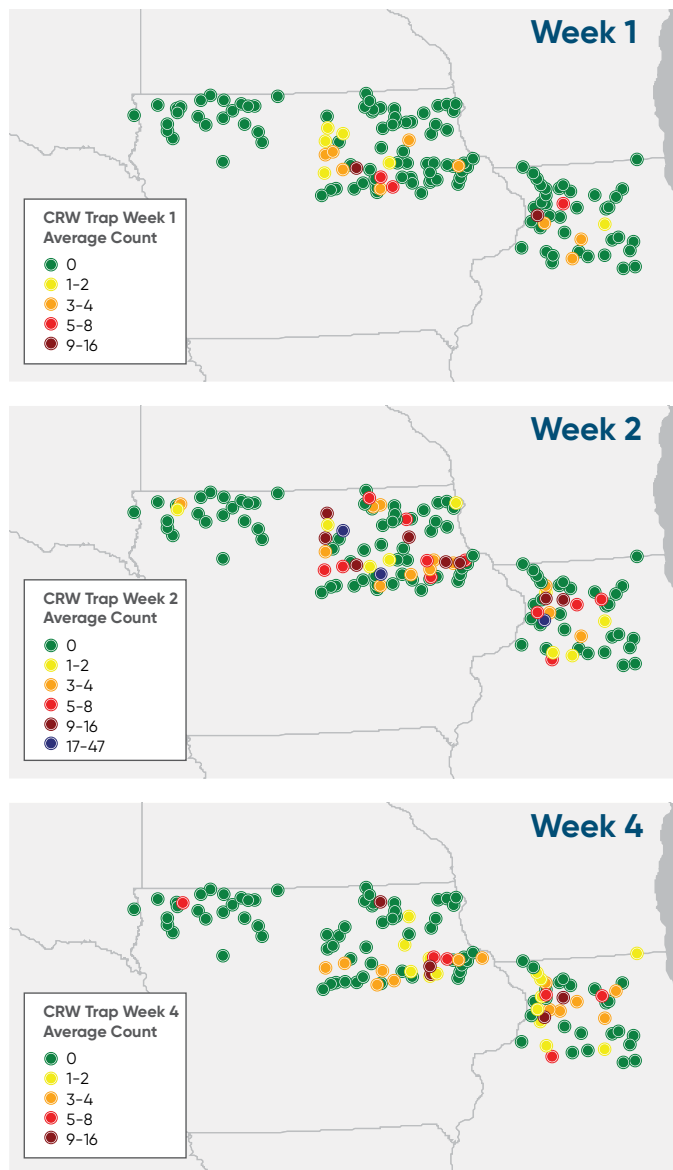


Figure 5. Weekly average beetle emergence by location for the first, second, and fourth weeks of the study.

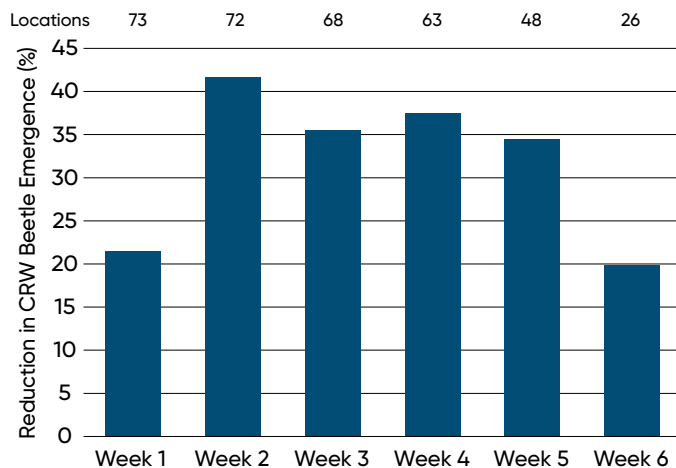


Figure 6. Percent reduction in CRW beetle emergence in Vorceed Enlist products compared to Grome products.

WHAT DOES THIS MEAN IN THE FIELD?

- Adult CRW populations emerging in your field could be reduced significantly by planting Vorceed Enlist products.
- Reduced emergence of CRW beetles make it less likely that you will need to spray insecticide to control adult populations.
- Vorceed Enlist technology combines the root feeding protection and yield of Qrome technology with reduced adult emergence.
- To best evaluate CRW presence in your field, place six CRW sticky traps at R2 across the length of your corn field. Attach the traps at ear height using a zip tie.
- Each week, count the number of beetles on the traps and replace with a new trap. Note: the number of CRW beetles on open sticky traps will be higher than those placed in emergence cages.
- Take the highest average trap count from the six weeks and use it to find a Best Management Practice, below, for your farm.

If traps average <21 beetles per week:

- **Low** rootworm populations are anticipated next year.
- Rotate acres to another crop.
- Plant a corn rootworm Bt corn product.
- Plant a non-Bt rootworm product with Lumisure® 1250 insecticide seed treatment OR a soil insecticide for larvae.

If traps average 21 – 50 beetles per week:

- **Moderate** rootworm populations are anticipated next year.
- Rotate acres to another crop.
- Plant a corn rootworm Bt corn product.
- Apply a soil insecticide at planting for larvae.

If traps average >50 beetles per week:

- **High** rootworm populations are anticipated next year.
- Rotate acres to another crop.
- Apply foliar insecticide in the current year to control beetles prior to egg laying and use a corn rootworm Bt corn product or soil-applied insecticide the following year.

Pioneer and university research suggests that continuous, uninterrupted use of the same corn rootworm Bt technology can lead to reduced product efficacy against these insects.

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

- **B**reaks the cycle
- **M**anages populations
- **P**rotects the Bt trait.

Please contact your Pioneer sales professional for more information.

CORN ROOTWORM

Hatch and Larval Stages

KEY POINTS

- Corn rootworm egg hatch in the U.S. Corn Belt typically begins sometime between mid-May and early June and continues for around a month.
- Newly hatched larvae are attracted by CO₂ released from corn roots and are capable of moving up to 1.5 feet (0.46 m) in the soil to reach roots to feed on.
- Feeding is most extensive in early through mid-July in most regions of the Corn Belt.
- Soil saturation following hatch can dramatically reduce larval survival, causing larvae to either drown or be unable to locate corn roots for feeding.

END OF OVERWINTERING

- Western corn rootworm (*Diabrotica virgifera virgifera*) and northern corn rootworm (*D. barberi*) complete one generation per year.
- Winter dormancy for eggs overwintering in the soil consists of two phases: obligate diapause and facultative quiescence (Krysan, 1978).
- Obligate diapause begins in the fall when embryonic development ceases in eggs that have been deposited in the soil. Embryos remain in this state until diapause ends.
- In the U.S. Corn Belt, the end of diapause often occurs sometime during the winter. At this point, dormancy enters the facultative quiescence phase, in which environmental conditions become the controlling factor.
- Embryonic development remains suspended until soil temperature increases above a threshold at which development can resume.
- In addition to the temperature threshold, eggs need to absorb water to complete development. If the surrounding soil is too dry, eggs will remain in a quiescent state until enough moisture is available to absorb for them to resume development.

CORN ROOTWORM HATCH

- The length of time between the end of facultative quiescence and egg hatch can vary based on soil temperature. In general, warmer and more consistent soil temperatures will enable faster embryonic development, with a constant temperature of 82°F (28°C) being ideal for development (Schaafsma et al., 1991).
- Numerous factors such as soil texture, tillage, and residue cover can influence the soil microenvironment and affect the timing of egg hatch.



Figure 1. Corn rootworm larva at the base of a corn plant near the brace roots. Corn rootworm larvae have a brown head and a brown plate at their posterior end.

- Rootworm egg hatch in the U.S. Corn Belt typically begins sometime between mid-May and early June and continues for around a month. Peak egg hatch may vary as much as 10-14 days from year to year based on differences in soil heat unit accumulation.

LARVAL STAGES

- Newly hatched larvae are less than 1/8 inch (3 mm) in length and nearly colorless. Larvae have three pairs of legs behind their head capsule.
- All species of corn rootworm go through three instars during their larval stage. An instar is the period of growth between two molts. Molting is when a larva sheds its skin to allow it to grow larger.
- Third instars are approximately 5/8 inch (16 mm) long and creamy white with a brown head and a brown plate on top of the last abdominal segment (Figure 1).
- At a constant temperature of 70°F (21°C), western corn rootworm first, second, and third instars complete development in 6, 5, and 12 days, respectively.
- Northern corn rootworm development is somewhat longer, with first, second, and third instars completing development in 7, 7, and 19 days.
- Newly hatched larvae are attracted by CO₂ released from corn roots and are capable of moving up to 1.5 feet (0.46 m) in the soil to reach roots to feed on.



Figure 2. Corn rootworm larva on a corn plant with a root system that has been badly damaged by corn rootworm feeding.

- Their ability to move through the soil can be limited by soil conditions. Corn rootworm larvae are small and soft-bodied, so they rely on pore spaces in the soil profile for movement. If pore space is restricted, such as in soil that has been compacted by wheel traffic, or highly saturated, larval movement will be reduced.
- Larvae initially feed on root hairs and smaller portions of roots. As larvae develop, they feed externally and internally on larger roots. Larger larvae tend to move toward the center of the corn root mass, feeding heavily on newer root tissue, including brace roots.
- Feeding is most extensive in early through mid-July in most regions of the Corn Belt.
- After a larva has completed the three instars, it will form a small chamber in the soil in which it will pupate. This is a dormant stage during which no feeding takes place (Figure 3).
- The pupa stage lasts around 10 to 12 days as the larva transforms into an adult.



Figure 3. The corn rootworm larva makes an oval chamber in the soil, then it transforms into a pupa before later emerging as an adult.

FACTORS INFLUENCING LARVAL MORTALITY

Proximity to Food

- Newly hatched larvae have very limited mobility in the soil, so the ability to quickly find a proximal food source is essential to their survival. Larvae typically move through about 6 inches (15 cm) of soil to reach corn roots but can move up to 18 inches (46 cm) when necessary.
- If a newly hatched larva does not locate a suitable host within 24 hours, it is much less likely to survive (Branson 1989).
- As larvae grow, they redistribute, moving to younger root nodes that emerge from the stalk. Larvae may also redistribute to other plants when high larval density creates intense competition for food (Hibbard et al., 2004).

Soil Conditions

- Soil conditions can affect the ability of corn rootworm larvae to reach corn roots to feed. Since larvae rely on soil pore space for travel, soils with high bulk density can restrict movement.
- Muck soils generally have lower incidence of rootworm larval feeding damage.
- Dry, sandy soils can cause scratching and abrasion to larvae as they search for food causing them to lose moisture and die.
- Silty or loam soils provide the best environment for larvae to move in search of food and generally have a higher survival rate.

Soil Saturation

- Soil saturation and flooding following corn rootworm hatch can dramatically reduce larval survival, causing larvae to either drown or be unable to locate corn roots for feeding (Riedell and Sutter, 1995).
- It is not unusual for portions of a field that are saturated early in the season to have the least amount of root lodging later in the season when rootworm pressure is high.
- Survival rate is reduced when water is warmer. Larvae that have established feeding on corn root tissue are better able to survive short durations of saturation.
- A wet spell during the spring can be helpful in lowering corn rootworm pressure. However, eggs that have not yet hatched are not greatly affected by soil saturation and hatch can extend for over a month, so the effect of soil saturation on the rootworm population will depend on its timing relative to peak rootworm hatch.
- Soil saturation that persists over a long enough duration to kill off a large proportion of the corn rootworm population may also be detrimental to early corn growth.

FIELD PERFORMANCE OF VORCEED® ENLIST® CORN ROOTWORM TRAITS

2020-2023



Jim Bing, Ph.D.,
Program Leader – Insect Control Traits

Tim Nowatzki, Ph.D.,
Sr. Research Scientist

Tim Mabry, M.S.,
Field Scientist

Jeff Klever,
Research Investigator

Mark Jeschke, Ph.D.,
Agronomy Manager

KEY FINDINGS

- The corn rootworm traits in Qrome® corn and Vorceed® Enlist® corn both provided effective control of corn rootworm larval feeding.
- The Vorceed Enlist traits had significantly lower corn rootworm feeding damage compared to the Qrome traits.
- Both corn rootworm trait products provided a significant improvement in yield compared to the negative control under corn rootworm pressure.

A NEW CORN ROOTWORM MANAGEMENT TOOL

- Western and northern corn rootworms have a history of adapting to and overcoming control practices, which has increased the complexity and difficulty of successfully managing these pests.
- Field-evolved resistance in western corn rootworm has now been documented for all four Bt traits for corn rootworm protection currently on the market.
- Ribonucleic acid interference (RNAi) technology has been commercialized to provide an additional unique mode of action for protection against corn rootworm and is available in Corteva Agriscience seed brands in Vorceed® Enlist® corn.

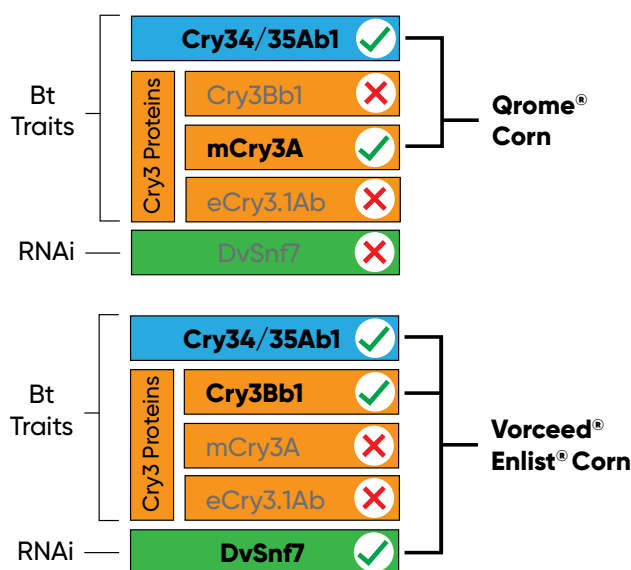


Figure 1. Corn rootworm protection modes of action in Qrome corn (dual-mode Bt) and Vorceed Enlist corn (Dual-mode Bt + RNAi).

STUDY DESCRIPTION

- Field experiments were conducted in 2020, 2021, 2022, and 2023 to evaluate efficacy of the corn rootworm traits in Qrome corn and Vorceed Enlist corn for reducing root feeding and protecting corn yield.
- The field experiments were conducted at locations with a history of continuous corn production or locations where a trap crop was used to boost corn rootworm pressure.
- A total of four different hybrid families were used across the research locations, representing 108 and 113 CRM groups.
- Three different combinations of corn rootworm traits and insecticide seed treatments were compared in the study (Table 1). The experiments used the major components of Qrome corn and Vorceed Enlist corn without the integrated refuge component.

Table 1. Corn rootworm treatments compared in 2020, 2021, 2022, and 2023 field experiments.

Treatment Description	CRW Traits	Insecticide Seed Treatment Rate (clothianidin)
Unprotected Check	none	250 IST
CRW Traits in Qrome + 1250 rate IST	Cry34/35Ab1 mCry3A	1250 IST
CRW Traits in Vorceed Enlist	Cry34/35Ab1 Cry3Bb1 DvSnf7	250 IST

RESULTS

- A total of 33 research locations over the four years of the study experienced moderate to high levels of corn rootworm feeding pressure.
- Both corn rootworm protection treatments were effective at reducing corn rootworm feeding relative to the unprotected check as measured by corn rootworm node injury score (CRWNIS) (Figure 2).
- Corn with the Vorceed Enlist corn rootworm traits (dual-mode *Bt* + RNAi) had significantly lower CRWNIS than the Qrome corn rootworm traits (dual-mode *Bt*) + 1250 IST.
- Both corn rootworm protection treatments had an average estimated CRWNIS score less than 0.50.

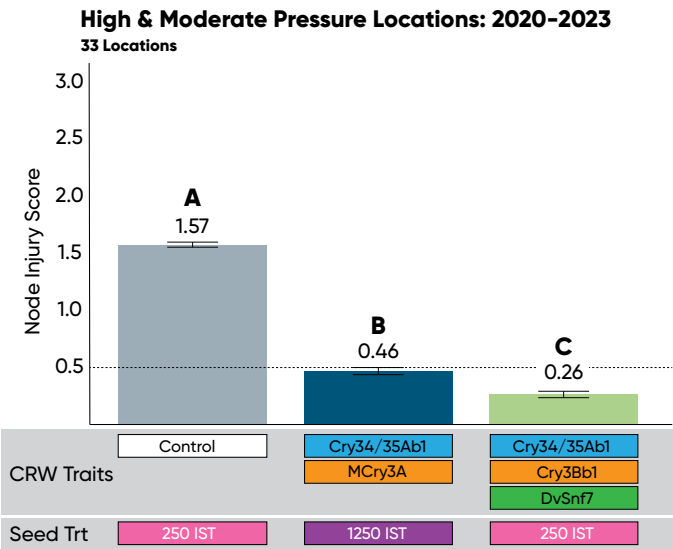


Figure 2. Corn rootworm node injury scores across 33 moderate and high-pressure locations. Bars with the same letter are not significantly different at $\alpha = 0.05$.

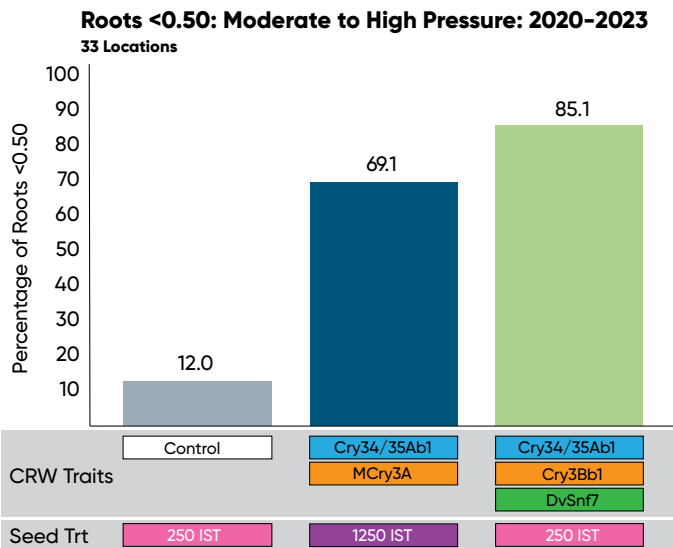


Figure 3. Percentage of sampled corn roots with CRWNIS of less than 0.50 across 33 moderate to high pressure locations.

- For corn with the Vorceed® Enlist® corn rootworm traits, 85% of sampled roots had a CRWNIS of less than 0.50, compared to 69% of roots for corn with Qrome® corn rootworm traits + 1250 IST and 12% for the unprotected check (Figure 3).
- Both corn rootworm protection treatments provided significant improvement to yield compared to the unprotected check under moderate to high corn rootworm pressure (Figure 5).
- Corn with the Vorceed Enlist corn rootworm traits had significantly higher yield than corn with the Qrome corn rootworm traits + 1250 IST (Figure 5).



Figure 4. The corn rootworm node injury score (CRWNIS) rating system ranges from 0 to 3 based on the number of roots pruned by corn rootworm feeding to within 1.5 inches of the crown. A maximum score of 3.0 corresponds to 3 full nodes of roots pruned.

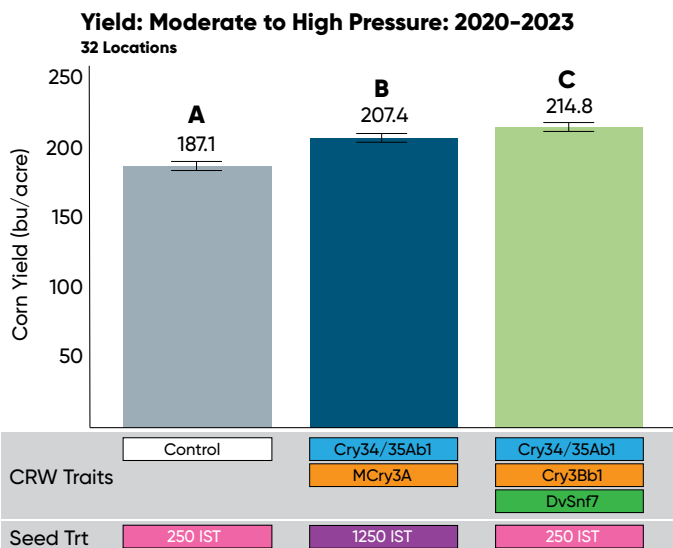


Figure 5. Corn yield across 32 moderate and high-pressure locations. Bars with the same letter are not significantly different at $\alpha = 0.05$.

REDUCED CORN ROOTWORM ADULT EMERGENCE WITH RNAi

2022-2023



Jim Bing, Ph.D.,
Program Leader - Insect Control Traits

Tim Nowatzki, Ph.D.,
Sr. Research Scientist

Tim Mabry, M.S.,
Field Scientist

Jeff Klever,
Research Investigator

Mark Jeschke, Ph.D.,
Agronomy Manager

KEY FINDINGS:

- Trials were conducted in fields with high corn rootworm pressure to evaluate the impact of corn rootworm traits on emergence of rootworm adults from the soil.
- The corn rootworm traits in Qrome® corn and Vorceed® Enlist® corn reduced emergence of western corn rootworm beetles by 65% and 90%, respectively.
- The addition of RNAi technology in the Vorceed Enlist trait package provided a significant advantage in managing adult emergence.

A NEW CORN ROOTWORM MANAGEMENT TOOL

- Ribonucleic acid interference (RNAi) technology has been commercialized to provide an additional unique mode of action for protection against corn rootworm and is available in Corteva Agriscience seed brands in Vorceed® Enlist® corn.

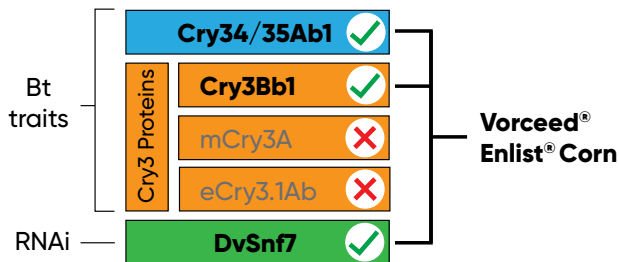


Figure 1. Vorceed Enlist corn contains three modes of action for protection against corn rootworm.

STUDY DESCRIPTION

- Field experiments were conducted in 2022 and 2023 to evaluate efficacy of the corn rootworm traits in Qrome corn and Vorceed Enlist corn for reducing adult emergence.
- Experiments were conducted at 12 locations with natural infestations of western and northern corn rootworm.
- Study locations were specifically targeted to fields with a history of high corn rootworm pressure that were located in regions with previously reported performance issues with Bt rootworm traits.
- Adult emergence was quantified using single-plant emergence cages (Figure 2).

Table 1. Corn rootworm treatments compared in 2022 and 2023 adult emergence experiments.

Treatment Description	CRW Traits	Insecticide Seed Treatment Rate (clothianidin)
Unprotected Check	none	250 IST
CRW Traits in Qrome + 1250 rate IST	Cry34/35Ab1 MCry3A	1250 IST
CRW Traits in Vorceed Enlist	Cry34/35Ab1 Cry3Bb1 DvSnf7	250 IST



Figure 2. Emergence cage used to capture corn rootworm adults emerging from the soil.

RESULTS

- Corn rootworm pressure was moderate to high at the study locations in 2022 and 2023 – the average node injury score in the unprotected checks was 1.40 on a 0–3 scale (Figure 3).
- The corn rootworm traits in Vorceed Enlist corn and Qrome corn + 1250 rate IST both provided effective protection of corn roots against corn rootworm damage.
- The corn rootworm traits in Vorceed Enlist corn and Qrome corn + 1250 rate IST both significantly reduced emergence of western corn rootworm compared to the unprotected check (Figure 3).

Western Corn Rootworm Adult Emergence: 2022-2023 12 Locations

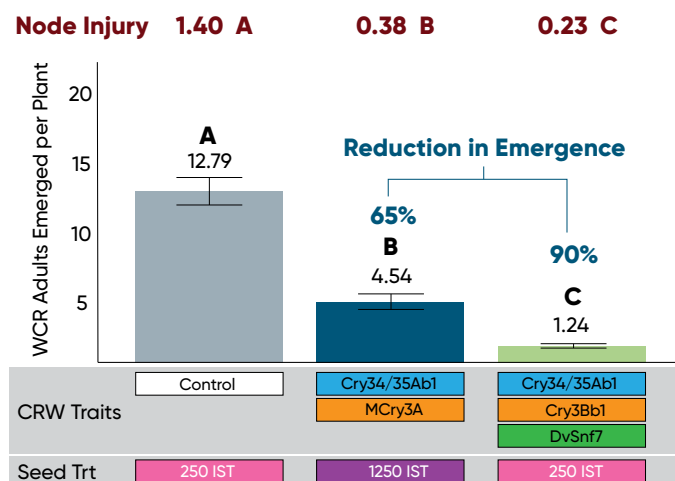


Figure 3. Western corn rootworm adult emergence (beetles/plant). Bars and values with the same letter are not significantly different at $\alpha = 0.05$.

- The addition of RNAi technology in the Vorceed® Enlist® trait package provided a significant advantage in controlling adult emergence.
- The corn rootworm traits in Qrome® corn + 1250 rate IST reduced adult emergence by 65%, which is lower than would generally be expected over a larger range of environments and is reflective of the high rootworm pressure conditions that were specifically targeted for this study.
- Results of this study demonstrate the additional value provided by the RNAi technology in the Vorceed Enlist trait package for reducing adult emergence under high corn rootworm pressure conditions.

MANAGEMENT CONSIDERATIONS

- Corn rootworm challenges are localized and need to be managed on a field-by-field basis with a proactive, multi-year approach that employs multiple tactics to maintain low corn rootworm populations in the field.

- Historically, the use of crop rotation and insecticidal sprays targeting corn rootworm adult beetles have been the primary tactics growers could use to lower corn rootworm populations in fields.
- The RNAi technology in the Vorceed Enlist trait package provides another tool for managing the density of corn rootworm populations in fields in addition to protecting roots.
- Use of Vorceed Enlist Corn along with in-season beetle scouting should allow for the effective use of pyramided Bt rootworm products (without the RNAi trait) or non-rootworm corn treated with soil insecticide as options in the field in the subsequent season, extending the life of the RNAi technology.

CORN ROOTWORM BEST MANAGEMENT PRACTICES

1. Plant the Required Refuge

2. Rotate Crops

- Rotate at least every 3rd year in the following scenarios:
 - In long-term continuous corn system
 - CRW populations are high
 - Experiencing problems with CRW trait performance
- In areas where rotational-resistant CRW variants exist, CRW management options may be needed the following year.

3. Rotate Traits

- Use Bt hybrids with multiple modes of action for CRW control whenever possible.
- Use a non-Bt-traited hybrid with insecticide.

Manage CRW With Insecticides

- Adult CRW management considerations:
 - Scout fields for CRW adults during silking stage, as CRW adults feed on corn silks and may reduce yield.
 - Foliar sprays may be an option if CRW beetle populations reach an economic threshold for damage.
 - Follow university extension or local crop consultant recommendations for products, rates, and proper timing of adult spray applications for reducing CRW beetle populations.
- Larval CRW management considerations:
 - Soil-applied insecticides are not recommended for control of CRW in Bt-traited corn hybrids except under limited circumstances.
 - Consult with extension, crop consultants or other local experts for recommendations when considering a combination of CRW traits and soil-applied insecticides.
 - Soil-applied insecticides should not be necessary for CRW control with pyramided CRW-traited Bt corn hybrids.

CORN LEAFHOPPER

KEY POINTS

- The corn leafhopper (*Dalbulus maidis*) is one of the most important pests of corn in Latin America and the Caribbean.
- Corn leafhoppers are a vector for *Spiroplasma kunkelii*, a bacterial pathogen commonly referred to as corn stunt spiroplasma (CSS), which is the primary causal organism for corn stunt disease.
- Corn leafhoppers need warm temperatures and a living host for survival and reproduction, which keeps their range in the U.S. largely confined to the southernmost corn production areas.



Figure 1. *D. maidis* adults. Photos courtesy of and used with permission of Ashleigh M. Faris, Ph.D., Oklahoma State University.

DISTRIBUTION AND PEST STATUS

- The corn leafhopper (*Dalbulus maidis*) is one of the most important pests of corn in Latin America and the Caribbean, primarily because of its ability to transmit pathogens associated with corn stunt disease complex.
- *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.
- As cultivation of corn spread throughout the tropical and subtropical regions of the Americas, corn leafhopper likely spread along with it, making it one of the earliest insect pests of corn production.
- The current range of the corn leafhopper in the Americas extends from the Southern U.S. to temperate parts of Argentina.

LIFE CYCLE

- *D. maidis* begins as an egg and then undergoes five nymphal instars before reaching adulthood.
- 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 final 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 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.

IDENTIFICATION

- The adult corn leafhopper is light tan and about 1/8 of an inch long.
- Its most distinguishing feature is two dark spots located between the eyes (Figure 1).
- The nymphs have no wings and are green to tan in color.
- Both adults and nymphs feed inside the whorl, particularly in young corn. Later, as the plants grow, they move out onto the underside of the leaves.

INJURY AND CROP IMPACT

- Corn leafhopper can damage corn in two ways – through feeding on the plant and by transmitting plant pathogens.
- Leafhoppers are piercing-sucking insects that feed on plant sap.
- Feeding by large populations of leafhoppers can cause leaf tissue to dry out and eventually die.
- Honeydew excreted by both the adults and nymphs as they feed can lead to sooty mold growth, which can reduce the photosynthetic capacity of the plant.
- 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.
- Corn leafhoppers are a vector for *Spiroplasma kunkelii*, a bacterial pathogen commonly referred to as corn stunt spiroplasma (CSS), which is the primary causal organism for corn stunt disease.
- *S. kunkelii* is transmitted by corn leafhoppers, 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.

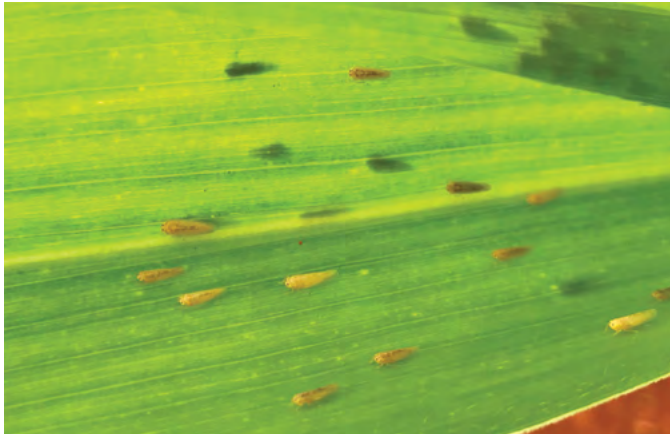


Figure 2. Adult corn leafhoppers (*D. maidis*) on a corn leaf.

HOST SPECIES

- *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*.
- 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.
- Outbreaks of corn stunt in the U.S. are likely driven by leafhopper populations moving up from Mexico, where corn is under continuous cultivation.

ECOLOGY

- Leafhopper populations can move with prevailing winds, sometimes over long distances.
- 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.
- 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 life cycle.
- 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.
- The number of corn leafhopper generations per year can vary greatly based on environmental conditions and host availability.
- 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.



Figure 3. A single adult corn leafhopper on a corn leaf.

MANAGEMENT

- Management of corn leafhoppers is primarily focused on preventing the spread of the corn stunt disease pathogens that they carry.
- In the U.S., outbreaks of corn stunt disease have been sporadic, so field experience with managing corn leafhoppers thus far is largely from South America.
- A critical 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.
- 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 3 to 6 times per crop for control of corn leafhoppers.
- Corn hybrids can differ in their resistance to corn leafhopper feeding, and resistant hybrids have been an important tool for management of corn stunt disease in South America.
- Given the infrequency of corn stunt outbreaks in the U.S., leafhopper resistance ratings have not been developed for U.S. corn hybrids.
- Corn leafhoppers need warm temperatures and a living host for survival and reproduction, which keeps their range in the U.S. largely confined to the southernmost corn production areas.

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Mark Jeschke, Ph.D.
Agronomy Manager

CORN STUNT DISEASE IN THE U.S.

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.

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 in the U.S. though – in Florida in 1979–1980, in California in 2001, and in Texas and Oklahoma in 2024 – and there is some concern that outbreaks could become more frequent.

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.

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).

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



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



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.

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 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).



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 LIFE CYCLE

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 three 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.

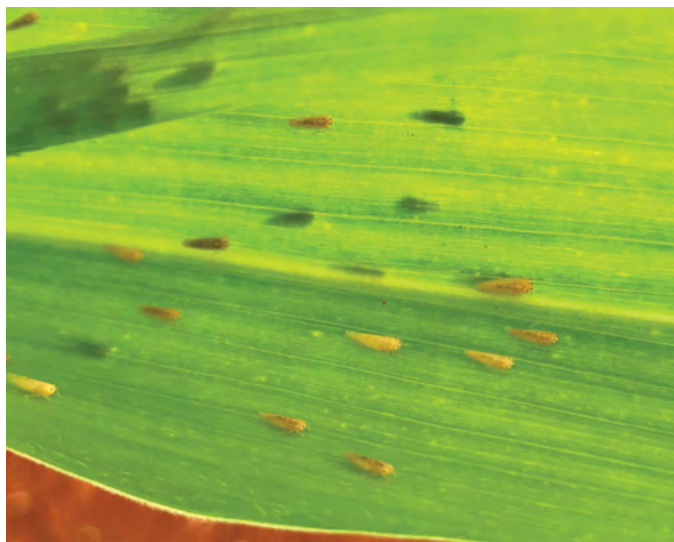


Figure 7. Adult corn leafhoppers (*D. maidis*) on a corn leaf.

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. Leafhopper 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.

Life Cycle

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.



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

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 life cycle. 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 3 to 6 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 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 disease has been observed sporadically in the U.S. and could become a more frequent occurrence in southern corn production areas. Rising temperatures increase the risk of corn leafhopper populations moving north from Mexico and creating more corn stunt outbreaks in the Southern U.S.

Corn stunt disease is unlikely to pose a 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.

BACTERIAL LATE-SEASON DECLINE DISEASE OF CORN

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

KEY POINTS

- Bacterial late-season decline is a newly identified bacterial disease of corn first documented near Bushland, Texas, in 2021 by Texas A&M scientists.
- Late-season decline has shown the potential to significantly reduce corn yield.
- Late-season decline is favored by high temperatures and moisture, as is generally the case for bacterial diseases.
- Partial gene sequence analysis of the bacterium found it to be very closely related to *Pantoea ananatis*, a known pathogen of several plant species.
- *P. ananatis* does not always function as a pathogen. It has been found in a diverse range of environments functioning as a saprophyte.
- At this point, it is unclear whether the late season decline pathogen is a strain of *P. ananatis* or a newly discovered species within the genus *Pantoea*.

INTRODUCTION

Bacterial late-season decline is a newly identified bacterial disease of corn first documented by scientists at the Texas A&M AgriLife Experiment Station at Bushland, Texas, in 2021. Researchers observed the sudden appearance of drought stress-like symptoms on previously healthy corn. Testing of symptomatic plants found that the presence of a bacterial pathogen was consistently associated with symptomatic tissues.



Figure 1. Foliar symptoms of late-season decline in a Texas corn field, 2024.

Partial gene sequence analysis of the bacterium found it to be very closely related to *Pantoea ananatis*, a known pathogen of several plant species – including corn – and close relative of *P. stewartii*, the causal pathogen of Stewart's wilt. Subsequent research confirmed the bacterium recovered from symptomatic plants in the field to be the causal pathogen of the disease. However, observed symptoms were distinct from those previously reported for either *P. ananatis* or *P. stewartii* in corn (Obasa et al., 2023), which is why it has been designated a new disease.

Late-season decline has shown the potential to significantly reduce corn yield, with up to 90% loss reported in the worst cases. It also appears to be spreading. Foliar symptoms similar to those observed at Bushland were observed in a field in Potter County in 2021. In 2022, the disease was found in all 22 counties of the Texas Panhandle (Obasa, 2024).

SYMPTOMS

Early-season symptoms during vegetative growth stages tend to be localized to the leaves. Leaves of infected plants have light green, elongated, slightly translucent, non-chlorotic streaks with non-wavy margins (in contrast to Stewart's wilt, which produces lesions with wavy margins). Foliar symptoms at this stage can vary and may be overlooked or misdiagnosed. Vegetative stage infections can also cause stunting of the plant and delayed tasseling (Obasa, 2024).

As plants reach reproductive growth stages, symptoms can become much more severe. Lesions on the leaves can coalesce as they become larger and eventually turn necrotic, resulting in leaf blight symptoms that can resemble severe drought stress (Figures 1 and 2). Other symptoms during reproductive growth include senescence of the tassel, as well

as small ears with few or no kernels on them. Stalk rot has also been associated with late-season decline in some cases (Obasa, 2024), which can lead to a higher incidence of stalk lodging.

WHAT IS KNOWN ABOUT THE PATHOGEN

The exact identity of the bacterial pathogen that causes late-season decline has not yet been determined. Partial gene sequence analysis of the bacterium found it to be very closely related, but phylogenetically distinct from *P. ananatis* (Obasa et al., 2023). At this point, it is unclear whether the pathogen is a strain of *P. ananatis* or a newly discovered species within the genus *Pantoea*. The Corteva Agriscience Diagnostic Lab does not currently have molecular tools to distinguish the late-season decline pathogen from *P. ananatis*, assuming that a such a distinction exists.



Figure 2. Leaf blight symptoms of late-season decline in a Texas corn field, 2024.

WHAT IS KNOWN ABOUT *P. ANANATIS*

Pantoea ananatis is a very unusual plant pathogen because it can occupy a wide range of ecological niches other than plants and does not always function as a pathogen. In some cases, it can even be beneficial to plants by promoting plant growth or protecting the plant from disease by fending off other pathogenic bacteria and fungi. *P. ananatis* is considered an emerging plant pathogen because of its increased incidence of plant disease, host species, and geographical range over the past few decades (Coutinho and Venter, 2009).

P. ananatis is a ubiquitous bacterium, found in nearly every environment on Earth. It is a common epiphyte of plants, living on the external surface of plant tissues without causing any detrimental effects to the plant. In several cases, *P. ananatis* has been shown to have antibacterial and antifungal properties, protecting host plants against disease caused by other pathogens.

P. ananatis can also be an endophyte, living inside plants, where it can be beneficial, neutral, or a latent pathogen, depending on the scenario. In pepper plants, it has been

shown to have plant growth promoting properties and induce systemic resistance to bacterial spot disease caused by *Xanthomonas axonopodis*. In rice, it can function as an endophyte, but it can also be a pathogen, causing palea browning and stalk rot.

P. ananatis has been found in a diverse range of environments functioning as a saprophyte, living off dead or decaying organic matter. Its habitats include rivers, soil, plant rhizospheres, and in the guts of several species of insect.

The first documented case plant disease caused by *P. ananatis* was fruitlet rot in pineapple in the Philippines in 1928 (Serrano, 1928). Since this initial discovery, it has been documented as a pathogen in several other plant species as well, and can cause a wide diversity of disease symptoms. In corn, *P. ananatis* has been previously reported to cause necrotic or white leaf spots or streaks (Krawczyk et al., 2021) and stalk rot (Goszczyńska et al., 2007). Leaf blight of corn caused by *P. ananatis* has been documented in South Africa, Brazil, Mexico, and Poland (Krawczyk et al., 2021).

P. ananatis is known to be transmitted by insects. It has been found in the gut microbiome of several insect species. Field research conducted in Poland found that western corn rootworm (*Diabrotica virgifera virgifera*) can be a vector of *P. ananatis* in corn (Krawczyk et al., 2021). In onions, it can be transmitted by tobacco thrips (*Frankliniella fusca*) (Gitaitis et al., 2003).

LATE-SEASON DECLINE KNOWN AND UNKNOWN

Much remains unknown about late-season decline, including sources of inoculum, mechanisms of transmission, and epidemiology of the pathogen. The bacterium that causes late-season decline appears to be an opportunistic pathogen. In samples analyzed by the Corteva Agriscience Diagnostic Lab, *P. ananatis* has been detected in diseased plants as well as healthy plants exhibiting no symptoms of bacterial disease. Opportunistic infections are infections caused by bacteria, fungi, viruses, or commensal organisms that normally live in or on a host organism without causing disease but become pathogenic when the organism's defense system is impaired. What triggers the bacterium to become pathogenic in corn is unknown.

LATE-SEASON DECLINE OVERVIEW

- **What is late-season decline?** A new bacterial disease of corn discovered in the Texas panhandle in 2021.
- **What does it look like?** Elongated non-wavy leaf streaks that coalesce into leaf blight, beginning at the leaf tips and progressing back to the base. Stalk rot has also been observed in some cases.
- **What is the impact on yield?** Highly variable, but it can be severe – over 90% yield loss in the worst cases.
- **What causes it?** A bacterium that is either a new strain of *Pantoea ananatis*, or newly identified species closely related to it. Work on this question is ongoing.
- **How does it spread?** Unknown. *P. ananatis* is insect-vectored in some cases, as is *P. stewartii* (Stewart's wilt), but it is not yet known if that is happening in this case.
- **What conditions favor disease?** High temperature and moisture. Instances thus far have been in irrigated fields.
- **What can be done about it?** Resistant corn hybrids are the main tool for managing bacterial diseases, but rating, for genetic resistance have not been developed yet.



Figure 3. Leaf blight symptoms of late-season decline in a Texas corn field and an ear from a symptomatic plant.

CROP IMPACT

Observations and yield data from late-season decline cases thus far indicate that the yield impact of the disease can vary widely depending on multiple factors (Obasa, 2024). Timing of infection and overall plant health can influence disease impact on yield. Generally, the earlier infection occurs, the greater the likely impact on the plant. The presence of other stressors may also increase the susceptibility of plants to infection. Environmental conditions appear to play a significant role in determining impact on the crop. Late-season decline is favored by high temperatures and moisture, as is generally the case for bacterial diseases. Overhead irrigation can create a favorable microclimate for the proliferation of bacterial disease. Fields under irrigation with a dense canopy, where moisture can persist on the plants for extended periods of time, are at higher risk. Initial field observations also suggest that corn hybrids can differ in their susceptibility to late-season decline.



Figure 4. Leaf blight symptoms of late-season decline can resemble those of Stewart's wilt (left) and sunscald (right).

POSSIBLE MANAGEMENT TACTICS

Resistant corn hybrids are the main tool for managing bacterial diseases. Ratings for genetic resistance to late-season decline have not been developed yet; however, continued occurrences of this disease should provide the opportunity to collect hybrid performance data under natural disease pressure. Management of irrigation timing and frequency may also be a useful tactic to mitigate the spread of late-season decline by reducing the duration of wetness in the canopy. Foliar fungicides are not effective since this is not a fungal pathogen.



Mark Jeschke, Ph.D.,
Agronomy Manager

SOUTHERN RUST OF CORN

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.

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 to 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.

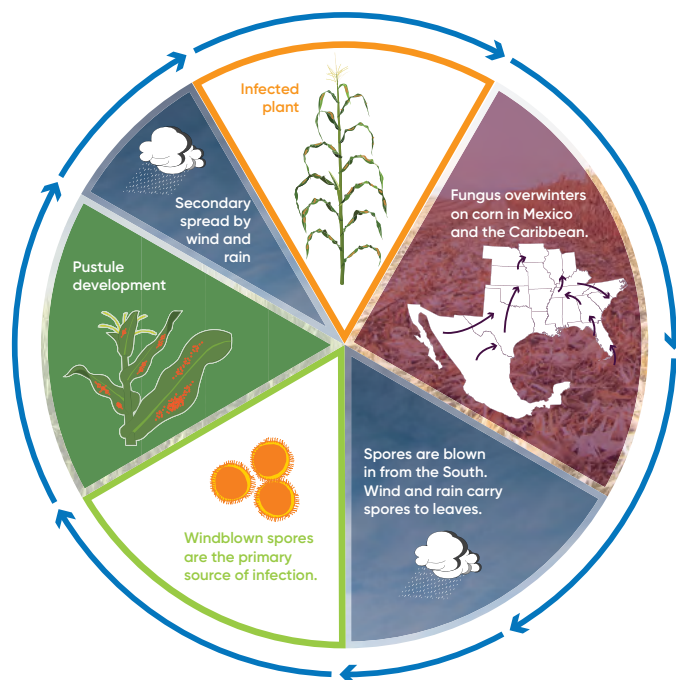


Figure 1. Life cycle of southern rust.

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.

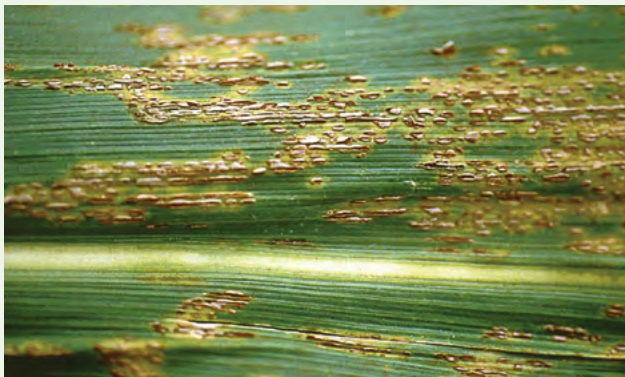
Southern Rust

- 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).



DISTRIBUTION

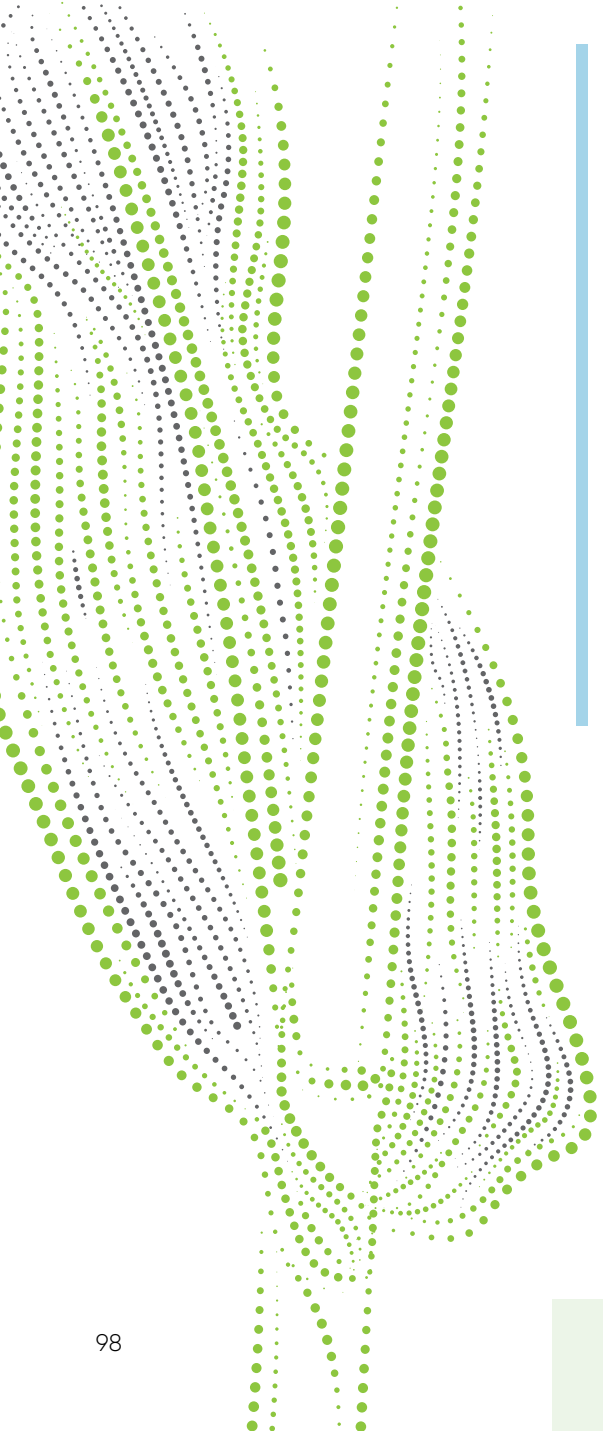
- In recent growing seasons, southern rust has occurred further north in the Midwestern U.S. earlier in the season than has been historically typical for this disease.
- Southern rust is now routinely observed in Indiana, Illinois, Iowa, Nebraska, and Kansas and has been detected as far north as South 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 2. 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 3. Later in the season, *P. polysora* forms darker pustules called telia that contain teliospores.



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Mark Jeschke, Ph.D.,
Agronomy Manager

TAR SPOT OF CORN IN THE U.S. AND CANADA

KEY POINTS

- Tar spot (*Phyllachora maydis*) is a relatively new disease of corn in the U.S., first appearing in Illinois and Indiana in 2015 and subsequently spreading to neighboring states.
- In 2018, tar spot established itself as an economic concern for corn production in the Midwest, with severe outbreaks affecting corn yield reported in several states.
- Tar spot gets its name from the fungal fruiting bodies it produces on corn leaves that look like spots of tar, developing black oval or circular lesions on the corn leaf.
- Tar spot is favored by cool temperatures (60–70°F, 16–20°C), high relative humidity (>75%), frequent cloudy days, and 7+ hours of dew at night.
- Tar spot can rapidly spread through the corn canopy under favorable conditions, causing premature leaf senescence.
- Commercial corn hybrids vary widely in their susceptibility to tar spot. Hybrid selection should be a primary consideration in managing for tar spot.
- Fungicide treatments have proven effective in reducing tar spot symptoms; however, application timing can be critical for achieving adequate control and two applications may be needed in some cases.

TAR SPOT: AN EMERGING DISEASE OF CORN

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

TAR SPOT ORIGINS

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

Historically, *P. maydis* was not typically associated with yield loss unless a second pathogen, *Monographella maydis*, was also present, the combination of which is referred to as tar spot complex. In Mexico, the complex of *P. maydis* and *M. maydis* has been associated with yield losses of up to 30% (Hock et al., 1995). In some cases, a third pathogen, *Coniothyrium phyllachorae*, has been associated with the complex. Only *P. maydis* is known to be present in the United States but it has proven capable of causing significant yield losses, even without the presence of an additional pathogen.

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

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



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

TAR SPOT SPREAD TO THE U.S. AND CANADA

The first confirmations of tar spot in North America outside of Mexico were in Illinois and Indiana in 2015 (Bissonnette, 2015; Ruhl et al., 2016). It has subsequently spread to Michigan (2016), Wisconsin (2016), Iowa (2016), Ohio (2018), Minnesota (2019), Missouri (2019), Pennsylvania (2020), Ontario (2020), Kentucky (2021), New York (2021), Nebraska (2021), Kansas (2022), South Dakota (2022), Maryland (2022), Delaware (2023), Virginia (2023), North Dakota (2024), and Quebec (2024). Its presence was also confirmed in Florida in 2016 (Miller, 2016) and in Georgia in 2021.

2018 Outbreak

During the first few years of its presence in the U.S., it appeared that tar spot might remain a relatively minor cosmetic disease of little economic impact. In 2018, however, tar spot established itself as an economic concern for corn production in the Midwest, with severe outbreaks reported in Illinois, Indiana, Wisconsin, Iowa, Ohio, and Michigan. Significant corn yield losses associated with tar spot were reported in some areas. University corn hybrid trials conducted in 2018 suggested potential yield losses of up to 39 bu/acre under the most severe infestations (Telenko et al., 2019). Growers in areas severely impacted by tar spot anecdotally reported yield reductions of 30–50% compared to 2016 and 2017 yield levels. Yield losses specifically attributable to tar spot were often difficult to determine however, because of the presence of other corn diseases due to conditions generally favorable for disease development. Instances of greatest tar spot severity in 2018 were largely concentrated in northern Illinois and southern Wisconsin, where other foliar diseases and stalk rots were also prevalent.

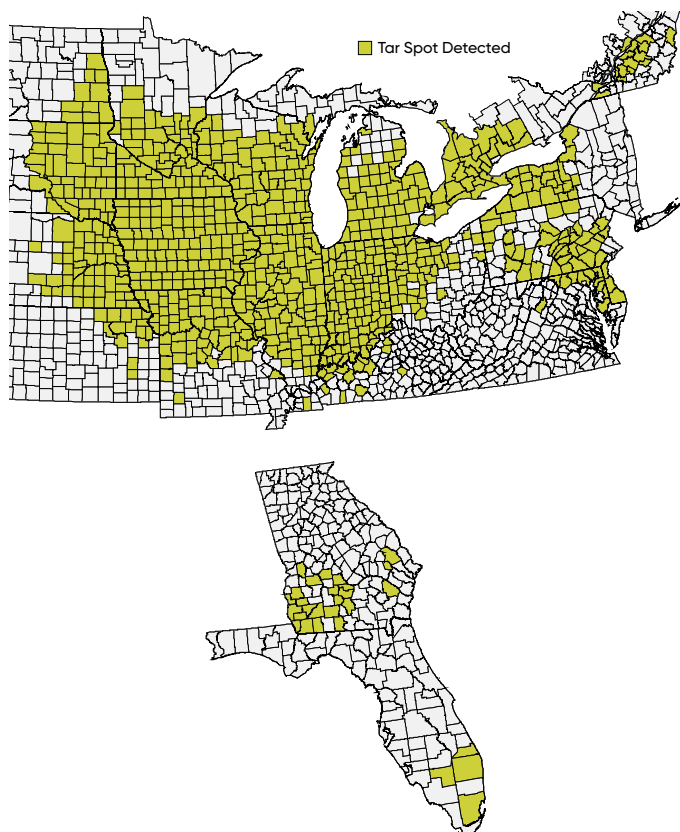


Figure 1. Counties with confirmed incidence of tar spot, as of November 2024. (Corn ipmPIPE, 2024; Corteva Plant Diagnostic Lab).

2019 and 2020 Observations

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

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

2020 brought another year of generally lower tar spot severity in the Corn Belt, with severe infestations mostly limited to irrigated corn and areas that received greater than average rainfall or developing late enough in the season

that they had minimal impact on yield. Tar spot continued to spread, however; with the first confirmation of tar spot in Pennsylvania. Tar spot was also confirmed to be present in corn in Ontario, marking the first time the disease had been detected in Canada.

2021 Outbreak

The 2021 growing season proved that the 2018 outbreak was not a fluke, with a severe outbreak of tar spot once again impacting corn over a large portion of the Corn Belt. Wet conditions early in the summer appeared to be a key factor in allowing tar spot to get a foothold in the crop. Whereas in 2018, when tar spot appeared to be mainly driven by wet conditions in August and September, in 2021, many impacted areas were relatively dry during the latter portion of the summer. Wet conditions early in the summer were apparently enough to allow the disease to get established in the crop and enabled it to take off quickly when a window of favorable conditions opened up later in the summer. The 2021 season also provided numerous demonstrations of the speed with which tar spot can proliferate, enabled by its rapid reinfection cycle (Figure 2).



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

2022: The Tar Spot Story Gets More Complex

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

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

Tar spot spread through South Dakota and was detected in North Dakota and Quebec for the first time in 2024.

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

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

Species 1 (In U.S. Corn)

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

Species 2 (In U.S. Corn)

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

Species 3 (In U.S. Corn)

- Widest geographic and host range
- Found in several U.S. states and a dozen other countries around the world
- Found in corn as well as 10 other host species, including monocots and dicots
- Includes first isolate collected from U.S. corn in 2015 and the original specimen collected in Mexico in 1904

- Herbarium samples indicate that Species 3 has been present in the Southwestern U.S. since at least the 1940s in native grass species, but not in corn

Species 4

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

Species 5

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

2023 and 2024 Observations

Drought and heat stress were major factors during the 2023 growing season across much of the Corn Belt, which tended to keep foliar diseases – including tar spot – in check in many areas. Tar spot pressure often stayed low or ramped up late enough in the season that it had little to no yield impact. A notable exception was parts of eastern Nebraska and northern Missouri along the Missouri River that experienced high levels of tar spot and areas with yield loss and standability challenges. Tar spot was detected in two new states in 2023 – Virginia and Delaware – and continued its westward expansion, with first detections in numerous counties in Nebraska, Kansas, and Missouri.

2024 was another year of generally low to moderate tar spot pressure. Tar spot continued its spread around the margins of previously infected areas, with a major expansion northwest in Minnesota, South Dakota, and into North Dakota. Tar Spot was also found in Quebec for the first time.

IDENTIFICATION AND SYMPTOMS

Tar spot is the physical manifestation of fungal fruiting bodies, the ascomata, developing on the leaf. The ascomata look like spots of tar, developing black oval or circular lesions on the corn leaf (Figure 3). The texture of the leaf becomes bumpy and uneven when the fruiting bodies are present. These black structures can densely cover the leaf and may resemble the pustules of rust fungi (Figure 3 and 4). Tar spot spreads from the lowest leaves to the upper leaves, leaf sheathes, and eventually the husks of the developing ears (Bajet et al., 1994).



Figure 3. A corn leaf with tar spot symptoms.

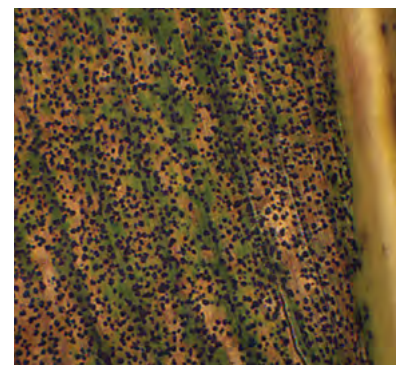


Figure 4. Corn leaf under magnification showing dense coverage with tar spot ascomata.

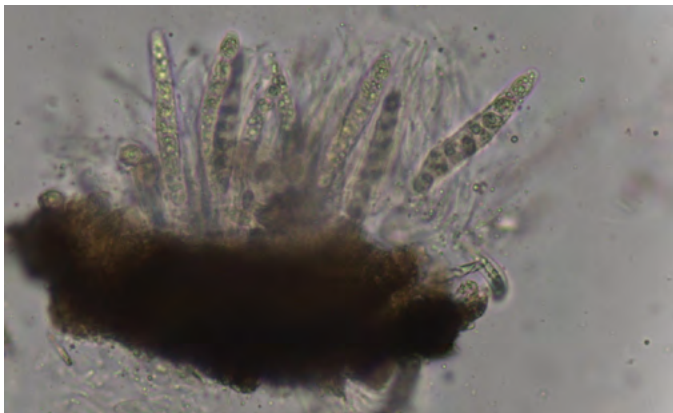


Figure 5. Microscopic view of fungal spores of *P. maydis*.

Under a microscope, *P. maydis* spores can be distinguished by the presence of eight ascospores inside an elongated ascus, resembling a pod containing eight seeds (Figure 5).

Tar Spot Look-Alikes

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

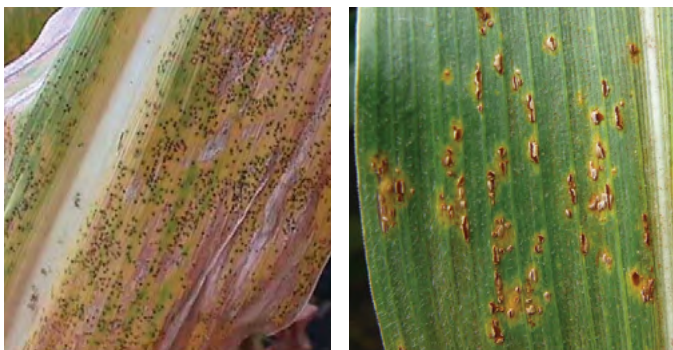


Figure 6a. Southern rust in the teliospore stage late in the season, which can resemble tar spot (left). **Figure 6b.** Corn leaf with common rust spores showing jagged edges around the pustules (right).

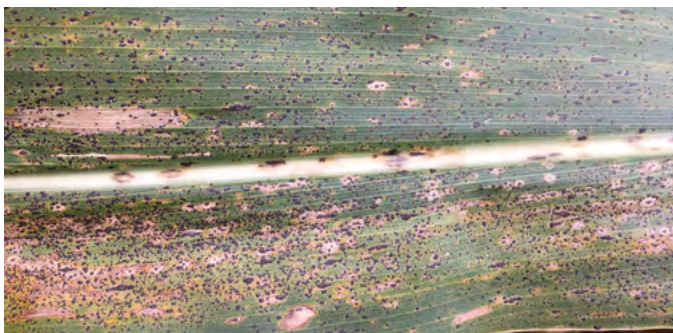


Figure 7. Corn leaf with tar spot symptoms.

TAR SPOT ARRIVAL AND SPREAD IN THE U.S.

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

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

As for the reason for tar spot's establishment and spread as a disease capable of severely reducing corn yield, Broders et al. (2022) note two possible contributing factors. The first is that changes in climate have favored the disease. Shorter and warmer winters may be allowing *P. maydis* to overwinter further north than previously possible and greater temperature and precipitation could contribute to epidemics during the growing season. Second, is that the overall lack of resistance to *P. maydis* in North American corn genetics has made corn in the U.S. and Canada a particularly vulnerable host population. Corn hybrids have been shown to vary in their susceptibility to tar spot. Corn breeding programs in Central and South American countries – where tar spot has long been present – would have selected for more resistant genetics, whereas breeding programs in the U.S. and Canada, until very recently, would not.

TAR SPOT EPIDEMIOLOGY

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

P. maydis is an obligate pathogen, which means it needs a living host to grow and reproduce. It is capable of overwintering in the Midwestern U.S. in infected crop residue on the soil surface. Tar spot is favored by cool temperatures (60–70°F, 16–20°C), high relative humidity (>75%), frequent cloudy days, and 7+ hours of dew at night. Tar spot is polycyclic and can continue to produce spores and spread to new plants as long as environmental conditions are favorable. *P. maydis* produces windborne spores that have been shown to disperse up to 800 ft. Spores are released during periods of high humidity.

Genetic resistance to tar spot should be the number one consideration when seeking to manage this disease.

MANAGEMENT CONSIDERATIONS

Yield Impact

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

Differences in Hybrid Response

Observations in hybrid trials have shown that hybrids differ in susceptibility to tar spot (Kleczewski and Smith, 2018; Ross et al., 2023). Tar spot affects yield by reducing the photosynthetic capacity of leaves and causing rapid premature leaf senescence. Longer maturity hybrids for a given location have been shown to have a greater risk of yield loss from tar spot than shorter maturity hybrids (Telenko et al., 2019). Pioneer agronomists and sales professionals continue to collect data on disease symptoms and hybrid performance in locations where tar spot is present to assist growers with hybrid management. Pioneer hybrid trials have shown differences in canopy staygreen among Pioneer® brand corn products* and competitor products under tar spot disease pressure (Figure 8). Genetic resistance to tar spot should be the number one consideration when seeking to manage this disease.



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

Stalk Quality

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

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

Fungicide Treatments

Research has shown that fungicide treatments can be effective against tar spot (Bajet et al., 1994; Da Silva et al., 2019; Ross et al., 2023). 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).



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

Severe infestations of tar spot may be challenging to control with a single fungicide application due to its rapid re-infection cycle, particularly in irrigated corn. A 2019 Purdue University study compared single-pass and two-pass treatments for tar spot control using Aproach® (picoxystrobin) and Aproach® Prima (picoxystrobin + cyproconazole) fungicides under moderate to high tar spot severity (Da Silva et al., 2019).

Severe infestations of tar spot may be challenging to control with a single fungicide application due to its rapid re-infection cycle.

Fungicide treatments were applied at the VT (August 8) and R2 stage (August 22), and disease symptoms were assessed on September 30. Results showed that all treatments significantly reduced tar spot symptoms relative to the nontreated check, with Aproach Prima fungicide applied at VT and two-pass treatments at VT and R2 providing the greatest reduction in tar spot stroma and associated chlorosis and necrosis on the ear leaf (Figure 10).

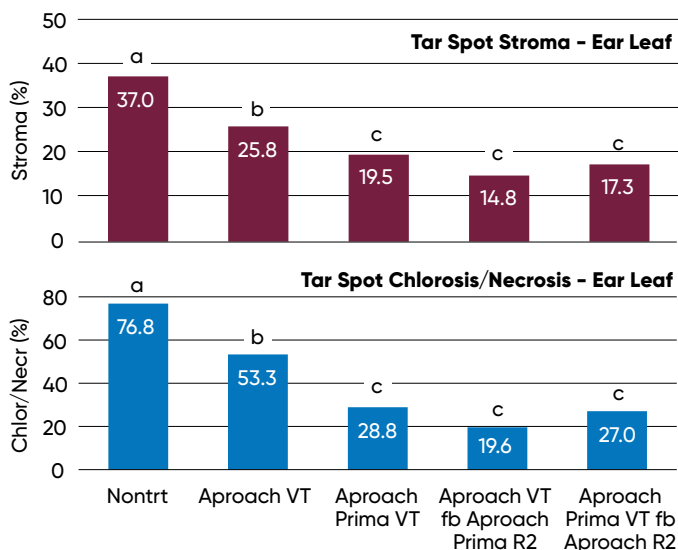


Figure 10. Fungicide treatment effects on tar spot symptoms in a 2019 Purdue University study. Visually assessed tar spot stroma and chlorosis/necrosis (0–100%) on the ear leaf.

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

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

On-farm fungicide trials conducted in 2021 appeared to confirm concerns that the rapid re-infection rate of tar spot would make it difficult to control with a single pass fungicide treatment. Precise application timing was often critical, and two applications were necessary in some cases to provide

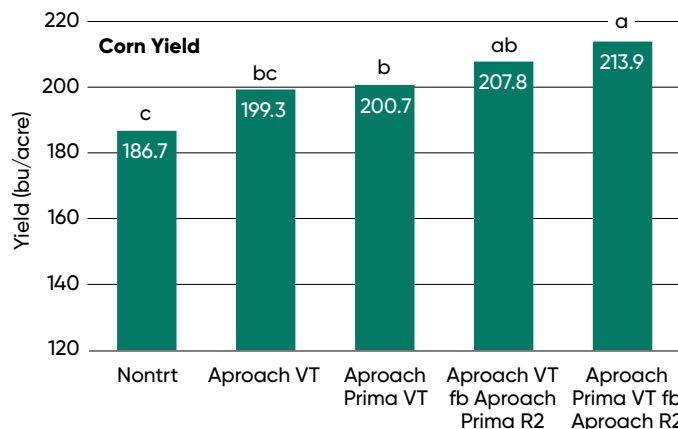


Figure 11. Fungicide treatment effects on corn yield in a 2019 Purdue University study.

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

adequate tar spot control. Disease forecasting models such as Tarspotter, developed at the University of Wisconsin, may be helpful in optimizing timing of fungicide applications. Tarspotter uses several variables including weather to forecast the risk of tar spot fungus being present in a corn field.

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

Several foliar fungicide products are available for management of tar spot in corn. (Table 2).



Corn leaf displaying tar spot symptoms.

Agronomic Practices

The pathogen that causes tar spot overwinters in corn residue but to what extent the amount of residue on the soil surface in a field affects disease severity the following year is unknown. Spores are known to disperse up to 800 ft, so any benefit from rotation or tillage practices that reduce corn residue in a field may be negated by spores moving in from neighboring fields. Evidence so far suggests that rotation and tillage probably have little effect on tar spot severity. A 3-year Purdue University study that compared strip-till and conventional tillage found no effect on tar spot severity in the subsequent growing season (Ross et al., 2023).



Agronomists have noted that infestation may occur earlier in corn following corn fields, where infection proceeds in a “bottom-up” manner from inoculum present in the soil, in contrast to rotated fields that more commonly exhibit “top-down” pattern of infection from spores blowing in from other fields.

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

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

Mycotoxins

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

Table 2. Efficacy of fungicides labeled for tar spot in corn (Wise, 2024).

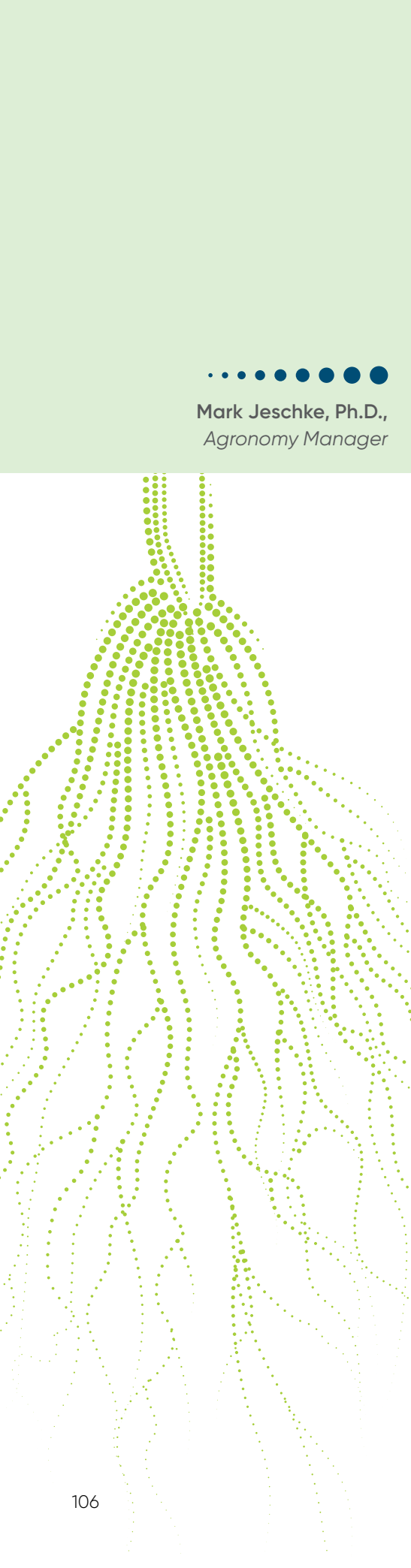
Product Name	Tar Spot Efficacy	Harvest Restriction
Aproach® 2.08 SC	G*	7 days
Aproach® Prima 2.34 SC	G-VG	30 days
Affiance® 1.5 SC	G*	7 days
Delaro® Complete 3.83 SC	VG	14 days
Delaro® 325 SC	G-VG	14 days
Fortix® 3.22 SC Preemptor™ 3.22 SC	G-VG*	30 days
Headline® AMP 1.68 SC	G-VG	20 days
Lucento® 4.17 SC	G*	30 days
Miravis® Neo 2.5 SE	G-VG	30 days
Revytek™ 4.44 SC	VG	21 days
TopGuard® EQ 4.29 SC	G-VG*	7 days
Trivapro® 2.21 SE	G-VG	30 days
Veltyma™ 3.34 SC	VG	21 days

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

HOW FAR WILL TAR SPOT SPREAD?

Mottaleb et al. (2018) used climate modeling based on long-term temperature and rainfall data to predict areas at risk of tar spot infection based on the similarity of climate to the current area of infestation. Model forecasts indicated the areas beyond the then-current range of infestation at highest risk for spread of tar spot were central Iowa and northwest Ohio. Observations in subsequent growing seasons have been consistent with model predictions, with further spread of tar spot to the east in Ohio, Ontario, and Pennsylvania and a dramatic expansion of tar spot across Iowa and into parts of Minnesota and Missouri.

As of 2023, spread of tar spot in the Corn Belt has proceeded largely as predicted back in 2018, with some expansion to the north and south but primarily to the east and west. The two primary remaining areas to which tar spot expansion was predicted but has not yet occurred are eastward across New York and westward across South Dakota, so corn growers in these areas should be on the lookout for tar spot in the coming years.



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Mark Jeschke, Ph.D.,
Agronomy Manager

HARNESSING THE POWER OF BIOLOGICAL NITROGEN FIXATION

KEY POINTS

- An adequate supply of plant-available nitrogen is critical to maximizing agricultural productivity.
- The development of industrial nitrogen fixation in the early 20th Century enabled tremendous gains in agricultural productivity, which has been critical to global food security.
- Some of the significant drawbacks associated with synthetic nitrogen fertilizer have led to a renewed interest in leveraging biological nitrogen fixation to provide plant-available nitrogen for crop production.
- Biological nitrogen fixation is carried out by a relatively small subset of bacteria and archaea, known as diazotrophs.
- The nitrogen-fixing organisms most familiar to agriculture are the rhizobia – bacteria that fix nitrogen in root nodules of legumes; however, there are numerous other types of non-symbiotic nitrogen-fixing bacteria.
- Multiple approaches are being explored to increase biological nitrogen fixation in non-legume crops, such as the creation of new types of symbiosis with nitrogen-fixing bacteria and engineering the nitrogen fixation pathway directly into plants.
- Some significant challenges have limited the success of these efforts thus far, including the high energy requirement of nitrogen fixation and the complexity of the nitrogen fixation pathway.

NITROGEN: A KEY BUILDING BLOCK FOR LIFE

Carbon and nitrogen have some important things in common: both are key building blocks for all life on Earth, and both exist in the atmosphere in forms that are not directly usable by living organisms – carbon dioxide (CO_2) and dinitrogen (N_2). Life on Earth is almost entirely dependent on biochemical processes that have evolved in certain organisms that convert atmospheric carbon and nitrogen into forms that are usable for building organic molecules. These processes are photosynthetic carbon fixation and biological nitrogen fixation.



Figure 1. Legumes like soybean derive a significant portion of the nitrogen needed for their growth from symbiotic associations with nitrogen-fixing *Rhizobium* bacteria.

Photosynthetic carbon fixation is ubiquitous in nature. There are an estimated 350,000 species on Earth that carry out photosynthesis (Sage and Stata, 2015), including numerous types of bacteria and nearly all plant species. Plants have evolved multiple types of photosynthetic carbon fixation – C3, C4, and CAM – that have allowed plant species to thrive in a wide range of terrestrial environments. The surface layer of the world's oceans is filled with photosynthetic plankton. While carbon dioxide makes up a relatively small fraction of the atmosphere, life on Earth is very good at accessing and making use of it.

Nitrogen, Nitrogen, Everywhere...

Biological nitrogen fixation, on the other hand, is far less common. While nitrogen exists in great abundance – comprising around 78% of the atmosphere – only a small fraction of living organisms on Earth are able access it. Biological nitrogen fixation is carried out by a relatively small subset of bacteria and archaea, known as diazotrophs. This process is limited almost exclusively to prokaryotes – until very recently, no eukaryotic organisms were known to fix nitrogen. As a result, biologically available nitrogen is the primary limiting factor for all life on Earth.

Overcoming this limitation has been critical in driving agricultural productivity in the 20th and 21st Century. The development of industrial nitrogen fixation in the early 20th Century, known as the Haber-Bosch process, is widely considered one of the most important innovations in human history.

Synthetic nitrogen fertilizer was one of the main drivers of the Green Revolution, which saw significant gains in yields of globally important crops, most notably wheat and rice. Synthetic nitrogen fertilizer has enabled tremendous gains in agricultural productivity, which has been critical to global food security; however, it has not been without its drawbacks.

Biologically available nitrogen is the primary limiting factor for all life on Earth.

Problems With Synthetic Nitrogen

One of the biggest drawbacks is the fact that industrial nitrogen fixation uses a lot of energy. The Haber-Bosch process combines dinitrogen with hydrogen under high temperature (750–930°F) and pressure (2,900–3,600 psi) (Gilchrist and Benjamin, 2017). Industrial nitrogen fixation relies heavily on fossil fuels, both for energy to produce the heat and pressure and a source of hydrogen (natural gas) for the reaction. The synthetic nitrogen fertilizer supply chain (including production, transportation, and field use) accounts for 2.1% of global greenhouse gas emissions (Menegat et al., 2022), more than the total amount produced by all aviation globally.

The other main drawback is that much of the nitrogen applied as fertilizer in agricultural production is lost to the environment. Globally, less than half of nitrogen applied to crop land is taken up by the crop (Zhang et al., 2015). Not only is this economically wasteful, the loss of reactive nitrogen from agricultural soils is associated with several adverse environmental consequences, including contamination of ground and surface water, algal blooms in lakes and rivers, hypoxic dead zones in coastal waters, and nitrous oxide emissions into the atmosphere.

Important Terms

Prokaryote – Single-celled organisms that do not have a nucleus or membrane-bound organelles. Prokaryotes include two domains – bacteria and archaea.

Eukaryote – Organisms whose cells have a membrane-bound nucleus. All animals, plants, fungi, and some unicellular organisms are eukaryotes.

Diazotroph – Bacteria and archaea that fix atmospheric nitrogen (N_2) into bioavailable forms such as ammonia.

Archaea – Single-celled prokaryotes originally classified as bacteria but now recognized as a separate domain of life. Archaea are often found living in extreme environments.

Symbiosis – Any type of a close and long-term biological interaction between two organisms of different species. In some cases, such as that of legumes and rhizobia, this relationship can be mutually beneficial.

Nitrogenase – An enzyme produced by some bacteria and archaea that is responsible for the reduction of nitrogen (N_2) to ammonia (NH_3).

The Need for Sustainable Alternatives

The drawbacks of synthetic nitrogen fertilizer have led to a renewed interest in leveraging biological nitrogen fixation to provide plant-available nitrogen for crop production. Biological nitrogen fixation is already utilized by crops species such as soybeans, alfalfa, and peanuts that form symbiotic associations with nitrogen-fixing *Rhizobium* bacteria. The amount of nitrogen fixed through these symbiotic associations can be substantial: grain legumes such as soybeans and peanuts can fix up to 250 lbs of nitrogen per acre and forage legumes like alfalfa and clover can fix 250–500 lbs of nitrogen per acre (Flynn and Idowu, 2015).

Crop scientists have long been interested in developing ways to use biological nitrogen fixation for other crops such as corn, wheat, and rice. Recent advances in plant microbiome research have increased our understanding of additional types of nitrogen fixing bacteria, such as those used in microbial biostimulant products like Utrisha® N (*Methylobacterium symbioticum*) and Pivot Bio PROVEN®40 (*Kosakonia sacchari* and *Klebsiella variicola*). Understanding the potential value of nitrogen-fixing microbial products such as these – both now and in the future – requires a basic understanding of how biological nitrogen fixation works and some of the factors that can enhance or inhibit it.

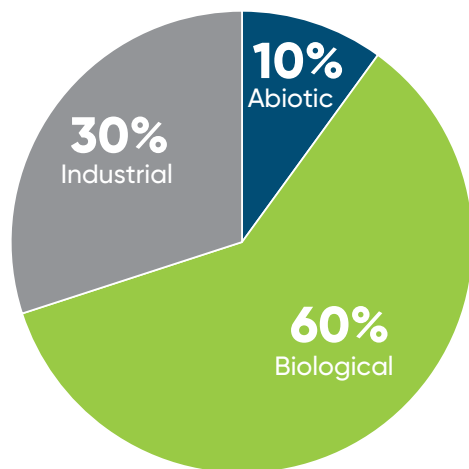


Figure 2. Relative contributions of abiotic, biological, and industrial nitrogen fixation to the total amount of fixed nitrogen on Earth (Hopkins, 1999).

NITROGEN (N) FIXATION

The first step to understanding biological nitrogen fixation is understanding what makes atmospheric nitrogen is so difficult to access. It seems counterintuitive that an element that makes up 78% of the atmosphere would also be the element that is most limiting to the growth of living organisms. The answer lies in the basic chemistry of nitrogen atoms. Nitrogen in the atmosphere exists in the dinitrogen form (N_2), which is two nitrogen atoms held together by a triple covalent bond. The triple bond between nitrogen atoms is extremely strong, which makes dinitrogen very stable and non-reactive. Breaking this triple bond to make nitrogen available for building useful compounds requires a large input of energy, and there are only a few processes in nature capable of doing this.

Abiotic Nitrogen Fixation

There are three natural abiotic phenomena that provide enough energy to break the dinitrogen triple bond and fix atmospheric nitrogen – fire, ultraviolet radiation, and lightning. All three oxidize atmospheric dinitrogen to nitrogen oxides (NO , N_2O). Subsequent reactions then convert these molecules to nitrous acid (HNO_2), and nitric acid (HNO_3) which can be precipitated out of the atmosphere by rain or snow. Once in the soil, these acids become nitrate (NO_3^-), which is usable by plants. Lightning is generally thought of as a sporadic occurrence and – in a given location – it is; however, over 3 million lightning bolts strike Earth every day, creating around 13,000 tons of nitrate. Collectively, abiotic nitrogen fixation accounts for around 10% of all nitrogen fixed on Earth (Figure 2).

Biological Nitrogen Fixation

Biological nitrogen fixation is the conversion of dinitrogen to reactive forms by living organisms and is the only other natural nitrogen fixation process aside from fire, lightning, and UV radiation. The protein complex that catalyzes the reaction is called nitrogenase and exists almost exclusively in a small subset of prokaryotes (bacteria and archaea). Biological nitrogen fixation likely evolved early in the history of life on Earth. The first life likely emerged between 3.5 and 4.1 billion years ago and nitrogen isotope ratios in rocks suggest that biological nitrogen fixation has been going on for at least 3.2 billion years (Stüeken et al., 2015). Despite its long history, genomic analysis indicates that only around 5% of bacteria and archaea species have the full set of genes involved in nitrogen fixation (Pi et al., 2022). Biological nitrogen fixation accounts for the majority (~60%) of all nitrogen fixed globally.



Figure 3. The amount of nitrogen fixed through symbiotic associations can be substantial: legumes such as soybeans can fix as much as 250 lbs of nitrogen per acre (Flynn and Idowu, 2015).

Industrial Nitrogen Fixation

The remaining 30% of nitrogen fixation comes from industrial nitrogen fixation via the Haber-Bosch process, which combines dinitrogen from the atmosphere with hydrogen to produce ammonia (NH_3). The process was developed by German chemists Fritz Haber and Carl Bosch in the early 20th Century and was first deployed on an industrial scale to

produce nitrates for munitions during World War I. Compared to other sources of reactive nitrogen, industrial fixation has

It is estimated that nearly 50% of the nitrogen found in human tissues originated from the Haber-Bosch process.

only existed for a tiny portion of Earth's history, thus it constitutes an extremely large and abrupt alteration to Earth's nitrogen cycle. It is estimated that nearly 50% of the nitrogen found in human tissues originated from the Haber-Bosch process (Ritter, 2008).

LEVERAGING BIOLOGICAL N FIXATION

An adequate supply of plant-available nitrogen is critical to maximizing agricultural productivity. Over the past century, synthetic nitrogen fertilizer produced using the Haber-Bosch process has been a crucial tool for providing that supply of nitrogen. It is estimated that around half of the world's current population likely would not exist if not for this one innovation (Ritchie, 2017). Recent interest in leveraging biological nitrogen fixation to replace a portion of this nitrogen stems from a desire to mitigate the two primary drawbacks of synthetic nitrogen. Biological nitrogen fixation does not rely on fossil fuel inputs for production and, by feeding nitrogen directly to the plant, can greatly reduce or eliminate nitrogen lost to the environment instead of going to produce yield.

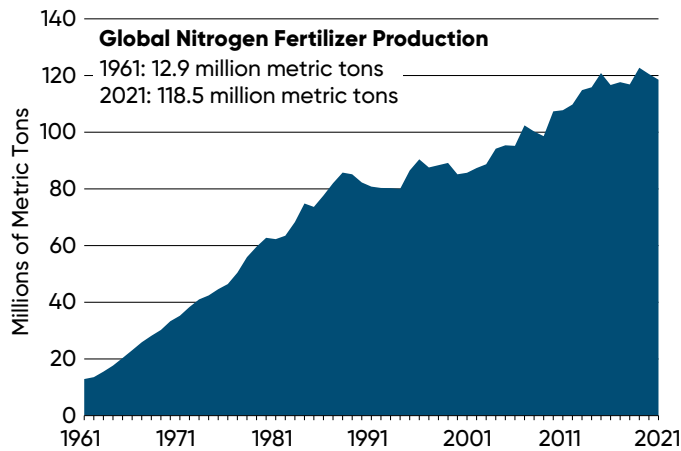
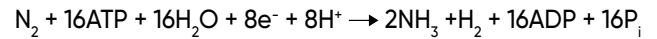


Figure 4. Total global production of nitrogen fertilizer from 1961 to 2021 measured in million metric tons of N (Ritchie et al., 2022).

Breaking Up is Hard to Do

The main challenge to biological nitrogen fixation is the amount of energy required to break the dinitrogen triple bond. Biological nitrogen fixation is one of the most metabolically expensive processes in all of biology, requiring energy from 16 ATP molecules to break one molecule of N_2 . (As a comparison, C4 photosynthetic carbon fixation costs 5 ATP molecules per molecule of CO_2 fixed [Yin and Struik, 2020].) This high energy cost of biological nitrogen fixation is likely a big reason why relatively few species have evolved the capability to do it. It also explains why some plants have developed symbiotic relationships with nitrogen-fixing bacteria. Plant-available nitrogen is a scarce and metabolically expensive resource, so if a plant can partner with bacteria to provide a continual supply, it would be advantageous to do so.

The enzyme responsible for catalyzing nitrogen fixation is called nitrogenase, and is the only enzyme known to do this. Four types of nitrogenases are known; three of them are similar and closely related and one is a different enzyme only found in a single bacterial species, *Streptomyces thermoautotrophicus*. Nitrogenase consists of two component metalloproteins (which is why it is sometimes referred to as an enzyme complex) that together mediate the reduction of dinitrogen (N_2) to ammonia (NH_3):



The Black Queen Hypothesis

Biologically available nitrogen is essential for all life on Earth and yet only a small subset of microorganisms are able to produce it – why is this? The Black Queen Hypothesis is a concept that seeks to explain reductive genome evolution and why certain essential functions are rare within some communities (Morris et al., 2012).

“Black Queen” refers to the queen of spades in the game Hearts, where the usual strategy is to avoid taking this card, yet one player must ultimately end up with it. Many vital genetic functions such as nitrogen fixation are “leaky,” meaning that organisms that carry out the function are unable to retain the benefits strictly to themselves. The Black Queen Hypothesis posits that the loss of a metabolically costly and leaky function like nitrogen fixation is selectively favored at the individual level and will proceed until production is just sufficient to support the community.

Simply put – if organisms can attain a costly resource from other organisms instead of producing it themselves, they will. The Black Queen represents the organisms that get stuck carrying the load for the entire community.

Biological Nitrogen Fixation in Agriculture

The nitrogen-fixing organisms most familiar to agriculture are the rhizobia – bacteria in the family Rhizobiaceae that form symbiotic associations with legume species and supply nitrogen to the host plants after becoming established inside nodules on the roots. Legumes include several agriculturally important species such as soybeans, chickpeas, peanuts, lentils, alfalfa, and clover. The supply of nitrogen the legumes receive through these symbiotic relationships allows them to produce seeds high in protein, which has made them important components of both animal and human nutrition. Historically, legumes have been used in agriculture both as a direct source of food and feed, as well as green manure crops that are tilled into the soil to serve as a source of plant-available nitrogen for other crops.

Types of Nitrogen-Fixing Bacteria

The most researched and well-understood diazotrophs are those that function as part of symbiotic systems. In addition to the *Rhizobium* species, bacteria of the genus *Frankia* also form symbiotic associations with numerous plants species – mostly trees and shrubs – known as actinorhizal plants. Not all diazotrophs are symbiotic though. Diazotrophs can be grouped into one of three categories based on their life habit (Figure 5).

Free-living: Bacteria that live in the soil and fix nitrogen without direct interaction with other organisms. These bacteria must find their own source of energy, typically by oxidizing organic molecules released by other organisms or from decomposition. Examples include species of *Azotobacter*, *Bacillus*, *Clostridium*, and *Klebsiella*.

Associative: Bacteria that live near or on plant roots. These bacteria receive energy from the plant via carbohydrates exuded by the roots and fix nitrogen that is usable by the plant but usually do not colonize plant tissues and do not form the same sort of organized interrelationship with a host plant that symbiotic bacteria do. Associative symbiosis is common with grasses such as corn, wheat, rice, and sugarcane and includes genera such as *Azospirillum*, *Gluconobacter*, *Acetobacter*, *Herbaspirillum*, and *Azoarcus*.

Symbiotic: Bacteria that colonize the host organism and rely on it for energy while supplying it with fixed nitrogen. The most common examples are root nodule-forming bacteria of the genera *Rhizobium* and *Frankia*, but this category also includes nitrogen-fixing cyanobacteria that live in symbiosis with a wide range of terrestrial and aquatic organisms.

Symbiotic diazotrophs account for the majority of total biological nitrogen fixation and are the most important in agricultural systems. Non-symbiotic bacterial diazotrophs have historically had less agronomic significance, but their capability to fix nitrogen is not inconsequential – it is estimated that around 30% of total biological nitrogen fixation comes from non-symbiotic bacteria (Peoples and Craswell, 1992; Kennedy and Islam, 2001).

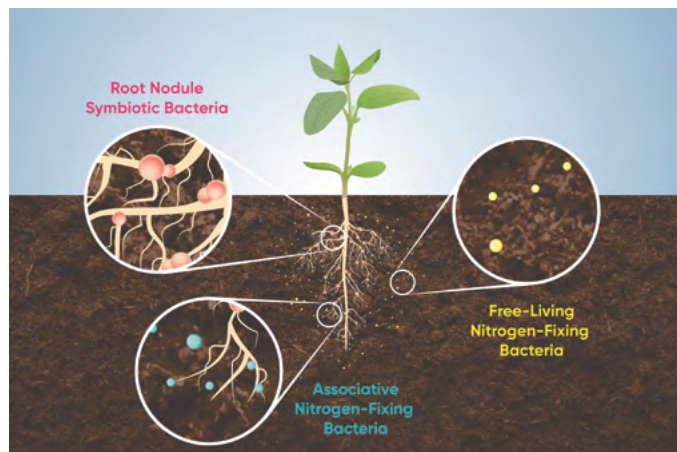


Figure 5. Diazotrophs can be grouped into one of three categories based on their life habit: free-living, associative, or symbiotic.

LOOKING BEYOND LEGUMES

Enhancing Non-Symbiotic Nitrogen Fixation

One approach to increasing biological nitrogen fixation in non-legume crops is to boost the contribution of free-living and associative nitrogen-fixing bacteria. Numerous genera of nitrogen-fixing bacteria are known to associate with grass crops such as corn and wheat. If the quantity of nitrogen fixed by these bacteria in agricultural systems could be increased, it could reduce the need for synthetic nitrogen fertilizer.

Leveraging non-symbiotic nitrogen-fixing bacteria in crop production is not a new idea. The first commercial inoculant using a free-living species of bacteria was Azotogen (*Azotobacter chroococcum*), introduced in 1946 (Timonin, 1949). However, several challenges have limited the value and adoption of microbe-based biofertilizers. Some of these challenges have to do with the production, handling, and application of these products – working with living organisms is very different from handling hard chemistries. Other challenges stem from the difficulty in establishing microorganisms in a diverse and dynamic environment where they must compete with other organisms that are already well-adapted to that environment (Roper and Gupta, 2016; Soumare et al., 2020).

Why are Rhizobia So Effective at Fixing Nitrogen?

In exploring ways to enhance non-symbiotic nitrogen-fixation, it is useful to first look at what makes symbiotic diazotrophs, such as rhizobia, so good at fixing large amounts of nitrogen. Rhizobia colonize the roots of legumes through a highly regulated process of signal exchange between the bacteria and the

Nodules on the roots of legumes provide bacteria with two important things that they need for fixing nitrogen: a source of energy and an anaerobic environment.

host plant. When plant-available nitrogen in the soil is limiting, legumes release flavonoids, which signal to rhizobia that the plant is seeking symbiotic bacteria. In response, rhizobia release nodulation factors (Nod factors), which stimulate the plant to create deformed root hairs, creating an entry path for the bacteria. Once the rhizobia are inside the root cells, the root cells undergo rapid cell division, forming a nodule.

The nodule provides the bacteria two important things that they need for fixing nitrogen: a source of energy and an anaerobic environment. Rhizobia are able to fix a lot of nitrogen because the host plants provide them the necessary energy to do it. The energy for splitting the nitrogen gas in the nodule comes from sugar produced by photosynthesis that is



Figure 6. Nodules that are actively fixing atmospheric nitrogen will be pink or red in color when cut open. The red color is caused by leghemoglobin, a protein that binds to oxygen and makes it available for cellular respiration while preventing it from degrading nitrogenase. Photo from the Manitoba Pulse & Soybean Growers.

translocated from the leaves of the plant. An anaerobic environment is necessary for nitrogenase to function because it is highly sensitive to oxygen, which irreversibly inactivates and degrades the enzyme. The nodule provides the bacteria with this environment. The nodule contains leghemoglobin, an iron-containing protein that binds to oxygen and facilitates its diffusion for use in cellular respiration. Leghemoglobin is what gives the root nodules their characteristic reddish internal color (Figure 6).

Challenges to Non-Symbiotic Nitrogen Fixation

Non-symbiotic diazotrophs do not enjoy the same optimized environment for nitrogen fixation that symbiotic ones do; however, they can still derive some advantages from associating with plants. The plant rhizosphere provides a favorable environment for microbial proliferation compared to bulk soil due to the secretion of root exudates rich in sugars, organic acids, and amino acids, which the bacteria can use as a source of energy. The root exudates of different plants can favor different kinds of bacteria, and several genera are known to associate with corn roots.

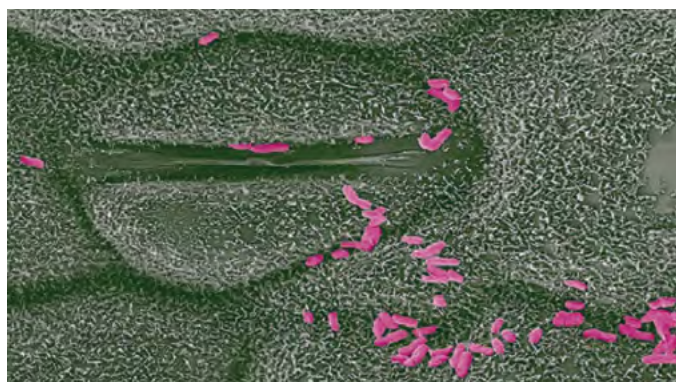


Figure 7. *Methylobacterium symbioticum*, the active ingredient in Utrisha® N on the surface of a plant leaf. *M. symbioticum* enter the plant through the stomata and rapidly colonize the entire plant.

The active component in Utrisha® N (*Methylobacterium symbioticum*) derives energy for nitrogen fixation from its host plant in a different way. Methylobacteria are a genus of bacteria that survive and multiply inside the plant by scavenging methanol, which is a byproduct of normal vegetative plant growth released to the atmosphere through the stomata. The bacteria use methanol as an energy source and fix atmospheric nitrogen. Endophytic bacteria such as *M. symbioticum* can live and reproduce in plants without causing damage.

Endophytes have an advantage over associative bacteria in the rhizosphere because they can directly access energy from the plant while escaping competition from other organisms. One of the challenges with inoculating soils with bacteria is that the inoculated bacterial populations often decline rapidly due to competition with native organisms (Roper and Gupta, 2016).

Even when non-symbiotic diazotrophs are able to receive energy from a host plant, they generally do not produce large quantities of nitrogen for the plant, simply because they have not evolved to do so. Non-symbiotic diazotrophs typically fix nitrogen for their own needs, not to secrete for up-

take by plants (Rosenblueth et al., 2018). These bacteria will reduce nitrogen fixation when it is not to their benefit. Given the high metabolic cost of nitrogen fixation, any bacteria that were investing significant energy into producing excess nitrogen would likely be outcompeted by those that did not. Furthermore, non-symbiotic diazotrophs in the soil typically reduce nitrogen fixation when mineral nitrogen is available, such as in fertilized fields (Knowles, 1980), which can make attempts to replace a portion of applied nitrogen with biological fixation challenging.

Non-symbiotic diazotrophs typically fix nitrogen for their own needs, not to secrete for uptake by plants. These bacteria will reduce nitrogen fixation when it is not to their benefit.

INCREASING N FIXATION FROM BACTERIA

The levels of nitrogen fixation attained from nitrogen-fixing bacteria in cereal crops such as corn have not been sufficient to support the needs of the crop, so scientists have researched – and continue to research – ways to increase this nitrogen supply.

One strategy has been to increase the amount of nitrogen supplied by associative bacteria. Numerous genera of nitrogen-fixing bacteria are known to associate with the roots of cereal crops such as corn; however, nitrogen supplied by these bacteria is limited by a number of factors, including insufficient colonization and persistence, lack of host specificity, and genetic regulation that limits nitrogen fixation to only what the bacteria need (Haskett et al., 2020). Selecting or modifying bacteria to overcome any one of these limitations could increase the amount available to the crop.

Does Nitrogen Fixation Reduce Yield in Legumes?

Nitrogen fixation is an energy intensive process. Symbiotic bacteria in legumes are able to produce a lot of nitrogen because the energy to carry out the process is supplied by the plant. This raises the obvious question of whether that fixed nitrogen is coming at the expense of productivity. Are the nitrogen-fixing bacteria drawing energy from the plant that could otherwise be going into producing more yield?

The answer is no, not really. Nitrogen fixation definitely has an energy cost for the plant, but so does assimilating nitrate from the soil. Plants need nitrogen in the ammonium (NH_4^+) form for building amino acids. Rhizobia convert N_2 to NH_4^+ , which costs the plant energy. Converting nitrate (NO_3^-) taken up from the soil to NH_4^+ also costs the plant energy. The estimated energy costs for these two processes are similar – 605 kJ/mol in the case of nitrate assimilation and 687 kJ/mol for nitrogen fixation (Roesenblueth et al., 2018).

If legumes were able to derive significant advantage from taking up nitrogen from the soil rather than fixing it, experimental evidence would show this, but this has not been the case. Field studies on applying nitrogen fertilizer to soybeans have generally shown small and inconsistent effects on yield (Mourtzinis et al., 2018).

Recent research on diazotroph mutants that overproduce and excrete ammonium has shown promise for promoting plant growth (Rosenblueth et al., 2018).

Another strategy has been to engineer new symbioses between non-legume plants and nitrogen-fixing bacteria. This strategy would involve genetically modifying the plant to release nodulation signals to initiate symbiosis and possibly inoculation with a strain of nitrogen-fixing bacteria that would specifically respond to these signals. One of the main challenges to overcome with this approach is the toxic effect of oxygen in the rhizosphere (Haskett et al., 2022; Mus et al., 2016; Soumare et al., 2020). Additional difficulties include efficient delivery of energy to the bacteria and fixed nitrogen to the plant, as well as the sheer complexity of nitrogen-fixing symbiosis, which requires the coordinated function of more than 30 essential genes (Rogers and Oldroyd, 2014).

An important recent discovery is a variety of tropical corn in Mexico that can derive a significant portion of its nitrogen supply from diazotrophic bacteria that live in the mucilage secreted by aerial brace roots. Corn root cap cells secrete a gel called mucilage that contains carbohydrates, amino acids, and other compounds. This gel plays an important role in forming the interface between the root tissue and soil and interactions with soil microbes. Mucilage secreted by brace roots is often visible as droplets that collect at the tips of roots that have not yet reached the soil (Figure 8).



ENGINEERED N FIXATION IN PLANTS

The most direct solution for bringing biological nitrogen fixation to non-legume crops would seem to be to engineer the necessary genes (known as *nif* genes) into plants so they can do it themselves. After all, engineering bacterial genes into crop plants is something that has already been done, and with great success. Bt corn has been engineered to express a gene from a soil bacterium, *Bacillus thuringiensis*, that produces a protein highly effective for controlling certain insect pests.

Engineering nitrogen fixation into a non-nitrogen-fixing species has also been done. The successful transfer of *nif* genes from a nitrogen-fixing bacterium (*Klebsiella pneumoniae*) to a non-nitrogen-fixing bacterium (*Escherichia coli*) was achieved all the way back in the early 1970s (Dixon and Postgate, 1972), which made scientists hopeful that this could be achieved with more complex organisms like plants. Creating varieties of agriculturally important crops like corn, wheat, and rice capable of fixing their own nitrogen has long been of interest to scientists and remains an ongoing area of research. However, there are a few challenges that make this a particularly difficult problem to solve and that have – so far, at least – kept this goal out of reach.

Nitrogen Fixation is Complex

The first challenge is that nitrogen fixation is not controlled by just one gene – the *nif* pathway is large and involves many genes. The *nif* genes include the genes that code for the two metalloprotein components of nitrogenase, as well as several regulatory proteins involved in nitrogen fixation. Transferring a large gene cluster is difficult enough, but the complexity of the *nif* pathway makes it particularly challenging. In order to engineer nitrogen fixation into plants, scientists would not only have to transfer the genes, but also replicate the cellular components that control the pathway. Adding to this complexity is the fact that prokaryotes such as bacteria organize their genes in a different way than eukaryotes, such as plants, making the transfer of a multigene cluster into the nuclear genome difficult.



Figure 8. A variety of tropical corn in Mexico was recently discovered that can derive a significant portion of its nitrogen supply from diazotrophic bacteria that live in the mucilage secreted by aerial brace roots.

This variety of corn was cultivated using traditional practices with little or no fertilizer, which may have selected for the evolution of unique microbial associations to provide nitrogen to the plants. It tends to develop multiple nodes of aerial brace roots that produce larger than normal amounts of mucilage. Research found multiple taxa of diazotrophic bacteria in the mucilage that were able to produce enough nitrogen to supply 30–80% of the plant's needs. The mucilage provided both the energy and the anaerobic environment necessary for nitrogenase to function (Van Deynze et al., 2018).

Creating varieties of crops like corn capable of fixing nitrogen has long been a dream of plant scientists.



The Oxygen Problem

Nitrogenase is degraded by oxygen – this is an issue that all nitrogen-fixing organisms must deal with but it is especially problematic for photosynthetic organisms like plants where oxygen is produced as a byproduct of photosynthesis. Overcoming this problem requires some means of compartmentalizing the two processes, either physically or temporally, so they are not going on in the same place at the same time.

Organisms that carry out both photosynthesis and nitrogen fixation require some means of compartmentalizing the two processes so they are not going on in the same place at the same time.

There are organisms in nature that can do both – cyanobacteria carry out photosynthesis and many of them also fix nitrogen. One strategy they have evolved to execute both processes successfully is to physically separate the two processes through the development of heterocysts, which are

specialized nitrogen-fixing cells. Heterocysts do not engage in photosynthesis and their unique structure allows them to create an anaerobic internal environment favorable for nitrogenase. The heterocysts supply neighboring cells with nitrogen which, in turn, supply them with energy produced through photosynthesis, creating a sort of division of labor among the cyanobacteria. Other cyanobacteria separate the processes temporally, with nitrogen fixation occurring during the night in the absence of oxygen production from photosynthesis (Berman-Frank et al., 2001). So, it is not impossible for photosynthesizing organisms to fix nitrogen, but it comes with some challenges.

Reasons for Optimism

Although the goal of engineering nitrogen fixation into non-legume crops remains elusive, recent advances in genetic analysis and synthetic biology have enabled significant progress toward this objective. The compilation of a library of thousands of *nif* gene sequences has given scientists a better understanding of the evolutionary history of nitrogenase (Soumare et al., 2020).

A major new scientific discovery reported in 2024 could provide important insights on a potential path toward nitrogen fixation in plants. Nitrogen fixation was thought to only exist in prokaryotes, but the first example

The first example of nitrogen fixation in a eukaryotic organism was discovered in 2024

of nitrogen fixation in a eukaryotic organism was recently discovered in a species of unicellular algae (*Braarudosphaera bigelowii*) (Coale et al., 2024). This species of algae was known to form symbiotic relationships with a nitrogen fixing cyanobacteria called *Candidatus Atelocyanobacterium thalassa*, or UCYN-A. This type of symbiosis, known as endosymbiosis, involved cyanobacteria living inside the algae cells and exchanging fixed nitrogen for fixed carbon from its host.

Scientists found that this relationship had evolved beyond endosymbiosis to the point where UCYN-A was now functioning as an organelle – its division had come under the control of the host organism, and the symbionts were transmitted to the daughter cells during cell division. Chloroplasts and mitochondria in eukaryotic cells are believed to have evolved in the same way – they were originally separate organisms that became endosymbionts and eventually part of the host organism. This newly discovered nitrogen-fixing organelle was given the name nitroplast. This discovery is a significant development in the pursuit of engineering nitrogen fixation into plants because it shows that nitrogen fixation in a eukaryotic organism is indeed possible.



Mary Gumz, Ph.D.,
Agronomy Innovation Leader

Matt Clover, Ph.D.,
Agronomy Innovation
Data Leader

Mark Jeschke, Ph.D.,
Agronomy Manager

UTRISHA® N

NUTRIENT EFFICIENCY BIOSTIMULANT EFFECTS ON SOYBEAN YIELD

KEY FINDINGS

- A study was conducted in 2023 to evaluate the impact of Utrisha® N nutrient efficiency biostimulant on soybean yield.
- Utrisha N treatment significantly increased soybean yield, by an average of 1.1 bu/acre.
- The average yield response to Utrisha N in trials where it was applied in the morning was 1.95 bu/acre, compared to only 0.5 bu/acre with afternoon applications.

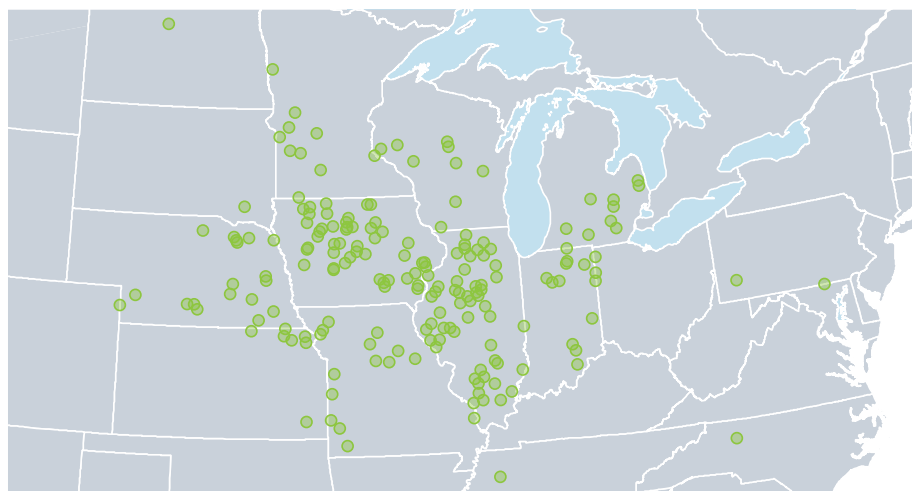


Figure 1. Locations of Utrisha N soybean trials in 2023.

UTRISHA N

- Utrisha® N nutrient efficiency biostimulant is natural bacterium that colonizes plant tissues and fixes nitrogen by converting N_2 from the air into a plant-available form (NH_4^+).
- *Methylobacterium symbioticum*, the active component in Utrisha N is an endophytic bacterium, which means it can live and reproduce in plants without causing damage.
- Methylobacteria are a genus of bacteria that survive and multiply inside the plant by scavenging methanol, which is a byproduct of normal vegetative plant growth released to the atmosphere through the stomata.
- The bacteria use methanol as an energy source and fix atmospheric nitrogen (N_2) into ammonium (NH_4^+) using an enzymatic pathway that is not found in most plants.
- After application to the leaves, the bacteria sense methanol released from the stomata and move towards these openings as entry points into the plant.
- Once in the plant, they continue to multiply and scavenge methanol produced in active growth regions.

2023 ON-FARM TRIALS

- Soybeans have a high demand for nitrogen due to their high seed protein content, which is typically met through a combination of uptake from the soil and fixation by rhizobial bacteria that colonize nodules on the roots.
- A study was conducted in 2023 to evaluate the potential of Utrisha N to increase soybean yield by providing an additional source of nitrogen to the plant.
- On-farm trials were conducted at 233 locations across the U.S. Corn Belt (Figure 1).
- Each field in the study included a treated area and non-treated area to determine yield response to application of Utrisha N.
- Utrisha N was applied at either the V4-V8 or R1-R3 stage.

RESULTS

- Utrisha N treatment significantly increased soybean yield, by an average of 1.1 bu/acre across all locations (Figure 2).

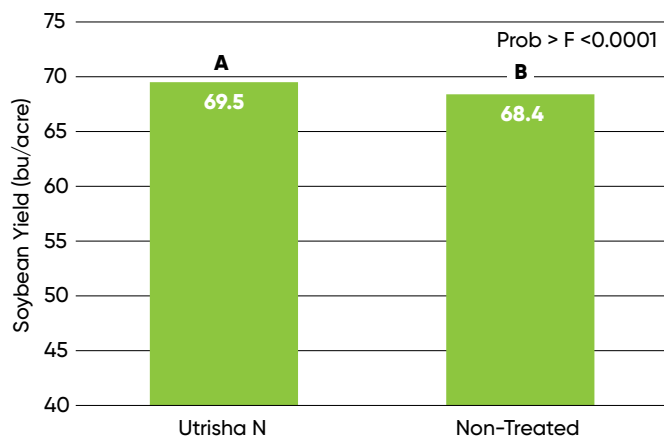


Figure 2. Average yield of soybean treated with Utrisha N and non-treated soybean across 233 on-farm trials in 2023.

Application Time of Day

- The time of day at which Utrisha N is applied could impact its efficacy due to the manner in which *M. symbioticum* colonizes the plant – through the stomata on the leaves.
- Stomatal conductance typically reaches its maximum during the late-morning hours and decreases into the afternoon as rising temperatures increase the vapor pressure deficit and the stomata close to help the plant conserve water.
- Consequently, applications made prior to the late-morning peak of stomatal conductance should allow more bacteria to successfully enter and colonize the plant.
- The 2023 on-farm trials provided an opportunity to look for trends in yield response based on application time of day because of the large number of trials and a relatively even split between morning and afternoon applications.
- Of the 83 trials that reported application timing, 36 were prior to 11:00 a.m. and 40 were between 11:00 a.m. and 4:00 p.m.
- The average yield response to Utrisha® N in trials where it was applied in the morning was 1.95 bu/acre, compared to only 0.5 bu/acre with afternoon applications (Figure 3), suggesting that application timing could indeed have an important effect on efficacy and yield response.

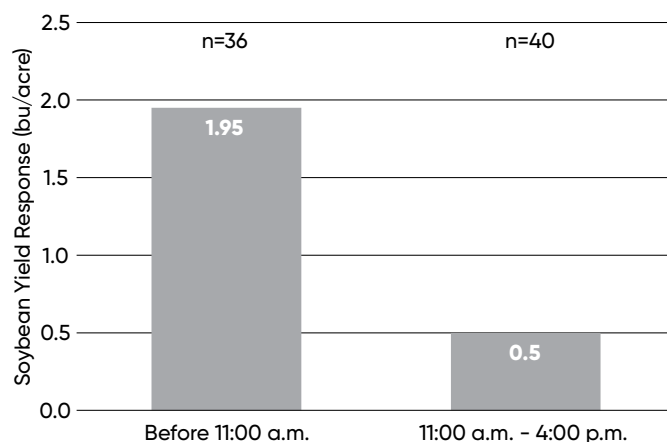
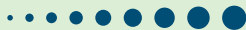


Figure 3. Average yield response of soybeans to Utrisha N across locations where applications were done in the morning compared to applications in the afternoon.



Matt Essick, M.S.,
Agronomy Innovation Leader

Matt Clover, Ph.D.,
Agronomy Innovation
Data Leader

Mark Jeschke, Ph.D.,
Agronomy Manager

EFFECTS OF UTRISHA® P MICROBIAL BIOSTIMULANT ON CORN YIELD

KEY FINDINGS

- A study was conducted in 2023 to evaluate the impact of Utrisha® P microbial biostimulant on corn yield.
- Utrisha P treatment significantly increased corn yield, by an average of 2.3 bu/acre across 33 locations.
- Yield response tended to be greater at locations where phosphorus availability could be limited by soil factors such as high clay content or soil pH outside the range for maximum phosphorus solubility.

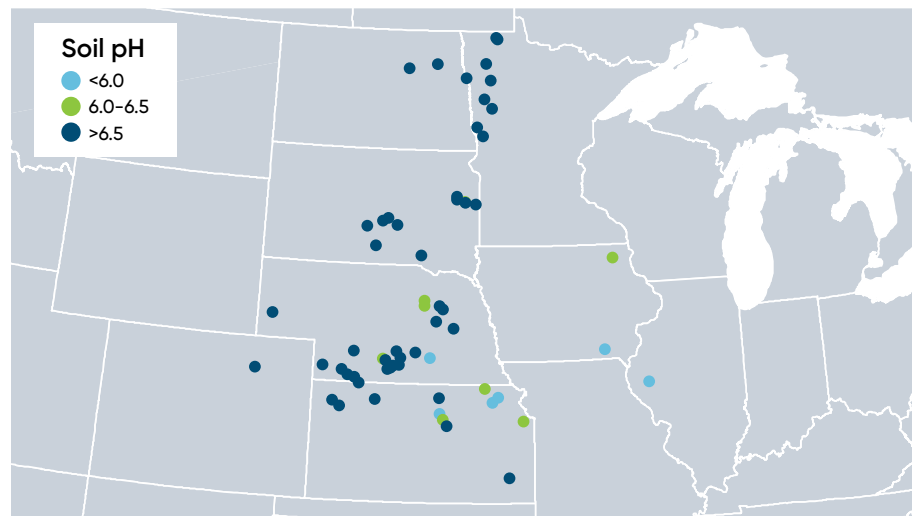


Figure 1. Locations of 2023 Utrisha P on-farm trials and soil pH of fields.

UTRISHA P

- Utrisha P is a microbial biostimulant that helps release soil-bound phosphorus (P) for plant uptake.
- The majority of P in the soil is not available for plant uptake – it is contained in organic compounds and P minerals, or it is adsorbed to clay particles.
- The active ingredient in Utrisha P, *Bacillus amyloliquefaciens* FZB45, is a phosphate solubilizing bacteria that colonizes plant roots and produces compounds that increase the availability of P for plant uptake:
 - Organic acids – (citric acid, acetic acid, lactic acid) lower the soil pH in the area around the roots, increasing the solubility of P bound to calcium
 - Phosphatase enzymes – solubilize organic P molecules into plant-available organic forms
 - Chelators – siderophores that degrade iron-phosphate compounds by chelating iron
- Utrisha P is applied in-furrow at planting at a rate of 3.5–7.0 fl oz/acre with either a starter fertilizer or water.
- Utrisha P is likely to provide the greatest value in soils where P availability is limited, such as high clay soils or soils outside the ideal pH range for P solubility.

2023 ON-FARM TRIALS

- A study was conducted in 2023 to evaluate the impact of Utrisha P on corn yield.
- On-farm trials were conducted at 33 locations, primarily in the western portion of the U.S. Corn Belt where soil pH levels tend to be higher (Figure 1).
- Each field in the study included a treated area and untreated area to determine yield response to application of Utrisha P.

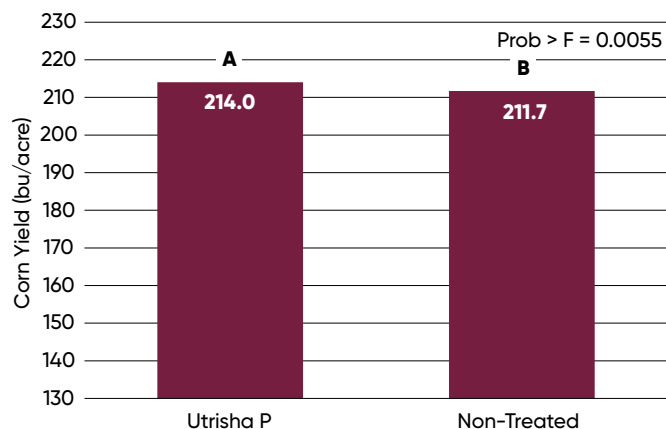


Figure 2. Average yield of corn treated with Utrisha P and non-treated corn across 33 on-farm trials in 2023.

RESULTS

- Utrisha P treatment significantly increased corn yield, by an average of 2.3 bu/acre across all locations (Figure 2).

Impact of Soil pH

- The soil pH range of minimum P absorption and maximum P solubility is 6.0 to 6.5 (Havlin et al., 1999).
- At pH levels above this range, P solubility decreases as fixation by calcium increases (Figure 3).

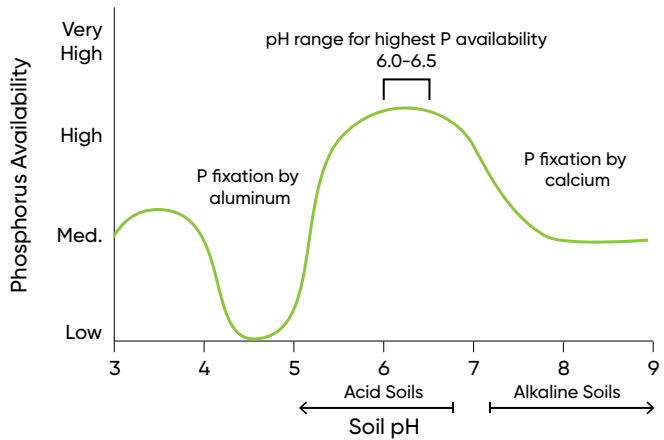


Figure 3. The effect of soil pH on phosphorus availability.

- Utrisha P would be expected to have a greater yield impact in soils with a pH outside the range of highest P availability.
- Yield results generally conformed to expectations based on soil pH of trial locations (Figure 4); however, the vast majority of locations in this study fell within the upper pH range, with relatively few locations represented in the lower and middle range. Further research is needed to refine performance expectations for Utrisha P based on soil pH.

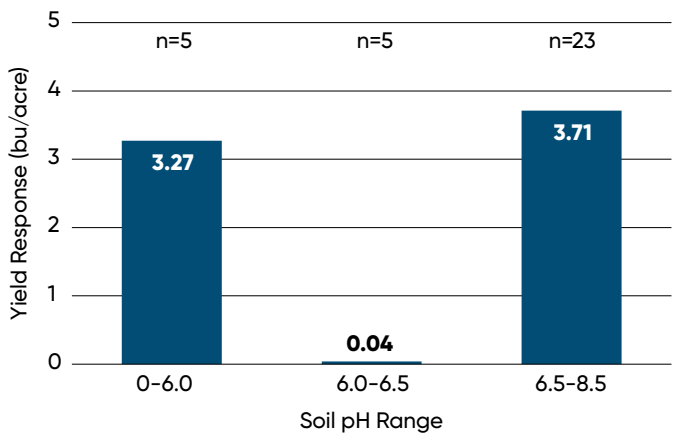


Figure 4. Corn yield response to Utrisha P treatment by soil pH range.



Soil Clay Content

- Utrisha P could potentially have greater value in soils with a high clay content.
- As the amount of clay in the soil increases, sorption capacity increases as well. Clay particles have a large amount of surface area where phosphate sorption can take place, which can reduce the amount of solution P available for plant uptake (Havlin et al., 1999).
- By increasing availability of P from organic matter and secondary minerals, Utrisha P could help offset lower solution P due to higher adsorption by clay.
- Comparing yield response to Utrisha P between trial locations with higher and lower soil clay content showed that higher clay locations did have a higher average yield response (Figure 5); however, the magnitude and consistency of difference that could be expected generally is not certain based on the limited number of locations in this study.

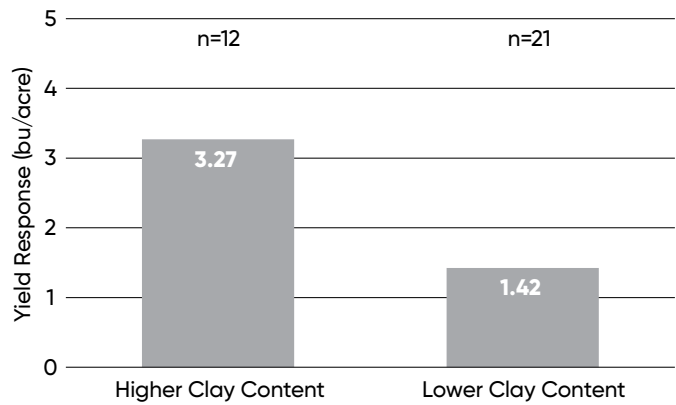


Figure 5. Corn yield response to Utrisha P treatment by soil clay content. (Lower clay content = ~0-30% clay; higher clay content = ~30-60% clay.)

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Matt Clover, Ph.D.,
Agronomy Innovation
Data Leader

Mark Jeschke, Ph.D.,
Agronomy Manager

EFFECTS OF SOSDIA® STRESS ABIOTIC STRESS MITIGATOR ON CORN YIELD

KEY FINDINGS

- A study was conducted in 2023 to evaluate the impact of Sosdia® Stress abiotic stress mitigator on corn yield.
- Treatment with Sosdia Stress significantly increased corn yield, by an average of 1.3 bu/acre.
- Applications during early reproductive stages (VT-R2) showed the greatest yield benefit, with an average yield response of 3.0 bu/acre.

SOSDIA® STRESS ABIOTIC STRESS MITIGATOR

- Sosdia Stress is an abiotic stress mitigator that helps reduce yield loss associated with stressful conditions.
- The active ingredient in Sosdia Stress is proline, an amino acid produced naturally by plants in response to abiotic stress such as drought, heat, and salinity.
- Proline helps plant cells protect against damage and maintain function during periods of stress in multiple ways, including balancing osmotic pressure, stabilizing proteins and membranes, and protecting against damage from reactive oxygen species.

- Research has shown that application of proline to corn can help induce tolerance to stress, resulting in enhanced antioxidant activity, reduced water loss, and better growth performance during periods of environmental stress (Ali et al., 2007; Mosaad et al., 2020; Ibrahim et al., 2022).
- Sosdia Stress abiotic stress mitigator can provide up to three weeks of stress mitigation.
- In corn, application at the VT growth stage is likely to provide the greatest benefit by increasing stress resilience during grain fill.

2023 ON-FARM TRIALS

- A study was conducted in 2023 to evaluate the impact of Sosdia Stress on corn yield.
- On-farm trials were conducted at 129 locations across the U.S. Corn Belt (Figure 1).
- Trial fields were split between treated and non-treated areas with a 30-60 ft harvest buffer in between.
- Application timings varied across locations, from mid vegetative stages (V5-V8) to grain fill stages (R3-R6).
- Drought was widespread in summer of 2023 and most of the study fields experienced some degree of drought stress during the growing season (Figure 1).

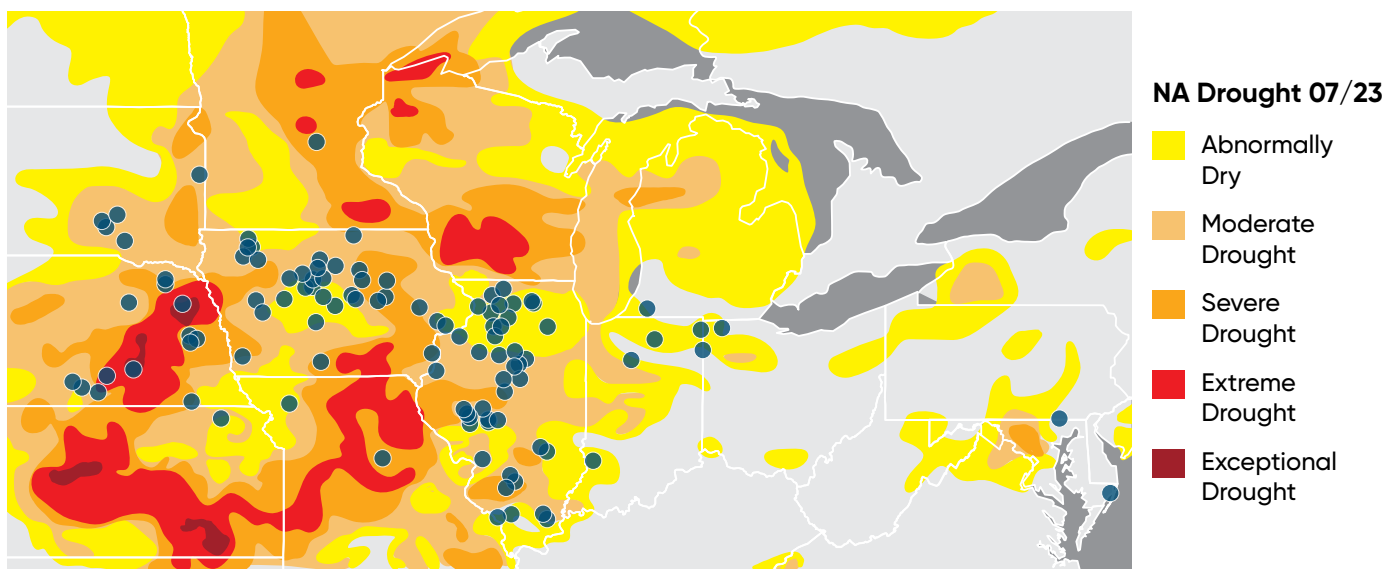


Figure 1. Locations of Sosdia Stress abiotic stress mitigator on-farm trials in 2023 and drought severity as of July 23, 2023. Nearly all trial locations were impacted by some degree of drought stress during the growing season.

RESULTS

- Treatment with Sosdia® Stress significantly increased corn yield, by an average of 1.3 bu/acre across all locations (Figure 2).

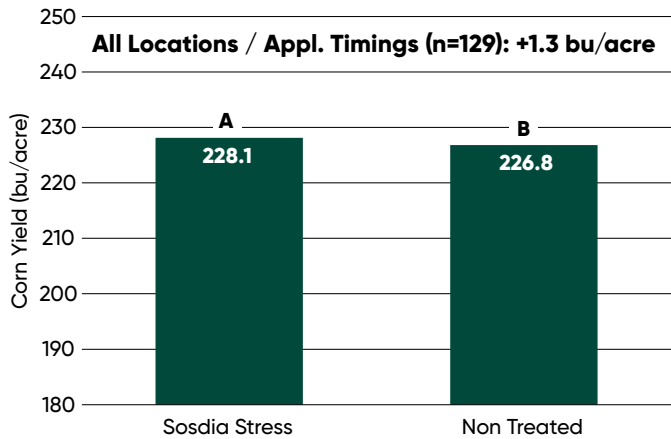


Figure 2. Sosdia Stress abiotic stress mitigator effect on corn yield across all locations and application timings (Prob. > F = 0.0103).



Application Timing

- Application timing appeared to be of key importance in affecting yield outcome.
- Sosdia Stress provides up to three weeks of stress mitigation, so yield impact will depend on application timing relative to stress incidence and corn growth stage.
- In general, the greatest benefit would be expected in corn with an application around VT in corn experiencing drought stress during the reproductive growth stages, which is the most critical period for yield.
- The 2023 study included 32 locations where applications were made between V5 and V8 and 35 locations with applications between VT and R2.
- Vegetative stage applications did not show a yield benefit in this study; however, applications during early reproductive stages increased yield by an average of 3.0 bu/acre (Figure 3).

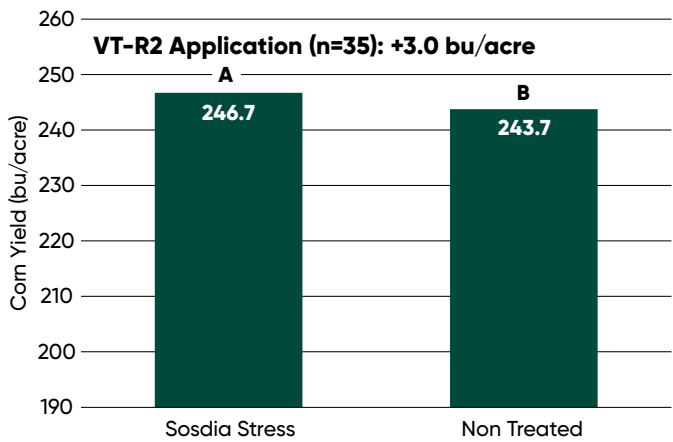


Figure 3. Sosdia Stress abiotic stress mitigator effect on corn yield when applied between the VT and R2 growth stages (Prob. > F = 0.0018).

CHARACTERIZATION OF DEOXYNIVALENOL ACCUMULATION IN CORN HYBRIDS

Southwestern Ontario 2022-2023

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Sheila Murphy,
Technical Services Manager

KEY FINDINGS

- Grain samples were taken from Pioneer Product Knowledge Plots (PKPs) across southwestern Ontario in 2022 and 2023 and tested for deoxynivalenol (DON).
- DON accumulation in corn is a complex biological process influenced by the host, environment, and disease.
- Hybrid results in this study were consistent with both anecdotal and research experience, where hybrids with a *Gibberella* ear rot trait score of 4 or less tended to have higher levels of DON.

GIBBERELLA EAR ROT OF CORN

- *Gibberella* ear rot is caused by the fungus *Gibberella zeae*.
- Spores of the fungus are produced on crop residue and spread to corn ears by wind and splashing rain.
- Infection of corn ears occurs through young silks and disease progression is favored by humid weather during and after pollination.
- *Gibberella* ear rot can be most readily identified by the red or pink color of the mold.
- *Gibberella zeae* produces the mycotoxin deoxynivalenol (DON), also called vomitoxin. DON causes feed refusal and poor weight gain in livestock.

STUDY DESCRIPTION

- Grain samples were taken from Pioneer Product Knowledge Plots (PKPs) across southwestern Ontario in 2022 and 2023.
- 2,396 grain corn samples were evaluated for DON content across 290 locations throughout southwestern Ontario representing 162 corn hybrids, which included 52 Pioneer® brand corn products.
- Grain submissions were subsampled, dried, ground, and run on an automated ELISA machine for analysis. DON results were validated and reported in ppm on a dry matter basis.

RESULTS

Location Results

- Figures 1 and 2 show the location means at sampled locations across Southwestern Ontario in 2022 and 2023, respectively, where location mean DON level was greater than 0.25 ppm.

- Disease severity in 2022 was low overall, but individual fields were still moderately affected by *Gibberella* ear rot. The mean location average was 1.56 ppm, and the highest location average was 9.4 ppm. The highest reported DON across all locations and hybrids was 17.8 ppm.
- Disease incidence and severity of *Gibberella* ear rot in 2023 was higher. The mean location average in 2023 was 2.9 ppm. The highest location average was 10.2 ppm, while the highest reported DON across all locations and hybrids was 30.2 ppm.

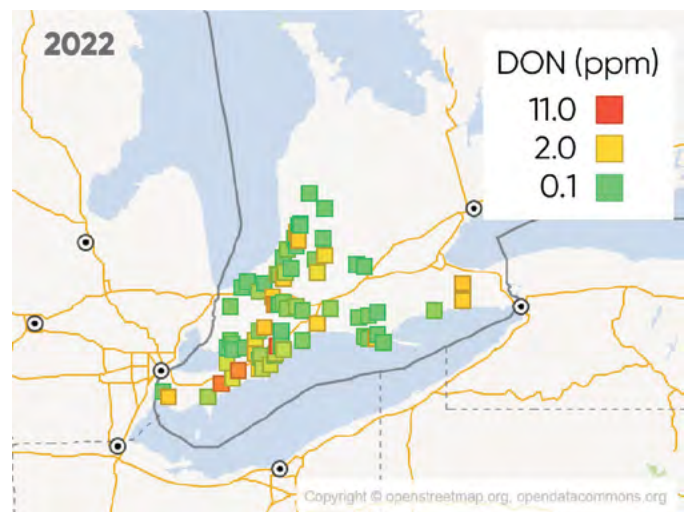


Figure 1. Location mean DON levels (ppm) at 2022 sampling sites.

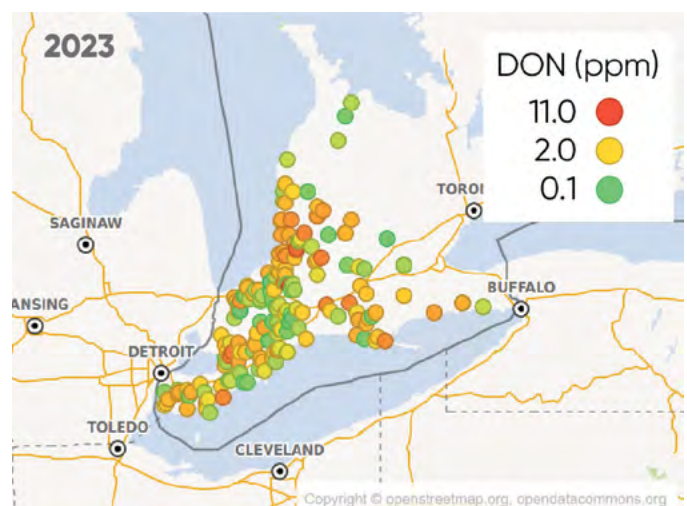


Figure 2. Location mean DON levels (ppm) at 2023 sampling sites.

Table 1. Average DON level by corn hybrid as a percentage of location mean across 2022 and 2023 sampling sites, total number of locations sampled, and hybrid Gibberella ear rot trait score.

Pioneer Brand Product ¹	DON Average (% of location mean)	n	Gibberella Trait Score (1-9)
P0075 _G ™ (Q,LL,RR2)	41.4%	88	6
P0306 _G ™ (Q,LL,RR2)	48.0%	9	4
P0035 _G ™ (Q,LL,RR2)	48.2%	161	5
P9624 _G ™ (Q,LL,RR2)	48.7%	51	7
P9233 _G ™ (Q,LL,RR2)	51.8%	15	5
P0806 _{AM} ™ (AM,LL,RR2)	52.0%	65	4
P9823 _G ™ (Q,LL,RR2)	54.9%	94	5
P0720 _G ™ (Q,LL,RR2)	59.0%	85	4
P9316 _G ™ (Q,LL,RR2)	63.7%	16	6
P0075 _{AM} ™ (AM,LL,RR2)	67.2%	67	6
P9998 _G ™ (Q,LL,RR2)	68.6%	5	4
P9845 _{AM} ™ (AM,LL,RR2)	72.5%	44	4
P0404 _{AM} ™ (AM,LL,RR2)	73.9%	33	5
P0506 _{AM} ™ (AM,LL,RR2)	74.0%	17	5
P0157 _{AMXT} ™ (AMXT,LL,RR2)	78.9%	10	4
P0035 _{AM} ™ (AM,LL,RR2)	80.4%	66	5
P0306 _{AM} ™ (AM,LL,RR2)	83.3%	10	4
P1136 _{AM} ™ (AM,LL,RR2)	84.2%	22	6
P87040 _{AM} ™ (AM,LL,RR2)	84.3%	4	
P9466 _{AML} ™ (AML,LL,RR2)	84.7%	43	5
P0404 _G ™ (Q,LL,RR2)	85.4%	79	5
P0529 _G ™ (Q,LL,RR2)	87.5%	161	5
P9026 _{AM} ™ (AM,LL,RR2)	107.1%	14	
P9845 _{PCE} ™ (PW,ENL,RIB)	112.2%	45	4
P9946 _{AML} ™ (AML,LL,RR2)	121.3%	13	6
P04511 _{AM} ™ (AM,LL,RR2)	124.1%	97	4
P9535 _{AM} ™ (AM,LL,RR2)	126.4%	33	4
P0720 _{AM} ™ (AM,LL,RR2)	127.9%	43	4
P0859 _{AM} ™ (AM,LL,RR2)	139.0%	41	3
P04922 _G ™ (Q,LL,RR2)	143.8%	70	3
P97299 _{AM} ™ (AM,LL,RR2)	164.6%	63	3
P9998 _{AM} ™ (AM,LL,RR2)	185.2%	5	4
P1197 _{AM} ™ (AM,LL,RR2)	215.5%	6	5
P0953 _{AM} ™ (AM,LL,RR2)	235.5%	56	3
P0487 _G ™ (Q,LL,RR2)	236.3%	72	3
P8859 _{AM} ™ (AM,LL,RR2)	242.5%	4	

¹All Pioneer products are hybrids unless designated with AM, AML, AMT, AMX, AMXT, Q, V, PCE, PCUE, PWE & PWUE, in which case they are brands.

Hybrid Results

- Across years, 162 unique hybrids were evaluated. Results are reported for 36 Pioneer® brand corn products for which more than four samples were collected. DON accumulation is reported for each hybrid as a percent of the location mean. (Table 1).



Figure 3. *Gibberella zeae*, the fungal pathogen that causes Gibberella ear rot, can produce the mycotoxin deoxynivalenol (DON). Gibberella ear rot can be most readily identified by the red or pink color of the mold.

- Across years, DON accumulation by hybrid – as a percentage of the location average – ranged from 41% to 243%.
- The results, expressed as a percentage of the location average, provide an indication of relative risk of DON accumulation under 2022 and 2023 environmental conditions. In many cases, hybrids that had above-average DON levels relative to the location average were still low in absolute terms.
- Pioneer brand corn products are rated for genetic resistance to Gibberella ear rot. Each rating is backed by thousands of research hours and on-farm trials. Trait scores range from 1 (most susceptible) to 9 (most resistant).
- Trait scores for Gibberella ear rot range from 3 to 7 for current Pioneer brand corn products, illustrating that – while there is no complete resistance for Gibberella ear rot – significant genetic differences do exist.
- Hybrid results in this study were consistent with both anecdotal and research experience, where hybrids with a Gibberella ear rot trait score of 4 or less tended to have higher levels of DON.

CONCLUSION

- DON accumulation in corn is a complex biological process influenced by the host, environment, and disease.
- The results of this evaluation support that, while no complete resistance exists for Gibberella ear rot, there are genetic mechanisms of tolerance to the disease in corn. Hybrids respond differently to infection by Gibberella ear rot and resulting DON accumulation.
- Understanding a hybrid's relative risk of infection and DON accumulation is important to manage the risk on your farm. Working closely with your Pioneer agency will allow you to select products as part of a package that will enable you manage risk of DON specific to your operation.
- Your Pioneer sales agency has the knowledge, including the PKP DON database, and experience to use the Pioneer product scores to help position products on your fields.



Dann Bolinger, M.S.,
Dairy Specialist

Special thanks to field trial cooperators Double
Eagle Dairy, Inc. and Countrywide Agricultural
Services, LLC, both of Middleton, Michigan.

CORN SILAGE PERSPECTIVE ON FOLIAR FUNGICIDE UTILIZATION

The merits of fungicide application for reducing negative impacts caused by foliar disease on corn grain yield are growing in appreciation. Based upon controlled research, field trials, and anecdotal observations, a variety of recommendations have been developed for if and when a fungicide should be applied to corn. Scout-and-spray and brown silk applications are among the most common practices. With corn for silage having critically important parameters beyond the considerations for mature grain, there is less certainty whether the recommendations for grain should also be the recommendations for whole plant corn silage.

INTERVAL HARVESTED FIELD TRIALS

Field trials were conducted from 2021–2023 in central Michigan with the objective of evaluating the merits of fungicide use on corn for silage. All foliar fungicide treatments were application of Aproach® Prima™ at R1 (green silk). Each treatment had 3–5 harvest dates, typically at 3–4 day intervals. Multiple harvest dates were leveraged to address changes in physiological maturity and health status through the harvest window. These changes would be expected to cause variation in yield and quality results relative to harvest timing. Trend lines for each scenario and treatment provided a more informed interpretation of the results.

Each of four site-years provided unique foliar disease scenarios:

- No Disease Pressure (NDP): 2022, high plant health hybrid, irrigated, no visible evidence of disease from plant to harvest.
- Late Disease Pressure (LDP): 2023, high plant health hybrid, irrigated, no visible evidence of disease until rapid onset of anthracnose and fusarium crown rot pre-harvest.
- Moderate Disease Pressure (MDP): 2021, high plant health hybrid with good tar spot resistance, irrigated/minimal drought stress followed by optimal tar spot infection conditions.
- High Disease Pressure (HDP): 2021, tar spot susceptible hybrid under significant drought stress followed by optimal tar spot infection conditions.

As a thumb rule each +1%DM a healthy plant increases as it physiologically matures, it will add:

+0.3 Tons/A@35%DM (equates to +5 bu/acre of grain);

+0.6 %Starch in feed analysis; -0.2 %NDFD30

YIELD RESPONSE

Positive yield responses were observed across all scenarios when averaged across harvest dates (Figure 1). Not surprisingly, the magnitude of yield increase was greatest for the HDP and MDP. LDP and NDP showed more modest yield responses, but approximately enough to cover application costs. In 3 of 4 scenarios, yield response to fungicide increased as the crop was allowed to mature in the field (Figure 2).

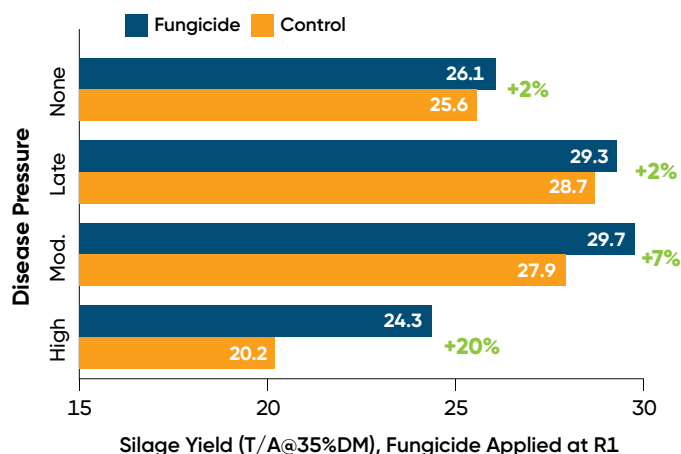


Figure 1. Average silage yields across all harvest dates within each disease pressure scenario (NDP n=5, LDP n=4, MDP n=4, HDP n=3).

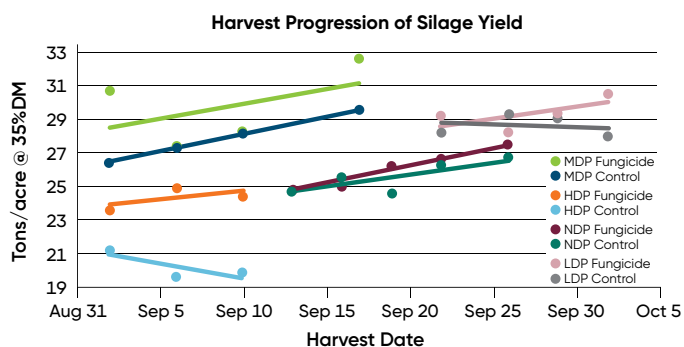


Figure 2. Silage yields by harvest dates within each disease pressure scenario (NDP n=5, LDP n=4, MDP n=4, HDP n=3).

SILAGE QUALITY OBSERVATIONS

Starch (%Starch of DM) and Fiber Digestibility (NDFD30) effects were less obvious (data not shown). The only discernable quality enhancement associated with fungicide was under the HDP scenario. In HDP, the control plants were completely dead at half milk line with arrested starch deposition and rapid loss of digestible fiber due to necrosis. It is logical to conclude that the measured yield responses were driven by added starch and greater preservation of fiber. However,

laboratory analyses did not detect a consistent feed quality difference. Fungicide is generally believed to enhance plant health, independent of disease pressure. A separate trial (Figure 3) observed that healthier plants tend to lose fiber digestibility more slowly through the harvest window than less healthy plants.

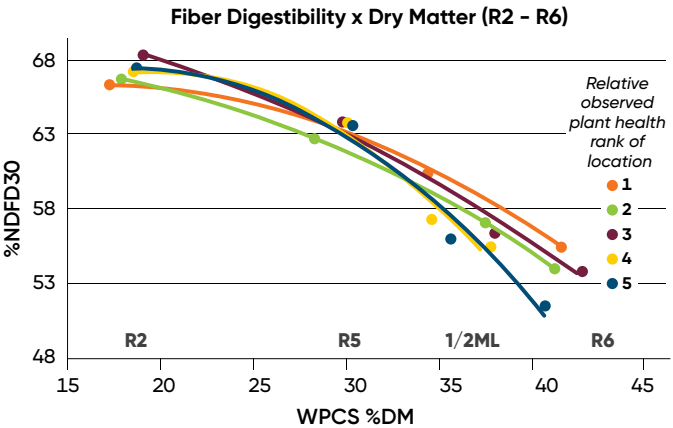


Figure 3. Location averages of whole plant corn silage dry matter (WPCS%DM) by 30 hour fiber digestibility (%NDFD30) from R2 (brown silk/blister) through R6 (black layer) of replicated hybrids (n=5) ranked by relative plant health at each location: 1 = healthiest location, 5 = least healthy location. (Pioneer, Michigan 2021)

WIDENING THE HARVEST WINDOW

A common reservation to applying fungicide to corn intended for silage is the perception that it will delay harvest. In all four disease pressure scenarios, fungicide did not delay entry into the harvest window (~32%DM WPCS) (Figure 4). Fungicide better maintained plant health, thereby slowing moisture loss through the harvest window when noteworthy disease pressure was present. This resulted in an expansion of the days within the harvest window (between 32%DM and 42%DM) by as much as 2X. The potential advantages to this impact on whole plant dry down include:

1. A more forgiving harvest window, with more days of opportunity to harvest within target WPCS dry matter range.
2. Greater opportunity to further mature the kernels capturing significantly more yield and starch with minimal sacrifice of fiber digestibility.

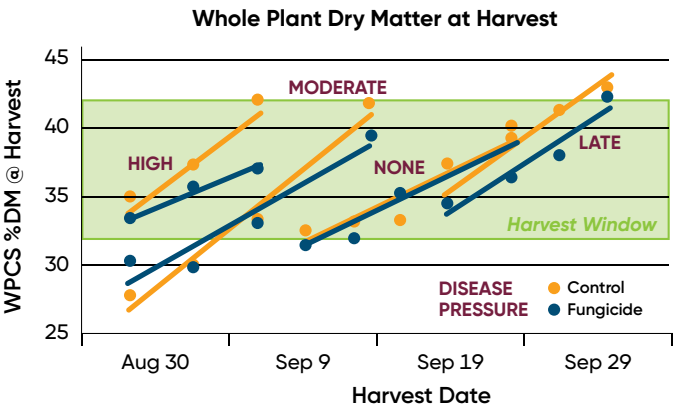


Figure 4. Whole plant dry matter changes across interval harvests, by treatment and disease pressure scenarios (NDF n=5, LDP n=4, MDP n=4, HDP n=3).

FUNGICIDE APPLICATION TIMING CONSIDERATIONS

In order to protect plant health for optimizing whole plant dry matter and maximizing yield potential, it is important to have foliar disease protection up to harvest initiation. This suggests an option of fungicide application as close to harvest as the preharvest interval allows. A scout-and-spray approach to fungicide application may make sense in response to later introduction of disease pressure. However, this approach has limitations in silage corn. While a later, e.g., brown silk, application with a scout-and-spray approach may provide similar results to the R1 application timing represented in this data, the later timing may not be ideal for providing continuous preharvest protection.

A unique consideration for corn intended for silage is the application preharvest interval (PHI). Foliar fungicide products may require a waiting period of 3 or 4 weeks (+/-) post-application before the crop may be harvested for silage. It is also typical to have residual fungicide protection for a 3-4 week period before an additional application would be necessary to extend foliar disease protection. (Consult product label for specific PHI, and any necessary waiting period between applications.) Working backwards from harvest, four weeks preharvest is likely during R4 (dough) stage of maturity, which is considerably later than R2 (brown silk/blister) timing more commonly recommended for grain corn. Another three weeks earlier places an application at VT/R1 (tassel/silk). This logic supports a VT/R1 application followed by a scout-n-spray second application as needed approximately four weeks prior to anticipated harvest (Figure 5).

Corn Silage Fungicide Strategies

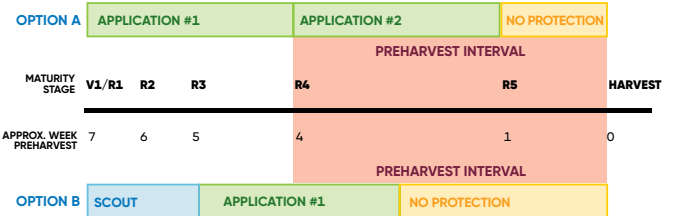


Figure 5. Potential fungicide application strategies with example residual and preharvest intervals. Consult product labels for product-specific interval guidance.

SUMMARY

Foliar fungicide utilization on corn for silage enhances plant health with the benefit of increased yield, even in the absence of visible foliar disease. The harvest window is also extended when disease becomes a factor.

Application timing should consider the preharvest interval of the specified fungicide to ensure opportunity for maximum time with fungicide residual efficacy. Due to the implications of plant health stretching beyond grain yield and late season stalk integrity, foliar fungicides may be more valuable in corn silage production than has been demonstrated in corn grain.



Nelson Lobos, Ph.D.,
Nutritionist

Adam Krull, DVM, Ph.D.,
Senior Nutritionist
and Veterinarian

FEEDING PLENISH® HIGH OLEIC SOYBEANS

WHY INCLUDE PLENISH® HIGH OLEIC SOYBEANS IN DAIRY DIETS?

Pioneer® brand Plenish® high oleic soybeans can be incorporated into dairy diets as a source of energy and protein in place of other commodities. The oleic fatty acid in Plenish soybeans does not have the same level of risk for causing milk fat depression (MFD) as does the linoleic acid in commodity soybeans. Oleic acid has also been shown to increase the digestibility of other dietary fatty acids. Depending upon dietary needs, Plenish soybeans can be fed in all stages of lactation but likely have most benefit to energy-deficit transition and high-producing cows. They can also be fed year round and may help minimize declines in milk fat typically seen in hot weather.

TYPICAL DIETARY INCLUSION LEVELS

Most dairies/nutritionists are feeding an average of 4–5 lbs of full fat Plenish soybeans/cow/day but can range from 2 to 10 lbs. Positive effects at even higher levels have been observed in research studies, while lower inclusion levels may not yield noticeable results. Inclusion rates depend upon individual herd dietary needs as well as availability, local commodity prices, any premiums required to grow Plenish soybeans, and cost of transportation, processing, and storage.

TYPICAL RESPONSES TO DIETARY INCLUSION

Field reported responses include increased milk fat, increased milk volume, and potentially increased milk protein. Herds that respond in milk fat typically see the response in about a week; those that respond in milk volume due to the energy provided see an almost immediate overnight response and herds that see a protein response typically observe the impact within 2–3 weeks.

The most predictable response comes from removing/diluting linoleic acid in the diet. Research has shown that milk fat % is increased by about 0.2% units for every 100g/day reduction in dietary linoleic acid.

Depending on the base diet and individual herd nutritive requirements, positive cow responses have also been observed without changing linoleic acid levels due to the increased energy supplied from the soybean oil and/or the rumen undegradable protein (RUP, bypass protein) gained from the roasting process.



FEEDING RESPONSE RANGE

The range in feeding responses is likely due to the nutritive profile of the original diet benefitting from what Plenish soybeans can provide (other than high oleic acid). This may be from providing additional (oil) energy or filling a gap in certain amino acids. Other factors may be how the Plenish soybeans were processed on different farms (not over or under-roasted) and/or differences in particle size when fed (ranging from 300 microns to over 1000 microns).

Some herds have seen responses increase over time due to cows maintaining better body condition, peaking higher, and/or maintaining more persistent lactation curves. When a cow response is less noticeable, it is frequently associated with diets that previously included more expensive ingredients of which Plenish may offer a lower cost alternative. It is difficult to have a valid controlled, on-farm comparison so it is important to work with a nutritionist to identify other factors that may influence a feeding response.

OTHER BENEFITS OF PLENISH SOYBEANS

Locally grown and locally sourced Plenish soybeans provide a reliable source of high-quality fat and protein to dairy farms. Like all commodities, they may have periods where they may not be the most least cost ingredient, but they can still offer a unique and substantial nutritional value. Beyond cost savings and cow production responses, increasing oleic acid in the diet has been proven to improve body condition, reproductive efficiency, and even immunity. Further, planting Plenish soybeans can have agronomic benefits such as breaking the corn rootworm cycle in corn-on-corn acres and providing nitrogen credits for the following crop year.

PLENISH SOYBEANS & FARM PROFITABILITY

Profitability may be improved beyond any positive cow response simply due to the lowering of ration costs by removing/reducing more expensive commodities such as palm fat and/or blood meal. The profitability of feeding Plenish soybeans depends on whether dairies are growing their own beans (valued at the cost of production versus opportunity cost) or if a premium is required should they be sourced from neighboring farmers. Other factors may include cost of infrastructure needed for on-farm handling, trucking, processing (roasting), and storage. If feeding as Plenish expeller meal, the availability, price, and transportation costs need to be considered.

EXPELLER MEAL FROM PLENISH BEANS

Expeller meal derived from Plenish soybeans may be available in certain geographic locations. It differs from feeding full fat soybeans in that approximately 2/3 of the oil has been removed leaving a product that is lower in energy but higher in percent protein. Depending upon each dairy's need for fat and protein, both Plenish soybeans or expeller meal may fit the diet.

GRINDING RECOMMENDATIONS

There is limited published data on recommended grind size for feeding Plenish soybeans, but recent University trials have ground beans to around 800 microns. Field surveys indicate some dairies feeding a coarser grind (>1000 microns) while others grind very fine (300 microns). It has been historically recommended not to fine grind commodity soybeans as the linoleic acid could lead to ruminal upsets and milk fat depression. Dairies feeding fine ground Plenish soybeans do not report these problems; however, fine grinding will decrease RUP, reducing the benefits of proper roasting given that small particle proteins are more likely to degrade rapidly in the rumen than larger-particle proteins.

ROASTING RECOMMENDATIONS

While feeding raw Plenish soybeans is possible and being implemented on some dairies, the protein in raw soybeans is highly soluble and readily degraded by rumen microbes, thus increasing ammonia levels in the rumen, blood, and milk and reducing the potential supply of dietary RUP.

The primary benefits for roasting soybeans are to improve RUP of the protein and remove anti-nutritional factors such as urease or trypsin inhibitor and typically outweigh the cost associated with roasting. If fed raw, care must be taken to remove urea from the diet as raw soybeans contain active urease. Under-roasting may lead to lower RUP levels and not fully inactivate urease. Over-roasting can irreversibly damage and destroy temperature-sensitive amino acids such as lysine.

For those wanting to feed full fat, roasted soybeans, there are several commercial companies that roast on-site and provide a very consistent product. On-farm roasting is also quite common and can be done successfully, although consistency may be less than commercial facilities, which blend batches of beans, dry them to a common moisture, and process under more consistent ambient temperatures. Steeping time and temperature are also very important to the success/quality of roasting and is more difficult to manage on-farm.

Stationary oil-jacketed, on-farm roasters tend to provide a more predictable roast but have slower throughput and require significant infrastructure to run autonomously 24 hours/day. In contrast, mobile propane roasters can dramatically increase throughput and require minimal infrastructure costs although they may not produce as consistent results as stationary roasters.

The industry today relies on PDI (Protein Dispersibility Index) as a readily available laboratory method that measures the solubility of feed ingredients. The protein in soybeans is highly soluble, and this solubility will decrease with heat exposure from roasting and steeping. A general thumb rule is a PDI value of 9-12% corresponds with high RUP without over-roasting, while a PDI above 14% is considered underheated and RUP can be greatly reduced.



WHAT ABOUT SHRINK LOSSES?

Calculating shrink from harvested to the final product entering the diet is very important to fully understand the economic viability of feeding Plenish soybeans. Roasting soybeans will significantly lower the moisture content from 13-15% down to 4-6%. This change needs to be accounted for when buying/selling soybeans and when determining inventory needs.

While both open-flame roasters and oil-jacketed roasters can effectively roast soybeans, open-flame roasters typically result in higher dry matter loss due to burnt soybean hulls.

Dry matter loss will also occur in all storage and feeding facilities, from equipment handling, facility design (open bay vs. bin), and exposure to the elements (open vs. enclosed).

PLANTING DATE EFFECTS ON SOYBEAN GROWTH AND YIELD

Mark Jeschke, Ph.D.,
Agronomy Manager

in the Southern U.S.

KEY POINTS

- Timely planting of soybeans in the Southern U.S. can help maximize yield potential and reduce the risk of lodging.
- A Mississippi State Study found that soybean planted in mid- to late April had the greatest yield potential and did not grow as tall as soybeans planted later.
- A Pioneer field study found that April planting significantly increased yield and reduced lodging compared to May planting.

SOYBEAN PLANTING DATES IN THE SOUTHERN U.S.

Early Soybean Production System

- As soybean production has increased in the Southern U.S. over the past 20 years, the range of planting dates has expanded as well, extending from late March through late June
- The Early Soybean Production System (ESPS), developed primarily in the southern states of Arkansas, Mississippi, and Louisiana, is a system that utilizes mid- to late-Maturity Group (MG) 4 soybean varieties planted in mid- to late April to maximize yields.

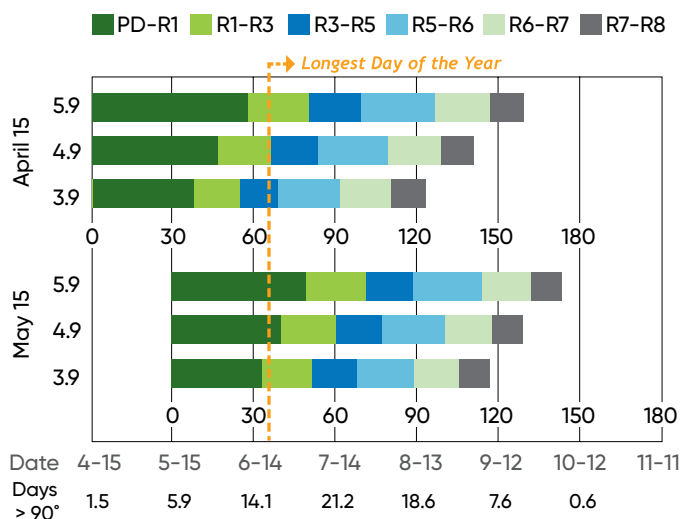


Figure 1. Development of MG 3.9, 4.9, and 5.9 soybeans planted April 15 (top) and May 15 (bottom) near Stoneville, MS, as modeled by the Mississippi State University SoyPheno growth model (Poston and Jeschke, 2015).

Yield Potential

- With the ESPS, soybean flowering and early grain fill occur in cooler parts of the summer when water use efficiency is higher, thereby escaping detrimental effects of heat stress later in the summer (Figure 1).
- Perhaps more important is the fact that flowering and pod set occurs during the longest days of the year, generally resulting in higher pod counts.

Lodging Risk

- Much of the soybean production in the Southern U.S. has shifted to productive silt loam soils once reserved for cotton production. Soybeans grown on these soils are often prone to lodging, especially if soybean is planted in single wide rows and following a highly fertilized corn crop.
- It is important to employ strategies that reduce the likelihood of lodging when growing soybeans on these soil types.
- Later-planted soybeans in this region tend to grow taller, which increases their risk of lodging on highly productive soils.
- Timely planting of soybeans can help maximize yield potential, as well as harvestable yield by reducing the risk of lodging.

SOYBEAN PLANTING DATE RESEARCH

Mississippi State Study

- A 2-year Mississippi State University field study evaluated planting date effects on growth and yield of two soybean varieties (MG 4 and 5) at two locations.
- Planting dates in the study spanned from late March through mid-July.

- Final plant height increased with later planting for planting dates extending through early June (Figure 2).
- Soybeans planted in late March reached an average height of 32 inches, while those planted in early June were around 10 inches taller.
- Final plant height declined for planting dates after early June, with soybeans planted at the latest timing in mid-July averaging only 23 inches.

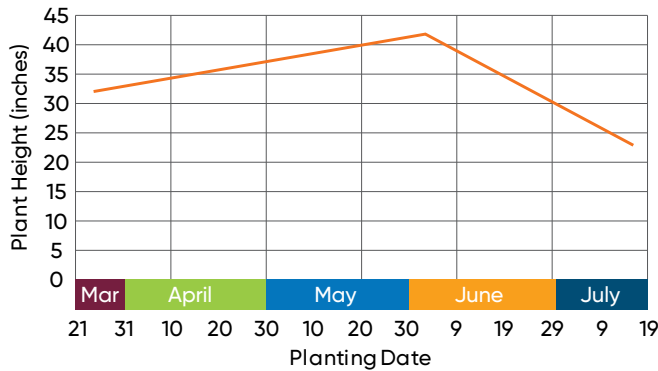


Figure 2. Soybean plant height by planting date in a 2-year Mississippi State University field study (Bateman et al., 2020).



- Soybean yield was maximized with planting around April 20 and declined with successively later planting after that point (Figure 3).
- Soybeans planted around April 20 reached an average yield of over 70 bu/acre, while those planted a month later averaged around 60 bu/acre.

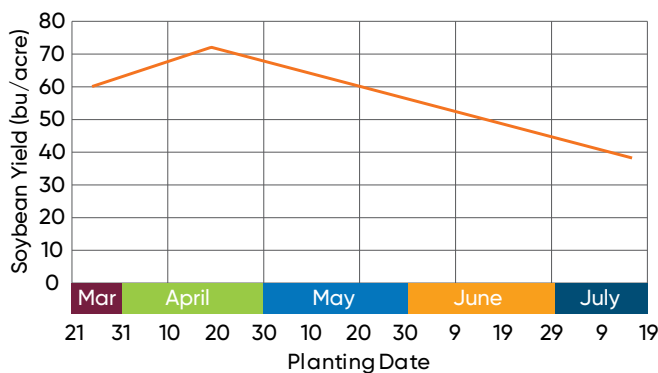


Figure 3. Soybean yield by planting date in a 2-year Mississippi State University field study (Bateman et al., 2020).

Pioneer Study

- Pioneer agronomists conducted a field study to evaluate the impact of planting date on yield and lodging of two indeterminate Pioneer® brand soybean varieties (MG 4.7 and 4.9) grown on productive soils in the Mississippi Delta.
- Planting dates in this study were April 9, April 23, May 10, and May 24.

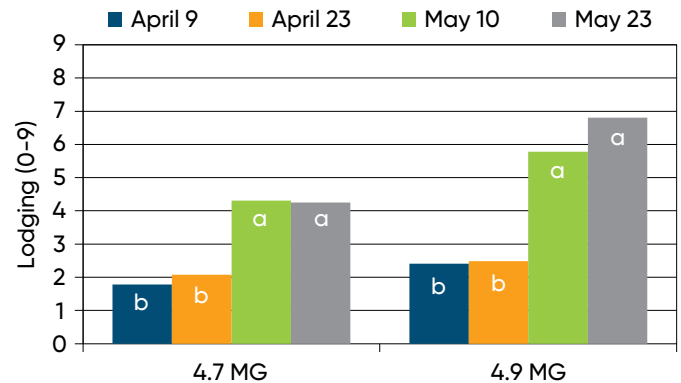


Figure 4. Planting date effect on yield of two soybean varieties in a Pioneer field study near Leland, MS (Poston et al., 2014).

Means with the same letter within a variety are not significantly different based on Tukey's HSD test conducted at the $\alpha = 0.05$ level.

- Soybean yield of both varieties was greatest with the April 23 planting date (Figure 4).
- Soybean lodging was significantly reduced for both varieties with April planting dates compared to May planting (Figure 5).

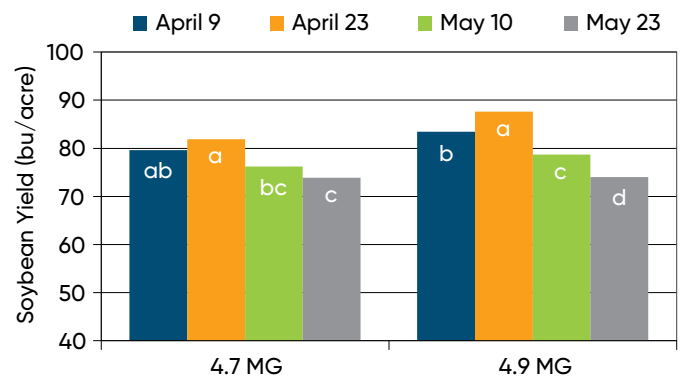


Figure 5. Planting date effect on lodging of two soybean varieties in a Pioneer field study near Leland, MS (Poston et al., 2014).

Means with the same letter within a variety are not significantly different based on Tukey's HSD test conducted at the $\alpha = 0.05$ level. Lodging rated using a 0-9 scale where 0=no lodging and 9=plants completely lodged.

- Results of both the Mississippi State study and the Pioneer study showed that timely planting can increase soybean yield potential, while also reducing the risk of lodging.

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Mark Jeschke, Ph.D.,
Agronomy Manager

DELAYED SOYBEAN PLANTING CONSIDERATIONS

KEY POINTS

- Switching to an earlier maturity variety is generally not necessary unless planting is delayed past mid-June.
- Soybean agronomists often recommend narrower rows (15 inches or less) with later planting to allow quicker canopy closure.
- Increasing seeding rate by around 10% is commonly recommended with late planting. Growers should target a final stand of 130,000 to 150,000 plants/acre.

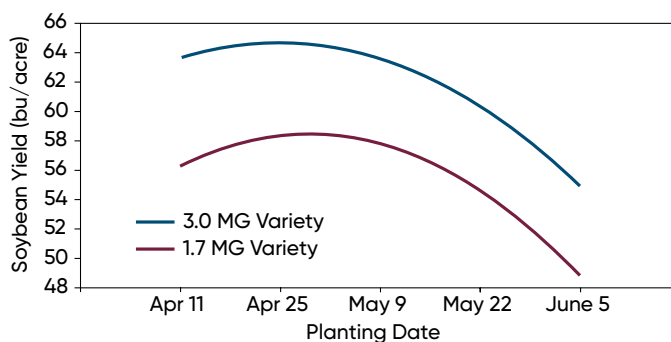


Figure 1. Influence of planting date on soybean yield of 1.7 and 3.0 MG varieties (Pecinovsky and Mueller, 2009).

- A South Dakota State University study found that switching from a 2.8 to a 1.8 MG variety with mid-June planting only reduced the time to maturity by 5 days (Nygren et al., 2019).
- If planting is delayed past mid-June, it is generally recommended to switch to a variety 0.5 to 1.0 MG shorter than normal for your area, as frost prior to maturity becomes more of a concern with very late-planted soybean. Consult your Pioneer sales professional for specific variety recommendations.

ROW SPACING

- Soybean agronomists often recommend narrower rows (15 inches or less) with later planting to allow quicker canopy closure.
- Earlier canopy closure is generally advantageous for maximizing yield potential and suppressing weeds.
- Narrower rows are generally advantageous in soybean regardless of planting date though, yielding 3–4 bu/acre more than 30-inch rows on average, and some studies have not shown this advantage to increase with later planting.

SEEDING RATE

- It is commonly recommended to increase soybean seeding rate by around 10% above normal with June planting, although research results have been somewhat mixed on this point.
- Seeding rate practices can vary widely, so the need for a bump up in seeding rate will depend somewhat on individual circumstances and what is “normal” practice for the operation.
- Ohio State University recommends targeting a final stand of 130,000 to 150,000 plants/acre for soybean planted in June (Lindsey, 2019).

DELAYED SOYBEAN PLANTING

- In wet springs, it is not unusual for soybean planting in the U.S. Corn Belt to extend into June.
- Drastic management changes are generally not required with later planting; however, some adjustments may be helpful in maximizing yield when soybean planting is delayed.

VARIETY RELATIVE MATURITY

- Switching to an earlier maturity variety is generally not necessary unless planting is delayed past mid-June.
- Compared to corn, soybean has a greater ability to adjust to later planting.
- A 5-year Iowa State University field study comparing yield of 1.7 and 3.0 MG varieties across a range of planting dates found that the later maturity variety had greater yield, even with planting in early June (Figure 1).
- Later planted soybean will take longer to reach physiological maturity, but not by a lot – generally, a 3-week delay in planting equates to a 1-week delay in physiological maturity.

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Mark Jeschke, Ph.D.,
Agronomy Manager

Don Kyle, M.S.,
Soybean Breeder

REFOCUSING ON SOYBEAN CYST NEMATODE MANAGEMENT

KEY POINTS:

- The most important management tactic for soybean cyst nematode (SCN) has been breeding and selection of soybean varieties with genetic resistance to SCN.
- The *rhg1b* gene from PI88788 source of SCN resistance has lost effectiveness for SCN control in many fields, meaning that SCN once again poses a threat to soybean yield that requires grower attention and management.
- SCN testing, rotations with varieties containing different sources of resistance such as Peking, rotation to non-host crops, and nematicide seed treatments are all important tools in a SCN management plan.

SOYBEAN CYST NEMATODE IN NORTH AMERICA

- Soybean cyst nematode (SCN; *Heterodera glycines*) is a major yield-reducing pest of soybean in North America.
- SCN was likely introduced to the U.S. from Japan. The first report of SCN in the U.S. was in North Carolina in 1954.
- This tiny worm-like parasite has now spread to practically all major soybean production areas of the U.S. and Canada (Figure 1) and is reaching economic levels in more areas.

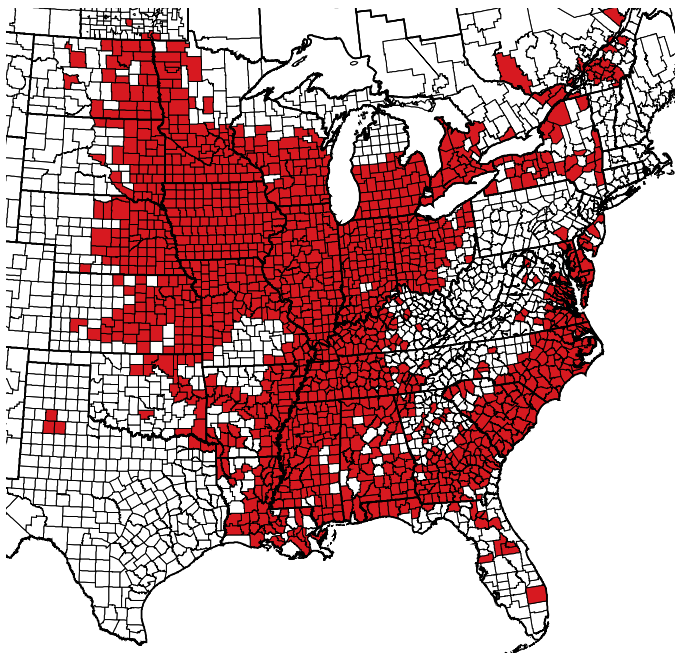


Figure 1. Known distribution of soybean cyst nematode in the United States and Canada as of 2020 (from Marett and Tylke, 2021).



Figure 2. Strips of SCN-resistant and non-resistant soybean varieties in a SCN-infested field, showing damage to the non-resistant varieties.

- SCN may reduce soybean yields substantially without inducing obvious symptoms. Studies have shown that in SCN-infested fields, yields can be reduced by over 30 percent without visible above-ground symptoms.

LEADERSHIP IN GENETIC RESISTANCE TO SCN

- The most important management tactic for SCN has been breeding and selection of soybean varieties with genetic resistance to SCN.
- Researchers have identified several soybean lines with the ability to resist nematode reproduction on their roots. Researchers then identify the specific genes causing resistance within these diverse soybean lines and breed those specific SCN resistance genes into elite soybean varieties.
- Breeding multiple genes for resistance into a soybean variety can produce more robust protection from SCN.
- Many of the soybean varieties across the industry today only contain a single gene for SCN resistance – the *rhg1b* resistance gene derived from PI88788.
- A smaller number of elite varieties currently use multiple genes for resistance, mostly derived from Peking (PI548402).
- Most current soybean varieties with resistance genes derived from Peking contain three genes for SCN resistance.

- Other varieties in the industry with resistance derived from Peking may only contain two genes for resistance. Varieties with three genes for resistance from Peking provide a more robust level of control against SCN.
- Continued SCN leadership is a priority as researchers develop soybean varieties with higher yield potential and resistance to SCN. Additional sources of SCN resistance (beyond Peking or PI88788) will be launched in elite varieties in coming years.

SCN HG TYPES

- SCN populations are genetically diverse and have historically been separated into races by their ability to reproduce on soybean tester lines.
- The most commonly used system separated SCN into 16 races.
- The most recent classification system, called the HG Type test, has now been widely adopted. The HG Type test is similar to a SCN race test but includes only the seven sources of resistance in available SCN-resistant soybean varieties.
- Results are shown as a percentage, indicating how much the nematode population from a soil sample increased on each of the seven lines.
- The HG Type test indicates which sources of resistance would not be suited for the field being tested. For example, if an HG type contains the number 2, this indicates that PI88788 would not be a fully effective source of SCN resistance (Table 1).

Table 1. Indicator lines for HG Type classification of SCN.

	Indicator Line		Indicator Line
1	PI548402 (Peking)	5	PI209332
2	PI88788	6	PI89772
3	PI90763	7	PI548316
4	PI437654 (Hartwig)		

DECREASED EFFICACY OF THE RHG1B GENE FROM PI88788

- 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, the rhg1b gene from PI88788 has been losing its effectiveness as a SCN management tool.
 - Studies in several states have shown that a high percentage of fields have SCN populations with elevated reproduction on the rhg1b gene from PI88788.



Figure 3. White SCN females on soybean roots.

- As the SCN HG types in these fields evolve increasing levels of parasitism, SCN populations rise in number and the soybean yield losses increase as well.
- The rhg1b gene from PI88788 source of SCN resistance has lost effectiveness for SCN control in many fields, meaning that SCN once again poses a significant threat to soybean yield that requires grower attention and management.

SCN MANAGEMENT RECOMMENDATIONS

- The SCN Coalition provides the following recommendations for developing a plan to manage SCN (www.thescncoalition.com):
 - Test your fields to know your numbers
 - Rotate resistant varieties
 - Rotate to non-host crops
 - Consider using a nematode protectant seed treatment
- Consult your university soybean extension specialist for specific management recommendations for your state.

Test Your Fields

- The first step in developing a SCN management plan is testing fields to determine the presence of SCN and/or the HG type of the population. Soybean specialists now recommend retesting infested fields every six years.
 - Sample at the same time of year and following the same crop each time – SCN populations vary during the growing season and in response to host and non-host crops.
 - Limit the area represented in a single sample to 10-20 acres to increase accuracy of results.
 - Use a soil probe, a small shovel, or a trowel to collect samples. Collect soil to a depth of 6-8 inches in the root zone of plants.
 - Collect 10-20 “cores” with the probe, or 10-20 ¼-cup samples with the shovel or trowel. Representative sampling is best achieved by collecting subsamples in a zigzag pattern across the entire sample area.



- Some universities recommend sampling markedly different soil textures separately. Also, areas with different cropping histories should be sampled separately.
- Deposit subsamples in a bucket and mix thoroughly. Place about 2 cups of soil in a plastic bag and label with a permanent marker. Paper bags allow soil to dry excessively and are not recommended for SCN.
- Do not store samples in direct sun or allow them to overheat. Ship as soon as possible to the lab you choose.

Rotate Resistant Varieties

- It is important to rotate varieties with different resistance genes that provide control of different HG types. This helps prevent SCN populations from increasing on a particular resistance source.
- There is a growing lineup of high yielding, adapted varieties that contain Peking resistance. Farmers should rotate Peking-derived resistant varieties with PI88788-derived resistant varieties across soybean crop years.
- Using varieties in rotation with different genes for SCN resistance will help maintain low SCN levels in these fields. It is best to begin rotating resistance before SCN levels build up.
- As a leader in SCN breeding, we have used precision molecular breeding methods to identify and isolate the SCN resistance genes found in multiple sources of resistance and move those specific genes into high yielding adapted varieties.
- New soybean varieties with expanded SCN resistance (beyond Peking or PI88788) will be available in the near future.

Rotate to Non-Host Crops

- Corn, alfalfa, and small grains are the most common non-host choices for reducing SCN numbers.
- Some SCN will hatch each season, and in the absence of a suitable host like soybean, those SCN will die. This causes a gradual reduction in SCN numbers the more years a non-host crop is planted. However, SCN persists in the soil for many years, so crop rotation will not eliminate SCN.

Seed Treatments

- Nematicide seed treatments are intended to supplement current SCN management strategies, not replace them.
- The LumiGEN® system offering includes ILEVO® HL fungicide/nematicide seed treatment, which has activity against SCN.
- A study including 193 on-farm trial locations found an average yield response of 4.9 bu/acre in high SCN fields when ILEVO fungicide/nematicide seed treatment was added to the standard fungicide and insecticide seed treatment package (O'Bryan and Burnison, 2016).

RED CROWN ROT IN SOYBEANS

KEY FINDINGS

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

NEW TO THE MIDWEST, BUT NOT NEW

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



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



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

INFECTION AND SPREAD IN SOYBEANS

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



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

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

SYMPTOMS AND IDENTIFICATION

- Red crown rot infection is often detected after the R3 stage with the appearance of yellowing on the leaves, although root and stem rot can occur without producing foliar symptoms.
- Foliar symptoms can be very similar to those of other common soybean disease such as sudden death syndrome, brown stem rot, and southern stem canker, so inspection of the stems and roots is necessary to determine the causal pathogen.
- Foliar symptoms typically do not appear uniformly across a field, often showing up as single plants or small patches of infected plants randomly throughout the field.
- The key distinguishing characteristic of red crown rot is the presence of perithecia on the crown and roots just below the soil line, which look like tiny red balls and will give the crown a reddish coloration.

- Under wet conditions, the perithecia can extend above the soil line on the lower stem.
- Other factors can cause a reddish coloration of the lower stem, so it is important to look closely to confirm the presence of fungal tissues.
- White fungal hyphae can also appear on infected tissue.
- The pith in the crown of an infected plant may have a gray discoloration.
- Plants with severely rotted roots can be easily pulled from the soil. Diseased plants may have more than one pathogen present.

MANAGEMENT CONSIDERATIONS

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



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



Mark Jeschke, Ph.D.,
Agronomy Manager

SUDDEN DEATH SYNDROME OF SOYBEANS

KEY POINTS

- Sudden death syndrome (SDS) has spread to most soybean-growing states and Ontario, Canada. Some states now rank SDS second only to soybean cyst nematode (SCN) in economic losses caused to soybeans.
- In North America, SDS is caused by the fungal pathogen *Fusarium virguliforme*, formerly known as *F. solani* f. sp. *glycines*.
- Early planting and cool, wet conditions early in the growing season often result in higher incidence of SDS. The disease is usually more severe if SCN is also a problem in the field.
- SDS often appears first in low, poorly drained or compacted field areas. Infection occurs early in the season but foliar symptoms do not appear until mid-summer.
- As plants lose leaf area and roots deteriorate due to SDS, yield components are affected. Flower and pod abortion are common, resulting in fewer pods and seeds. Seeds may be smaller, and late-forming pods may not fill or mature.
- SDS varies in severity from area to area, and from field to field. Growers must understand the extent of infection in each of their fields to effectively manage SDS.
- Management practices for SDS include tolerant varieties, seed treatments, planting problematic fields last, managing SCN, improving field drainage, reducing compaction, and reducing other stresses on the crop.

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 from the mid-South Mississippi River basin 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 (Malvick, 2018). In the Midwestern U.S., SDS ranks second only to soybean cyst nematode (*Heterodera glycines*) in its economic impact (Bandara et al., 2020).



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.

Origin and Spread

Symptoms of what would eventually be called sudden death syndrome were first documented in Arkansas in 1971 (Figure 1). The disease remained unnamed for over a decade (Roy et al., 1997). It was not until 1983, when the capability of the disease to significantly reduce soybean yields had become apparent, that it was given the name 'sudden death syndrome' (Hirrel, 1983). The name reflected two important aspects of the disease – first, the rapidity with which foliar symptoms could develop and culminate in premature plant death, and second, the fact that the causal pathogen remained unknown at the time. The term 'syndrome' reflected the fact that the disease was defined only as a set of symptoms at this point. It would be another six years before the soil-borne fungus *Fusarium virguliforme* was confirmed as the causal pathogen. During this time, the disease spread to several additional states. It was confirmed in Mississippi, Missouri, Kentucky, and Tennessee in 1984, and reached the Corn Belt states of Illinois and Indiana in 1985 (Roy et al., 1997). SDS has now been found in at least 29 states, spanning much of the soybean producing area of the U.S. (Figure 2).

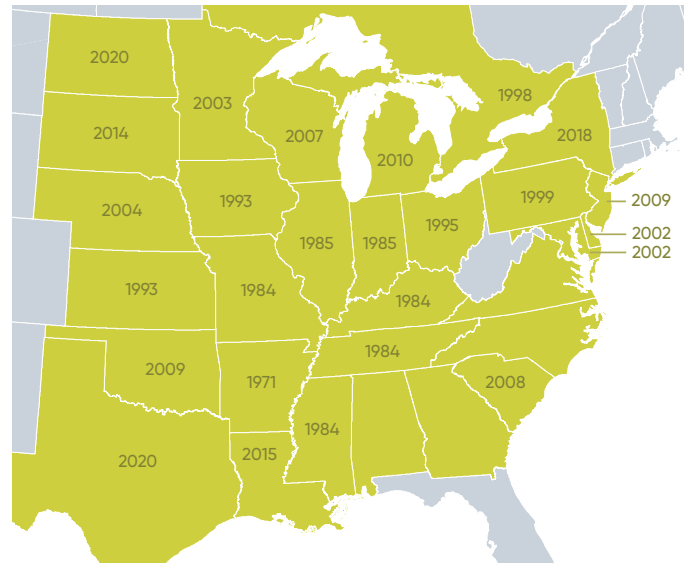


Figure 2. States and provinces in which SDS of soybean is present and year of first detection.

Causal Pathogen

In North America, SDS is caused by the fungal pathogen *Fusarium virguliforme*, formerly known as *F. solani* f. sp. *glycines*. The genus *Fusarium* is a large group comprised of over 1,500 species, including several important plant pathogens. *F. virguliforme* is part of a subgroup of species within the *Fusarium* genus called the *Fusarium solani* species complex (FSSC), which includes over 60 plant pathogenic and saprophytic species (Coleman, 2015). *F. virguliforme* is believed to be an invasive pathogen in North America, having originally evolved in South America where three additional *Fusarium* species are known to cause SDS in soybean – *F. tucumaniae*, *F. brasiliense* and *F. crassispitatum* (Spampinato, 2021). Genomic analysis suggests that these pathogens predate the presence of soybean in the Americas and likely jumped from some other host plant to soybean when it was brought over from Asia in the 18th Century (O'Donnell et al., 2010).

The fungal pathogen that causes SDS likely originated in South America, where three additional Fusarium species are known to cause SDS in soybean.

SDS LIFE CYCLE AND SYMPTOMS

Life cycle

F. virguliforme survives primarily as chlamydospores in root debris and freely in the soil (Roy et al, 1997). Chlamydospores are thick-walled, asexual fungal spores that are survival structures for many fungi and can survive in the soil for multiple years. Chlamydospores are very resilient – they can survive freezing temperatures and they are resistant to desiccation. 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 (Roy et al., 1997). Later in the season the fungus will penetrate the xylem tissue in the roots, at which point a toxin produced by the pathogen can be translocated up the plant and cause the characteristic foliar symptoms of SDS.

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 along with rotted cortical tissue. 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 within a field and into new fields.



Figure 3. *F. virguliforme* spores.

Phytotoxin

The toxin responsible for the foliar symptoms of SDS was first isolated and identified in 2011 (Brar et al., 2011). The fact that *F. virguliforme* had never been detected in symptomatic leaf tissue, as well as the fact that many *Fusarium* species were known to produce plant and animal toxins, had long led scientists to suspect that one or more toxins were responsible for the foliar symptoms of SDS. A small protein, given the

Scientists believe the purpose of the toxin produced by the SDS pathogen is to weaken the plant and reduce its ability to fight off infection.

name FvTox1, was found to be the cause. Scientists found that foliar symptoms only developed in the presence of light, leading them to believe that FvTox1 works by interrupting photosynthesis, resulting in the production of free radicals that cause chlorosis and necrosis of leaf tissue (Brar et al., 2011).

The fact that *F. virguliforme* undergoes its entire life cycle in the roots of the plant raises the question of what possible advantage it would derive from causing damage to foliar tissue. Producing FvTox1 would incur a metabolic cost to the pathogen, so it would need to gain some survival benefit from doing so. Scientists believe this is a tactic by the pathogen to weaken the plant by reducing its photosynthetic capacity, thereby reducing its ability to resist infection and allowing *F. virguliforme* to establish and proliferate more successfully (Brar et al., 2011).

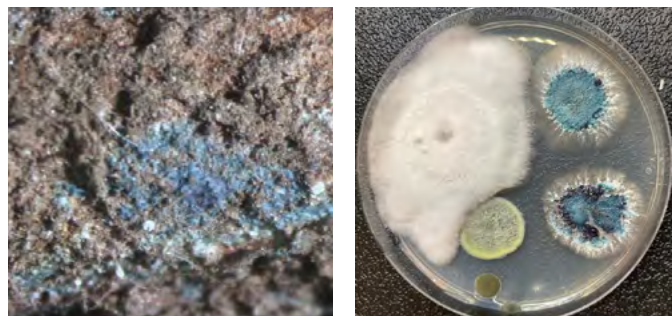


Figure 4. Microscopic view of blue colored spore masses on the root of a soybean plant infected with SDS (left) and *F. virguliforme* growth on artificial media (right).

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 4). However, these fungal colonies may not appear if the soil is too dry or too wet. 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 5). The general discoloration of the outer cortex can extend several nodes into the stem, but its pith also remains white.



Figure 5. Split soybean plant stems showing the discolored cortical tissue of a SDS-infected plant compared to a healthy plant.

Leaf Symptoms

Though SDS infects soybean plants just after germination and emergence, leaf symptoms usually do not appear until the reproductive stages of crop development (typically mid-summer or later in the Midwestern U.S.). 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. First symptoms are often noticed about 10-14 days after heavy rains that saturate soils. Wet soils can increase the production and translocation of the toxin responsible for foliar symptoms.

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 6). 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.

Whole-Plant Symptoms

As plants lose leaf area and roots deteriorate, yield components are affected. Flower and pod abortion are common, resulting in fewer pods and seeds produced. Seeds that do develop are usually smaller. Later-developing pods may not fill, or seeds may not mature. Because plants and pods dry down faster, harvest losses may also increase in SDS-infected plants. Severity of yield reduction is highly dependent on the growth stage of the soybean plant when infection and symptoms occurred. In some cases, premature death of the entire plant can occur without the typical defoliation symptoms, as affected plants yellow and die gradually.



Figure 6. 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 SDS DEVELOPMENT

Like other soil-borne root rots, SDS often appears first in localized spots in the field, such as low, poorly drained, or compacted areas. In some cases, severe SDS outbreaks can also occur on highly productive soils with high moisture-holding capacity. Because disease severity is highly dependent on environmental conditions, time of infection, and other stresses on the soybean crop, severity varies from year to year and within field areas. Higher incidence of SDS

SDS symptoms are often concentrated in low, poorly drained, or compacted areas of a field.

often occurs when soybeans have been exposed to cool, moist soil conditions early in the growing season. Early planting is, therefore, more likely to predispose the crop to SDS.

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.

Distinguishing SDS from Other Diseases

Leaf symptoms of SDS can be similar to those of multiple other soybean diseases, including brown stem rot (*Cadophora gregata*), stem canker (*Diaporthe* spp.), charcoal rot (*Macrophomina phaseolina*), and red crown rot (*Calonectria illicicola*). However, there are several characteristics that readily differentiate these diseases. To distinguish SDS from the other diseases, first examine the outside of the stem. If the outside of the stem has large brown-black sunken lesions, then it is likely stem canker. The key distinguishing characteristic of red crown rot is the presence of perithecia on the crown and roots just below the soil line, which look like tiny red balls and will give the crown a reddish coloration. Charcoal rot can be identified by scraping the outer stem tissues, which will reveal black, dusty microsclerotia.

If none of these symptoms are present, split the bottom eight inches of the soybean stem. If SDS is the problem, the pith of the stem will be white, and the surrounding cortex will appear grayish brown. In contrast, brown stem rot will cause the pith to be dark brown while the cortex remains green.



Sudden Death Syndrome

Infected cortex tissue appears grayish brown, while the pith remains white.



Brown Stem Rot

Pith tissue in the lower stem is dark brown, while the cortex tissue remains green.



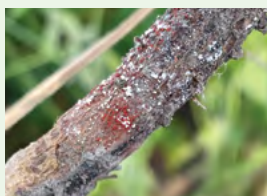
Charcoal Rot

Light gray discoloration on the surface tissues of the roots and lower stem. Scraping the outer tissues will reveal black, dusty microsclerotia.



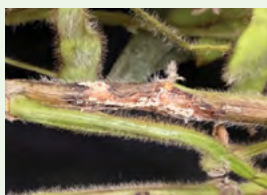
Red Crown Rot

Perithecia on the crown and roots just below the soil line, which look like tiny red balls, give the crown a reddish coloration.



Stem Canker

Large brown-black sunken lesions on the outside of the stem.



Tolerant Soybean Varieties

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. For that reason, variety selection is a key management practice to reduce plant damage and yield loss.

To assist growers in choosing tolerant varieties, Corteva Agriscience researchers rate products in multiple test sites with known historical SDS occurrence. These sites, located in states where SDS is problematic, are irrigated and/or planted early to encourage SDS development. Pioneer® brand soybean varieties are scored on a 1 to 9 scale for SDS tolerance, with 9 being the most tolerant. Continued improvements in breeding for this trait have increased SDS tolerance in commercial varieties over time. For example, Pioneer Z Series soybean varieties, introduced in 2024, scored an average of 0.5 points higher across the entire product lineup for SDS tolerance compared to the preceding A Series.

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.

SCN resistance is also an important consideration for variety selection, since SCN injury can exacerbate SDS problems. The *rhg1b* gene from PI88788 source of SCN resistance has lost effectiveness for SCN control in many fields, meaning that SCN once again poses a threat to soybean that requires grower attention and management. A smaller number of elite varieties currently use multiple genes for resistance, mostly derived from Peking (PI548402). Continued SCN leadership is a priority as Corteva Agriscience researchers develop soybean varieties with higher yield potential and resistance to SCN. Additional sources of SCN resistance (beyond Peking or PI88788) will be launched in elite varieties in coming years.

MANAGEMENT OF SDS

Sudden death syndrome varies in severity from area to area and from field to field; therefore, growers must clearly understand the extent of SDS infection in each of their fields to effectively manage the disease. This requires scouting fields when disease symptoms are present, ideally using GPS tools to map SDS-prone areas. Such maps could be overlaid with yield maps to reveal the extent of yield losses from SDS.

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. Consequently, scouting and management strategies are focused on mitigating disease impact in subsequent seasons. A combination of crop management practices can help minimize the damage from SDS. These include selecting SDS-tolerant varieties, using effective seed treatments, planting the most problematic fields last, managing SCN, improving field drainage, reducing compaction, evaluating tillage systems, and reducing other stresses on the crop.



Figure 7. Soybean trifoliate showing SDS symptoms.

Seed Treatments

ILEVO® HL fungicide (active ingredient: fluopyram) is a seed treatment that provides protection of soybean seedlings from *F. virguliforme* infection, the causal pathogen of SDS. A Corteva Agriscience study conducted at field locations across eight states found that Pioneer® brand soybeans treated with ILEVO® HL seed treatment (fluopyram use rate of 0.15 mg ai/seed) yielded 1.8 bu/acre more than the base seed treatment across all locations (n=46) and 3.8 bu/acre more than the base treatment at locations with moderate to high SDS pressure (n=12).*

Planting Timing

Newly germinated soybean plants are more vulnerable to infection by *F. virguliforme* in cool, wet soils. Although growers may be reluctant to delay planting when fields are ready, research has demonstrated later planting to be effective in reducing SDS occurrence. For this reason, growers may consider planting high-risk fields last in their planting sequence. If this results in a 1- or 2-week delay in planting, the impact on SDS occurrence could be significant.

Managing Soybean Cyst Nematode

SCN is a problem requiring management in many soybean fields that are also at risk to SDS. SCN increases the stress on the soybean plant and also provides wounds through which the SDS pathogen can enter the roots. Scientists have also discovered the SDS pathogen can be carried in SCN bodies. This means that managing SCN and limiting its stress on the soybean plant is critical to also limiting damage due to SDS.

Like SDS, SCN cannot be eradicated from an infested field. However, planting SCN-resistant varieties, use of seed treatments effective against SCN, rotating crops, and rotating sources of SCN resistance can reduce SCN populations in the field. Keeping SCN numbers below levels that will cause significant yield loss is the primary goal of SCN management. In addition, any practice that promotes good soybean health and growth will also help against SCN.

Improving Field Drainage and Reducing Compaction

Improving field drainage and reducing compaction go hand-in-hand as wet areas are easily compacted, and compacted areas stay wetter due to restricted soil drainage. Wet, compacted field areas are more susceptible to SDS infection (Figure 8). SDS infection is aided by high soil moisture conditions, and soybean roots already inhibited by compacted and saturated soils are further diminished by the disease.

When stress conditions develop in these fields, yields are often severely reduced due to a limited root system as well as the devastating effects of the SDS toxin on the plant. Growers should strive to improve field drainage and remediate compacted areas as a high priority to reduce the effects of SDS.



Figure 8. Aerial view of a soybean field with SDS. Symptoms are more prevalent near waterways and areas with poor drainage.

Evaluating Tillage Systems

Research findings on the effects of tillage on SDS have been mixed (Westphal et al., 2018), with some studies showing no effect (Kandel et al., 2019). However, several studies have shown that tillage can reduce the severity of SDS by helping soils warm up and dry out in the spring ahead of planting. A study conducted at the University of Missouri showed that no-till systems resulted in much higher percentages of SDS-infected leaves than disking or ridge-till with both May and June planting dates. High crop residue levels are known to result in colder, wetter seedbeds in the spring. In fields with high levels of SDS infection, growers may want to re-evaluate the tillage system they are using.

Reducing Other Stresses

Other plant stresses can render soybeans more vulnerable to SDS attack. These include herbicide stress, nutrient deficiencies, high pH, and pest pressure. Maintaining adequate soil fertility; reducing compaction; and controlling weeds, diseases, and insects all improve soybean growth and plant health and enable the plants to better withstand the effects of SDS.

.....●●●●●●●●
Paul Hermans,
Sales Agronomist
Mark Jeschke, Ph.D.,
Agronomy Manager

VIATUDE™ FUNGICIDE FOR CONTROL OF WHITE MOLD IN EASTERN CANADA

KEY FINDINGS

- On-farm trials were conducted in 2023 to evaluate the effectiveness of using a foliar fungicide treatment for the control of white mold in soybeans.
- The 2023 growing season was very favorable for white mold development in the study area in Eastern Canada.
- Soybeans treated with Viatude™ fungicide yielded an average of 3.2 bu/acre more than non-treated soybeans.

BACKGROUND AND RATIONALE

- Sclerotinia stem rot, or white mold (*Sclerotinia sclerotiorum*) is the leading disease in soybean production areas in Eastern Ontario, Quebec, and the Maritimes.
- White mold infections take place during the start of flowering (R1) stage and continue while flowers are present.
- Higher incidence is often observed during periods of high relative humidity and average temperatures around 21°C.
- Various management practices have been shown to help manage white mold, including use of a preventative fungicide.
- Viatude™ fungicide (picoxystrobin + prothioconazole) is a new foliar fungicide labelled for suppression of white mold in soybeans.



Figure 1. White fungal mycelia visible on the stem of a soybean plant infected with white mold.

• 2023 WHITE MOLD FUNGICIDE TRIALS

- On-farm trials were conducted in 2023 to evaluate the effectiveness of using a foliar fungicide treatment for the control of white mold.
- A total of 30 paired comparisons (fungicide-treated vs. non-treated) were conducted across 10 locations with 1 or 2 replications per location.
- Seeding rates ranged from 130,000 to 165,000 seeds per acre across locations. Locations were planted in either 15- or 30-inch rows.
- Nine different Pioneer® brand soybean varieties were used in the study with 1 to 6 varieties at each location (Table 1).
- Viatude™ fungicide was applied at the R2–2.5 growth stage at a rate of 0.3 L/acre (10 fl oz/acre).

Table 1. Pioneer® brand soybeans, relative maturities, white mold scores, and number of trial locations in which they were planted in 2023 white mold fungicide on-farm trials.

Variety/Brand ¹	Relative Maturity	White Mold Score ² (1–9)	Locations
P04A98E™	0.4	6	4
P05A35X™	0.5	6	1
P06A38E™	0.6	7	6
P06A48X™	0.6	6	2
P07T59E™	0.7	2	5
P08A44E™	0.8	4	5
P09A62X™	0.9	6	1
P12T94E™	1.2	4	4
P14A12E™	1.4	3	2

¹All Pioneer products denoted with ™ are brand names.

²Scores based on Pioneer research observations of comparative white mold tolerance among various soybean products across multiple locations and years. All products are capable of developing white mold symptoms under severe infestations. To our knowledge, there are no totally resistant products in the industry. However, differences exist in the ability of products to tolerate white mold (i.e., the rate at which the infection develops and the extent of damage it causes). These scores reflect those differences.

RESULTS

- The 2023 growing season was very favorable for white mold development in the study area – with high humidity levels, saturated soils, and average temperatures of 21–24°C during peak flowering periods – and high white mold pressure was observed.
- Soybeans treated with Viatude™ fungicide yielded an average of 3.2 bu/acre more than non-treated soybeans (Figure 2) with a positive yield response observed in 90% of comparisons (Figure 3).

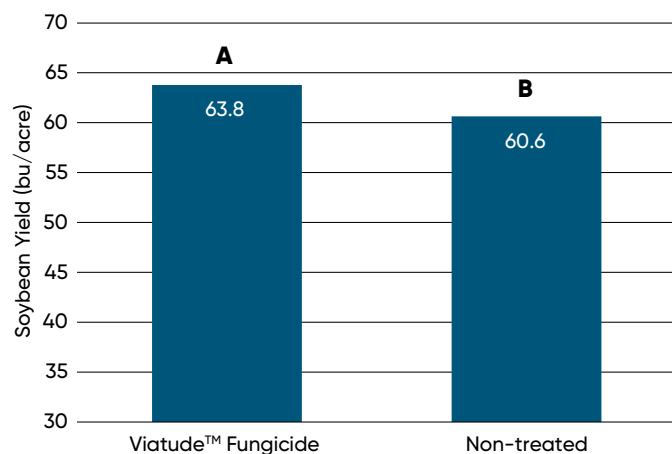


Figure 2. Average yield of fungicide-treated and non-treated soybeans across all on-farm study locations in 2023 (Prob > F = 0.0155).

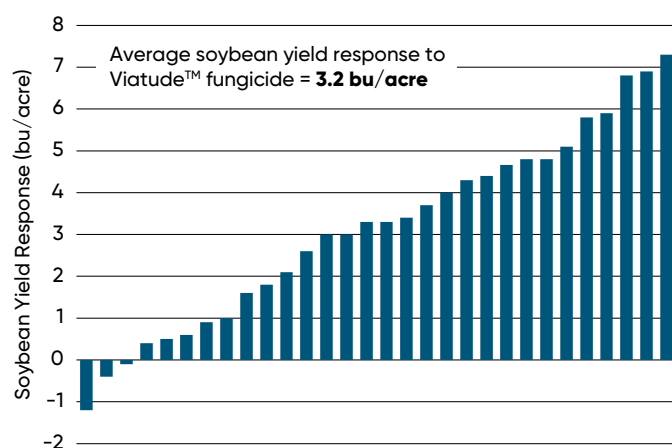


Figure 3. Yield difference of all paired comparisons of fungicide-treated vs. non-treated soybeans.

Planting Date

- Two of the locations in the study were in adjacent fields with the same set of varieties but different planting dates – one was planted on May 18 and the other 5 days later on May 23.
- Planting date can influence white mold severity by affecting the timing of flowering and degree of canopy closure.
- Yield response to fungicide treatment was 4.1 bu/acre greater in the later-planted field (Table 2).

Table 2. Soybean yield response to fungicide treatment for two study locations in adjacent fields with different planting dates.

Variety/Brand ¹	Planting Date		Difference
	May 18	May 23	
P04A98E™	0.6	4.8	4.2
P06A38E™	2.1	5.1	3
P07T59E™	-1.2	6.8	8
P08A44E™	0.5	1.6	1.1
P12T94E™	-0.1	4.4	4.5
Average	0.4	4.5	4.1

One-Pass vs. Two-Pass

- Two of the study locations also included a second fungicide treatment on a portion of the study area.
- Previous studies have shown that a two-pass program can provide significant yield benefit when white mold pressure is severe.
- Both locations had higher yields with the two-pass treatment; substantially higher for one of them (Table 3). Late-season plant health imagery for Location 2 is shown in Figure 4.

Table 3. Soybean yields by fungicide treatment at the two locations that included a two-pass program.

Location	Non-treated	Single-Pass	Two-Pass
	— bu/acre —		
1		72.3	75.9
2	48.6	52.0	68.2
Average		62.2	72.1

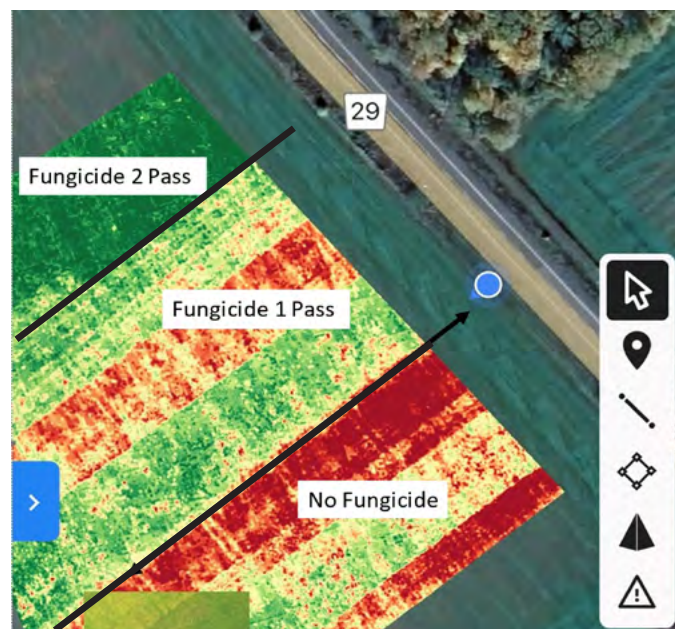


Figure 4. Late-season plant health imagery showing differences among non-treated, single-pass fungicide, and two-pass fungicide areas of the study field.

Fungicides have little activity on established disease and must be applied prior to white mold invasion of senescing flowers.

Because soybeans normally flower for 30 days or more, a second application may be necessary if conducive environmental conditions persist into mid-summer.

SOYBEAN POD AND SEED ROTS

KEY POINTS

- Warm and wet conditions at the end of the growing season prior to harvest can promote fungal pathogens capable of infecting soybean pods and seeds.
- Fungal pathogens that commonly infect soybean pods and seed overwinter in crop residue, so are present in essentially all soybean fields at some level.
- Anything growers can do to reduce the amount of time mature soybeans remain in the field before harvest will help reduce the potential for seed quality issues.

COMMON POD AND SEED DISEASES

- Excessively wet and warm conditions following maturity can negatively affect seed quality and yield in soybeans by causing pod shattering, seed sprouting in the pods, and growth of fungal diseases.
- Conditions favoring pod and seed rots in mature soybeans can result from extended periods of above-average rainfall and temperatures or from extreme rainfall events often associated with hurricanes or tropical storms.
- There are a few common fungal pathogens that infect soybean pods and seeds causing reductions in yield and seed quality.



Rotted and sprouted soybean seeds resulting from persistent wet conditions following maturity.



Cercospora Leaf Blight and Purple Seed Stain

- Caused by the fungal pathogen *Cercospora kikuchii*, which attacks both the leaves and the seeds of soybeans.
- Seeds are infected through their attachment to the pod, the hilum. Infected seeds may show a pink to pale or dark purple discoloration, which varies in size from specks to blotches to the entire seed coat.
- Sporulation occurs under conditions of high humidity and temperatures of 75°F or higher. Sporulation increases as temperatures rise above 80°F.

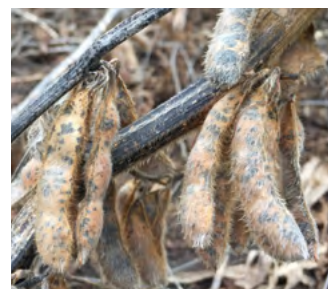
- Spores carried by wind and water infect leaves and stems. Infection may remain latent until favorable conditions develop during soybean pod-fill stages.
- *Cercospora* diminishes seed appearance and quality, but usually does not decrease yields significantly.



Cercospora purple seed stain.

Phomopsis Seed Decay

- Caused by the fungal pathogen *Phomopsis longicolla*, which forms a complex with *Diaporthe phaseolorum* var. *sojae* to infect soybeans.
- Seeds appear shriveled, cracked, elongated, and may be covered with a thin white layer of mold. Small black specks of pycnidia may occur on the seeds.
- Infection can cause reductions in soybean yield and grade.



Phomopsis seed decay (left) and pod and stem infection (right) likely attributable to multiple pathogens.

Frogeye Leaf Spot

- Caused by *Cercospora sojina*, a fungus that infects leaves, stems, and pods of soybeans.
- Lesion development on pods begins as water-soaked spots that progress to dark reddish-brown lesions.
- The fungus can also grow through the pod wall to infect maturing seeds. These seeds may show cracking of the seed coat and discoloration ranging from small specks to large blotches.



Anthracnose

- Anthracnose in soybean is primarily caused by the fungal species *Colletotrichum truncatum* in the Midwestern U.S.

- Anthracnose can infect stems, leaves, and pods of soybean.
- Infected pods may be completely filled with mycelium and can have no seeds or fewer/smaller seeds form. Seeds that do form may be discolored, shriveled, and moldy.



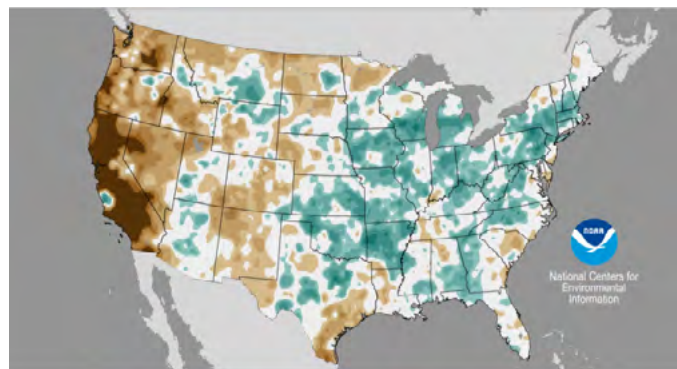
Anthracnose on a soybean stem.

Opportunistic Fungi and Bacteria

- Opportunistic pathogens are those that are normally associated with degradation of crop residue.
- Once the plant tissue is dead, it can no longer defend itself against these pathogens and is susceptible to infection.
- Soybean plants that remain in the field for extended periods following maturity can be degraded by opportunistic pathogens when conditions are favorable for diseases.

WEATHER IS THE DRIVING FACTOR

- Fungal pathogens that commonly infect soybean pods and seed overwinter in crop residue, so are present in essentially all soybean fields at some level.
- The severity of infection that actually occurs is largely determined by the favorability of weather conditions.
- Soybean seed quality problems are often the result of an unusual confluence of weather conditions that both delay harvest and provide a uniquely favorable environment for fungal diseases.



Created: Wed Sep 05 2018
Percent
Data Source: Skm Gridded (nClimGrid)

Precipitation deviation from normal in August 2018, a year in which soybean seed quality issues were common due to wet late-season conditions.

OBSERVATIONS FROM THE 2018 SEASON

- Soybean seed quality issues associated with abnormally warm and wet conditions after maturity impacted a large area during the 2018 growing season.
- In general, seed quality issues tended to be more prevalent in earlier-planted soybeans.

- Problems did not appear to be associated with any particular soybean maturity groups or varieties.
- It is likely that the interaction between maturity timing and weather conditions was the primary determinant of seed quality problems in a given field.
 - Soybean plants that are mature and weathering in the field under conditions favorable for disease are highly prone to infection.
 - The longer the soybeans remain in the field before harvest, the more time diseases have to work.
 - Soybeans easily take up water, which can cause seed swelling and pod splitting and increase susceptibility to diseases.
 - Warmer temperatures drive faster fungal growth.
- Effects of foliar fungicide applications varied in terms of preventing yield loss from pod and seed diseases in 2018.
 - In many cases it appears there was no effect. An application made around the typical timing (R3 stage) would not have any activity left to control pathogens invading the mature plant late in the season.
 - In areas with heavy frogeye leaf spot pressure, more consistent yield benefits were observed, particularly on soybean varieties with lower genetic resistance.

HARVEST, HANDLING, AND STORAGE

- Affected fields should be harvested as soon as feasible to prevent further loss of yield and quality.
- If soybean plants have retained green foliage due to wet conditions, a desiccant may be needed.
- Soybeans should be dried down to 11% moisture to inhibit fungal growth, aerated, and delivered as soon as possible.
- Soybeans should be dried at temperatures between 100 and 130°F. Higher temperatures can cause damage to the seed.
- Damaged soybeans can be blended with good quality soybeans, if possible.
- Growers should open a claim with their crop insurance provider if there is a concern over soybean quality and yield.

MANAGEMENT CONSIDERATIONS

- Seed quality problems are often the product of a highly unusual set of weather conditions that favor disease growth and delay harvest, so there are often no simple management changes that could have prevented problems or that will prevent problems in the future.
- In general, anything growers can do to reduce the amount of time mature soybeans remain in the field before harvest will help reduce the potential for seed quality issues.

SOYBEAN POD SPLITTING AND SEED SPROUTING

KEY POINTS

- Excessive rainfall late in the season can allow water to soak through the pods of mature soybeans and cause the seeds to swell inside the pods.
- Soybeans that experienced drought stress earlier in the season can have an elevated risk of pod splitting due to smaller and weaker pods.
- If soybean seeds swell to above 50% moisture and temperatures are above 50°F, they may begin to germinate in the pods.

WEATHER CONDITIONS DURING HARVEST SEASON

- Prolonged wet conditions late in the season can cause substantial delays in harvest and lead to yield losses due to pod splitting and seed germination in the pods.
- Two conditions are necessary for soybeans to germinate in the pods following physiological maturity:
 - Seed moisture raised back above 50%
 - Temperatures greater than 50°F

SEED SWELLING AND POD SPLITTING

- Soybean seed moisture is around 35% at physiological maturity and will decline quickly under dry conditions, drying down much more rapidly than corn.
- However, soybeans will readily re-absorb water and expand when exposed to moisture.
- Frequent rains and persistent wet conditions can allow water to soak through the pods and cause the seeds to swell inside the pods.
- If the seeds swell enough, they can cause the pod to rupture (Figure 1).
- Soybeans that experienced drought stress earlier in the season can have an elevated risk due to smaller and weaker pods.
- When pods are ruptured, seeds are prone to loss, particularly when they dry back down, either before or during harvest (Figure 2).

GERMINATION IN THE PODS

- Once the pod has ruptured, the seeds are directly exposed to soaking rainfall. If the seeds swell to above 50% moisture and temperatures are above 50°F, they may begin to germinate (Figure 3).
- Germination will continue as long as moisture and temperatures remain favorable.



Figure 1. Soybeans that have swollen and ruptured the pods due to persistent wet conditions in Iowa in 2018. (Photo: Chris Doud, Pioneer Field Agronomist)

HARVEST

- Affected fields should be harvested as soon as feasible to prevent further loss of yield and quality.
- If soybean plants have retained green foliage due to wet conditions, a desiccant may be needed.

Combine Speed and Settings

- Slowing down harvest speed can help reduce gathering losses. Keep forward speed at about 3 mph for most combines. Slow down for uneven soil surface or other abnormal conditions.
- Equipment must be properly adjusted and carefully operated to minimize losses. Soybeans that never get inside the combine can account for 80 to 85% of harvest losses.
 - Be sure knife sections and ledger plates are sharp, and that wear plates, hold-down clips, and guards are properly adjusted. Chains and bearings should be properly lubricated, and belts tight.
 - Proper reel speed in relation to ground speed will reduce gathering losses. Shatter increases if the reel turns too fast; stalks may be dropped if the reel turns too slow. Use a reel speed about 25% faster than ground speed.

- The reel axle should be 6 to 12 inches ahead of the sickle in most cases. Operate a bat reel just low enough to tip cut stalks onto the platform. The tips of the fingers on a pickup reel should clear the cutterbar by about 2 inches.



Figure 2. Soybeans that have fallen to the ground after the pods ruptured. (Photo: Chris Doud, Pioneer Field Agronomist)

HANDLING AND STORAGE

- Swollen and/or germinated seed will negatively affect seed quality.
- Germinated seeds will die and break into pieces during harvest, most of which will likely go out the back of the combine.
- Pieces that remain in the harvested grain can promote spoilage due to the breakdown of carbohydrates, proteins and fats in the seed that is initiated during the germination process.
- Soybeans subjected to conditions capable of causing germination in the pods will also likely have pod and seed diseases present as well, which can also contribute to grain quality concerns (Figure 4).
- Soybeans should be dried down to 11% moisture to inhibit fungal growth, aerated, and delivered as soon as possible.
- Soybeans should be dried at temperatures between 100 and 130°F. Higher temperatures can cause damage to the seed.
- Damaged soybeans can be blended with good quality soybeans, if possible.
- Growers should open a claim with their crop insurance provider if there is a concern over soybean quality and yield.



Figure 3. Soybeans germinating in the pods due to persistent wet conditions in Iowa in 2018. (Photos: Chris Doud, Pioneer Field Agronomist)



Figure 4. Swollen seeds and ruptured pods with disease visible on both the pods and seeds. (Photo: Chris Doud, Pioneer Field Agronomist)



Scott Eversgerd,
Pioneer Field Agronomist

Daniel Wiersma,
Wheat Production Manager

Jerron Schmoll,
Product Life Cycle Manager



MANAGEMENT FOR HIGH YIELD WINTER WHEAT

Eastern North America

KEY POINTS

- Seed winter wheat at 1.4 to 1.8 million seeds/acre within the normal planting window for the area.
- Plant where the previous crop was not wheat, preferably after soybeans or corn.
- Use top yielding varieties with fungicide and insecticide seed-applied treatments.
- Aim for uniformity in stand establishment, fertilizer, and crop protection product applications.
- Fertilize for high yield potential – split applications of nitrogen to wheat are often beneficial.
- Use frequent scouting to identify weeds, insect pests, and disease issues and control as needed.

PLANT FOR UNIFORM STANDS

Seeding Rates

High density wheat stands are critical for high yields and helpful for weed control. In high yield environments, wheat growers typically seed 1.4 to 1.8 million seeds/acre where soil conditions are good and when seeding is done in an optimal timing window. In late-planted wheat, adjust seeding rates upward to the range of 1.8-2.2 million seeds/acre since there is less time for tillering.

Know the optimum head count at harvest for maximum yield potential to understand ideal seeding rates. The goal of stand establishment is 25-35 plants/ft² with each plant producing 3 to 5 tillers. Maximum yield potential can be achieved with 60-80 heads/ft².

Aim for stand uniformity – stand consistency comes back to good seedbed conditions and accurate seed placement with your planting equipment. Target a consistent planting depth of 1 to 1.5 inches.

Planting Date

Optimum wheat planting dates are based on regional recommendations along with conditions and experience on a grower's own farm. The planting window for most regions is typically 2-3 weeks in length before yield potential declines. Delayed planting can occur for a variety of reasons, resulting in fewer fall tillers, greater risks of winter injury, and lower yield potential. High temperatures at planting can speed up germination rates but may result in fewer established seedlings when soil moisture is adequate. Low soil moisture at planting may slow germination and hinder early wheat growth.

Variety Selection and Seed Treatment

High yield starts with elite genetics adapted to the area. Other considerations like winterhardiness, disease or insect resistance, and lodging resistance are important to help protect yield. When using high seeding and nitrogen (N) fertilizer rates, resistance to powdery mildew is important. Always plant new, certified wheat seed and use seed-applied fungicide and insecticide treatments to protect seedlings from early pest pressure.

Crop Rotation

Wheat has the greatest potential for high yields when planted after soybeans or corn. Crop rotation breaks the disease and pest cycles of each crop and increases canopy competition for earlier and better weed suppression. More frequently, growers are planting rotations of corn, wheat, and double-crop soybeans after wheat harvest, where three crops are harvested in two years.

SOIL FERTILITY FOUNDATIONS

Nutrient Needs of Wheat

Wheat performance is very responsive to good soil fertility and timely fertilizer applications due to its shallow root



system. Every soil type has different capabilities to supply essential nutrients to high yield wheat plants. Fertile soils can only be highly productive if the physical structure (texture, density, porosity, drainage) and biological (microorganisms) properties of the soil are maintained.

Wheat prefers a soil pH between 6 and 7 for optimal growth. Manage soil pH for the crop with the highest pH need in the rotation. Primary nutrients for high yield wheat are nitrogen (N), phosphorus (P), and potassium (K). Removal rates for grain and straw are shown in Table 1. For secondary and micronutrients, wheat is a high demand crop for manganese (Mn), a medium demand crop for sulfur (S) – when straw is removed – and copper (Cu), and a low demand crop for boron (B), molybdenum (Mo), and zinc (Zn).

Fertilizer application rates are not the same as nutrient removal rates for wheat and wheat straw. Always soil test to help determine baseline levels of nutrients in the field. Wheat yield response to P and K fertilizer depends on soil nutrient test levels, organic matter, prior crop legume credits, and weather. Use state and local fertilization recommendations coupled with on-farm experience to develop a wheat fertilization plan.

Table 1. Winter wheat nutrient removal in grain and straw.

Nutrient	Grain 120 bu/acre	Straw 2 tons/acre	Total
———— lbs/acre ————			
Nitrogen (N)	140	25	165
Phosphate (P ₂ O ₅)	48	12	60
Potassium (K ₂ O)	30	60	90

Fertilize at the Start

Adjusting soil pH to a range of 6-7 maximizes nutrient availability and uptake, providing the mineral resources for optimum plant growth and grain production. To hit a target pH of 6.5, plan to apply lime 6-12 months prior to seeding.

Paying attention to the biggest nutrient needs of the plant starts prior to seeding. Growing high-yielding varieties in high yield environments means total N, P, and K demand is greater. Phosphorus (P_2O_5) and potash (K_2O) fertilizers are most effective when banded compared to broadcast applications because it can help roots have better access to nutrients and helps prevent off-site movement of nutrients due to snow melt or rainfall. Cooler soils benefit most from banded or seed-placed P and K fertilizer applications.

Starter fertilizer containing 20–30 lbs/acre of P placed with the seed or banded at planting helps promote early season growth and tillering in the fall and improve winterhardiness. Potash (K_2O) fertilizers help promote strong stem growth, prevent lodging, and help promote plant development and good plant health. When starting with high or excessively high soil test K levels, response to additional K fertilizer will likely be minimal.

If broadcast spreading fertilizer, aim for uniform distribution of the applied fertilizer – spend time pattern testing spreader equipment to improve distribution. Many have found boom-type air applicators or liquid N application systems to be more accurate than spinning disk technology.

Nitrogen Powers Yield Potential

Nitrogen (N) is frequently the most yield-limiting nutrient for winter wheat. It promotes tillering and shoot number, drives photosynthesis, and is the building block of protein in the plant and grain. Wheat can use up to 1.0–1.5 pounds of nitrogen for each bushel of expected yield and utilizes 70–75% of the total nitrogen requirement between Feekes growth stages 6 and 10. The greatest amount of nitrogen should be available at that time.

In general, growers aiming for high wheat yields apply a total of 100–140 lbs N/acre. Managing N in wheat can be challenging because of yield and quality penalties for running short of N and the increased lodging potential when over-applied. When tiller counts are high ($>70/\text{ft}^2$), a single application of N at Feekes growth stage 4–5 (prior to jointing) should be sufficient to maximize yield potential.

At planting, it is often beneficial to apply a small amount of N (20–30 lbs N/acre) to encourage early growth and fall tillering, especially if planting is delayed. Split applications of N to wheat often help maximize yield potential, especially if planted on light or sandy soils or if a stand is marginal and tiller counts are low ($<70/\text{ft}^2$). A first application of 40–60 lbs/acre of N is applied prior to green-up at Feekes stage 3. Then another 60–80 lbs N/acre is applied at Feekes stage 4–5.

What form of nitrogen should be used? The form of nitrogen is not as important as how accurately it is applied. Common forms of nitrogen used include ammonium sulfate, urea, and 32% or 28% liquid N. Apply a uniform rate across the entire application width. Liquid 28% N solutions may result in leaf burning but can be managed by using streaming or flood nozzles, keeping the N rate lower, or avoiding using 28% N tank-mixed with herbicides.

MANAGING FOR LODGING RISK

Growing wheat in high yield environments can lead to plant lodging, reducing harvestability and yield potential. Many growers use Palisade® EC plant growth regulator (PGR) to reduce the risk of lodging and harvest delays and to protect yield potential of the crop. Palisade works by shortening stem internodes and thickening stem diameter resulting in shorter plants with a lower center of gravity that are less likely to lodge. Palisade is applied between Feekes GS 4–7 and can be tank-mixed with many pesticides and liquid fertilizers.



PEST MANAGEMENT

Timing

Timing of pesticide products to control weeds, disease, or insects is critically important and growers may only have a 48-hour window. Be prepared by scouting frequently and having equipment ready to go when needed.

Weeds

Start clean, stay clean! Weeds emerging at the same time as the wheat crop are most likely to reduce yield potential. Keep weeds in check early in their life cycle and do not let weeds get too big. Use a burn down herbicide well before planting in no-till environments to eliminate weeds and volunteer corn. Use multiple tillage passes in a conventional tillage program if needed to start with a weed-free seedbed. The best cultural weed control strategy is to manage wheat seedlings for quick emergence and vigorous early growth.

Recommendation: Apply Quelex® herbicide at a rate of 0.75 oz/acre to actively growing wheat. Weed control is best when applied to weeds that are growing, and when wheat is at the 2- to 4-leaf stage, or less than 4 inches tall. Be sure to read and follow all label directions. Do not apply a total of more than 0.75 oz/acre of Quelex herbicide per season. Consider the fall weed management program before proceeding with spring treatments.

Diseases

Wheat disease management is key to producing high-yielding wheat crops. Disease control begins with variety selection and the use of a seed-applied treatment at planting. Wheat crops with 100+ bu/acre yield potential have a high density of stems and leaves, which – with wet weather – creates a favorable environment for disease development and growth.

A major disease of wheat is Fusarium head blight, also known as head scab, which is caused by *Fusarium graminearum* and other *Fusarium* spp. This disease occurs during flowering and grain fill stages of growth and is most prevalent with warm, wet weather conditions. A foliar fungicide treatment that protects the emerging flag leaf at Feekes stage 9 is most effective at protecting yield and grain quality.

Recommendations: Apply Aproach® fungicide at 3–4 fl oz/acre between tillering and jointing (Feekes GS 4–6) for early-season disease control or suppression. Apply Aproach® Prima fungicide at 6.8 fl oz/acre as the flag leaf emerges (Feekes GS 9) for optimal flag leaf disease control. Apply Prosaro® fungicide at early flower (Feekes GS 10.5) for improved control of Fusarium head blight.

Insects

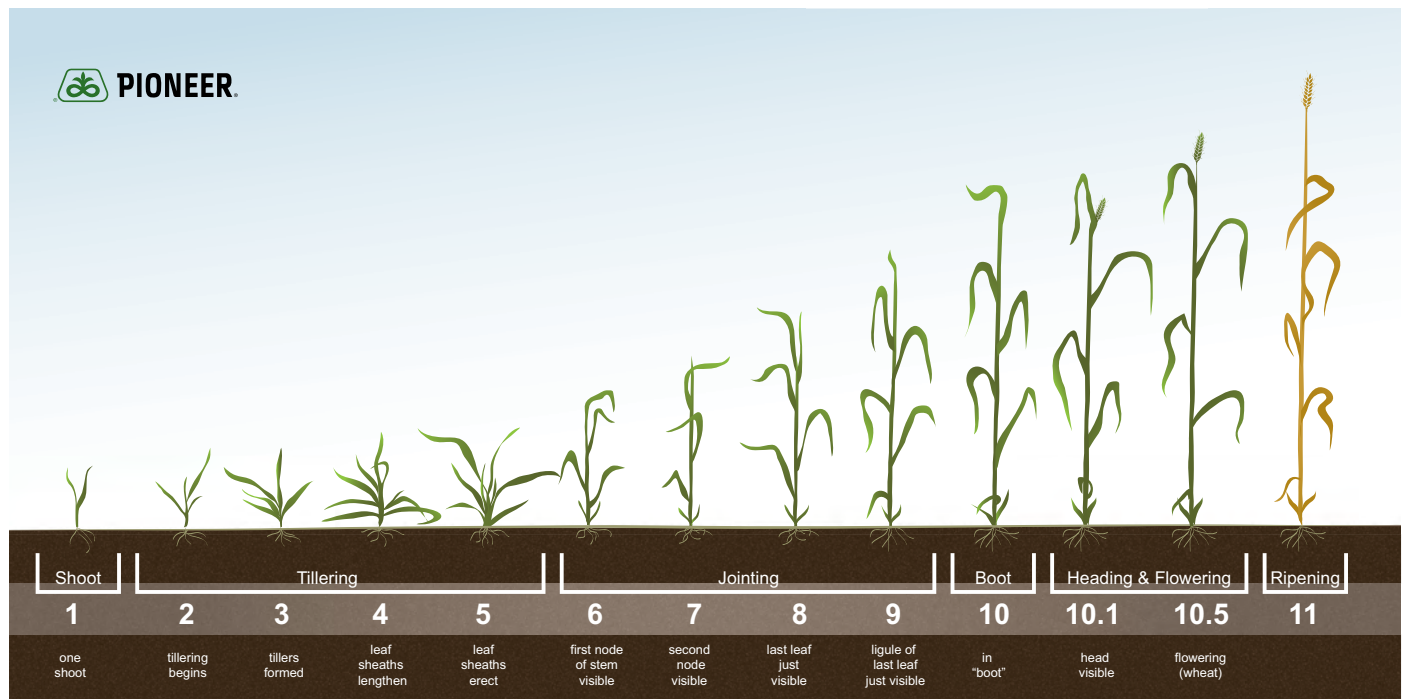
The probability of severe insect infestations is relatively low in winter wheat. Regular field scouting is necessary to help identify insect issues early. Aphids are the most common insect pest in wheat. Aphids suck sap from plants and move barley yellow dwarf virus (BYDV) within a field. When aphid populations exceed thresholds (10 per foot of row with early green-up and good conditions) a treatment should be applied to protect the wheat crop.



ACHIEVING TOP-END YIELD

Big yield potential is driven by large inputs of sunlight energy and water. The ability to capture and use as much sunlight and water as possible is key to success. To do this means keeping plants healthy and having all essential nutrients available for use by the crop.

Yield contest growers are intensive thinkers about managing the crop. They work within a framework of soils, farm microclimates, and crop input options to promote high yield. Attention to crop needs is accomplished by frequent visits to the field to observe crop growth or to identify crop growth setbacks. Timely treatments with fertilizers and crop protection products can help push the wheat crop to perform at its highest potential. Using the best wheat genetics will give growers an opportunity to stretch yield limits on their farm.



Stage of Growth	Description	Management
Feekes 1 SEEDLING GROWTH	- Germination, coleoptile, and first true leaf emergence - Development of multiple leaves and seminal root system	- Evaluate plant stands and uniformity of establishment – target is 25–35 plants/ft². - Observe weed growth and monitor for aphids and Hessian fly damage – take control measures as needed. - Using a drone, capture pictures of vegetation development to identify areas of the field with potential nutrient deficiencies, poor soil characteristics, low or high soil moisture, and weed or pest issues.
Feekes 2–3 TILLERING	- Primary tiller formation begins - Winter dormancy and vernalization - Spring growth and secondary tiller formation from primary tillers	- Tillers contribute 30–50% of yield potential – tillers formed between emergence of 4th and 6th leaves on the main stem have the best opportunity to form grain and contribute to yield – late forming tillers may fail to produce grain, especially when under stress. - Apply nitrogen fertilizer in the fall to stimulate early growth and tillering. - Check stands for winter injury and determine if herbicide is needed to control weeds. - Early spring applications of nitrogen fertilizer prior to initiation of green-up will promote post-winter tillering and increase stem density of the crop (apply up to 30% of total N need at this stage).
Feekes 4–10 STEM EXTENSION	- Stem elongation begins and stem nodes form (jointing, Feekes 6) when the growing point moves above the ground surface and plants become more erect – also known as the green-up stage - Feekes 8–9 – flag leaf emergence - Feekes 10 – booting stage where a fully grown head is seen as swelling in the stem area just below the flag leaf	- Apply additional nitrogen as needed prior to Feekes stage 6 to supply sufficient N for the upcoming stem elongation and heading stage when nitrogen demand is greatest. - Growth regulators that limit upper stem elongation can be used to help prevent lodging of a wheat crop. - Scout for weeds, insects, and foliar diseases during this time and initiate control measures when needed. - Application of nitrogen at flag and boot stage may increase grain protein and increase the size of seeds produced. - Fungicide application to protect the flag leaf can be made during the flag leaf and booting growth stages – the flag leaf is 75% of effective leaf area at this stage and is critical for high grain fill potential.
Feekes 10.1–10.5 HEADING & FLOWERING	- Heading – inflorescence and flower organs are fully developed and emerge from the stem - Flowering and anthesis – pollen producing anthers extrude from the floret and flowers are pollinated beginning with the middle spikelets	- Wheat is susceptible to Fusarium head blight at this time and fungicides can effectively minimize damage from this disease when applied during the onset of flowering. - Pollination takes about 4 days for an individual head after which grain fill begins. - Grain fill duration depends on temperatures, soil moisture, or plant stress and can take anywhere from 13 to 20 days or more.
Feekes 11 RIPENING	Ripening and senescence – kernel moves from milky to soft dough to hard dough stages reaching physiological maturity when kernel moisture content is below 30%	- During ripening, plants continue to need adequate soil moisture to make sure grain fill continues without interruption and maximum yield potential is reached. If irrigation is available, use it to avoid water stress in the ripening stage of growth. - Harvest begins when kernel moisture drops to the 15% level or lower and storage is safe when grain moisture is in the 12–14% range.

CHINCH BUGS

KEY POINTS

- The common chinch bug (*Blissus leucopterus*) is an economically important pest of grass field crops in the eastern High Plains of the U.S.
- Chinch bugs pierce vascular tissues of plants to feed on sap and secrete digestive enzymes that break down surrounding plant tissues.
- The greatest threat of economic damage from chinch bugs comes from the large migration of immature bugs from maturing wheat fields into nearby corn and sorghum fields that occurs in late May to early June.

DISTRIBUTION AND PEST STATUS

- The chinch bug (*Blissus leucopterus*) – often referred to as the common chinch bug – is an insect pest of grass crops that is native to North America and found throughout the U.S. and southern Canada.
- *B. leucopterus* is the most common species in the genus *Blissus*, all of which are referred to as chinch bugs, including the closely related southern chinch bug (*B. insularis*) and hairy chinch bug (*B. leucopterus hirtus*), both of which are primarily pests of turfgrass.
- *B. leucopterus* is an economically important pest of grass field crops in the eastern High Plains of the U.S. – particularly corn and sorghum – as well as small grains such as wheat and barley.
- Outbreaks of chinch bug can cause substantial yield loss in corn and sorghum if left uncontrolled.

LIFE CYCLE

- Chinch bugs have three life stages: egg, nymph, and adult, and typically go through two generations per year in the eastern High Plains.
- Adult chinch bugs primarily overwinter in grassy areas such as grass pastures, CRP acres, fencerows, and road ditches near fields that they infested during the prior summer.
- Their preferred overwintering sites are dense clumps of native warm-season bunchgrasses.
- Adults leave overwintering sites during the spring when temperatures rise above 70°F (21°C) for several consecutive days and fly to fields of small grains where they mate and lay eggs.
- In the eastern High Plains, chinch bugs typically lay the first generation of eggs in wheat because it is the most readily-available host, although they prefer barley and other grasses.



Figure 1. Adult chinch bugs (*Blissus leucopterus*).

- Females will lay eggs over a 2- to 4-week period. Females can lay up to several hundred eggs each, although the number of eggs laid can vary greatly from year to year.
- Eggs take 1 to 2 weeks to hatch, and newly hatched nymphs take around a month to reach full maturity. Nymphs molt five times before becoming adults.
- Chinch bugs move from wheat fields to nearby corn or sorghum fields in late May and early June – first a flight of adults when the wheat canopy closes and then a larger migration of both nymphs and adults as the wheat ripens.
- The migrating population consists mostly of nymphs, which do not have wings and must walk to nearby corn or sorghum fields.
- After moving into corn or sorghum, the nymphs feed on the plants and, once they reach adult stage, fly and disperse throughout the field before depositing eggs for the second generation.

IDENTIFICATION

- Chinch bug eggs are oblong and tiny – typically less than 1 mm long. They are white to yellow when laid and darken to a reddish color before hatching.
- Eggs are laid individually but may be found in clusters. In small grain crops, they are deposited around the base of plants, behind lower leaf sheaths and at the crowns of plants near or just below the soil surface.
- Nymphs change in appearance with each molt – newly hatched nymphs are bright red, and they are red to brown with a white band across their backs through the first four instars.
- Fifth instar nymphs are nearly black, with the white band partially covered by the developing wings.

- Adult chinch bugs are about 3/16 inch (5 mm) long, with a black body and white wings that have a triangular black area in the middle of the outer margin, and dark yellow to reddish legs (Figure 1).

INJURY SYMPTOMS AND IMPACT ON CROP

- Chinch bugs pierce vascular tissues of plants to feed on sap and secrete digestive enzymes that break down surrounding plant tissues.
- Feeding punctures can also serve as an entry point for plant pathogens

Small Grains

- Healthy stands of winter wheat rarely experience economic levels of damage; whereas thin stands are more susceptible.
- Spring planted small grains – especially barley – can be heavily damaged when large populations survive the winter.
- Under heavy infestations, leaves will turn yellow, then brown, starting with the lower leaves and proceeding up the plant.

Corn and Sorghum

- The greatest threat of economic damage from chinch bugs comes from the large migration of immature bugs from maturing wheat fields into nearby corn and sorghum fields.



Figure 2. A plant infested with chinch bugs.

- Sorghum is a highly preferred food source that is very susceptible to damage, particularly with later planting.
- Feeding begins at the crowns and below the soil surface on the roots and stems of small plants and then above ground on the lower portion of the stem.
- Under high infestations, chinch bugs may be present in large enough numbers to completely cover the lower part of the plant (Figure 2).
- Damaged plants can display a variety of symptoms including yellowing, stunting, wilting, and necrotic lesions.
- Damage usually first appears along the field margin but can spread quickly into the interior.
- In earlier planted corn – which is larger and more resilient to damage at the time of migration – damage is usually confined to the field edge.
- In later-planted corn and sorghum that is smaller at the time of migration, plants may be completely killed.
- As few as 2-3 chinch bugs can kill a seedling sorghum plant, while 5-10 bugs per plant can kill larger plants.
- Plants suffering from drought or other types of stress will have less capacity to recover from feeding damage.
- Damage from second-generation bugs can occur in sorghum when a severe infestation is coupled with drought stress.



Figure 3. Second-generation chinch bugs on the leaves of corn plants.

WEATHER EFFECTS

- Heavy infestations are most common in growing seasons with above-normal temperatures and below-normal rainfall.
- Heavy rainfall in May and June can significantly reduce survival of first-generation nymphs by burying them in mud and triggering fungal infections that can lead to heavy mortality.
- Extended periods of hot and dry weather can also kill off young nymphs.
- Large overwintering populations are favored by below-normal rainfall later in the season and mild winters, which increases survival in less-protected overwintering sites.



Figure 4. Close-up view of an adult chinch bug.

MANAGEMENT CONSIDERATIONS

- Historically, cultural control methods, such as burning of overwintering sites and the construction of physical barriers to impede migration, were widely used to manage chinch bugs.
- Separating small grain fields and sorghum/corn fields with a non-host crop has also been recommended, although migrating nymphs can travel considerable distances to find a suitable host crop.
- An early planted strip of corn or sorghum along the field margin can be used as a trap crop, which can then be treated with an insecticide.
- Insecticide seed treatments are an important tool for management of chinch bugs – systemic neonicotinoid insecticides such as clothianidin and imidacloprid provide sorghum plants with about three weeks of protection, giving the plants a better chance of making it through the seedling stage when they are most susceptible to damage.
- Protection from seed treatments has its limits though – early planted sorghum may lose seed treatment efficacy before the bugs migrate in, and heavy enough infestations may still be able to overwhelm and kill treated plants.
- Timely applications of foliar insecticides can be used to rescue corn or sorghum fields that have been invaded by chinch bugs.
- Applications should be made as migrations begin, before large numbers of insects have entered the field.
- Insecticides can be applied as a border treatment or full field treatment if the infestation is widespread.
- Chinch bugs are difficult to control – it is important to use the full recommended rate of insecticide and a high carrier volume (20 to 40 gallons of water per acre).
- For plants up to 6 inches tall, consider banding the spray over the row.
- For taller plants, applications directed at the base of the plant provide the best control.
- A second application may be necessary if heavy migration extends for more than 10 days.
- **Always read and follow insecticide label recommendations.**

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TRADEMARKS

AM – Optimum® AcreMax® Insect Protection system with YGCB, HX1, LL, RR2. Contains a single-bag integrated refuge solution for above-ground insects. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax products.

AML – Optimum® AcreMax® Leptra® products with AVBL, YGCB, HX1, LL, RR2. Contains a single-bag integrated refuge solution for above-ground insects. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax Leptra products.

AMXT (Optimum® AcreMax® XTreme) – Contains a single-bag integrated refuge solution for above- and below-ground insects. The major component contains the Agrisure® RW trait, a Bt trait, and the Herculex® XTRA genes. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax XTreme products.

Q (Qrome®) – Contains a single-bag integrated refuge solution for above- and below-ground insects. The major component contains the Agrisure® RW trait, the Bt trait, and the Herculex® XTRA genes. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Qrome products.

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.

PWE – PowerCore® Enlist® corn products with HX1, VTP, ENL, LL, RR. A separate 5% corn borer refuge in the corn belt, and a separate 20% corn borer refuge in EPA-designated cotton-growing counties must be planted PowerCore Enlist products

V – Vorceed™ Enlist® products with V, LL, RR, ENL. Contains a single-bag integrated refuge solution with multiple modes of action for above- and below-ground insects. The major component contains the Herculex® XTRA genes, the RW3 trait and the VTP trait. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted for Vorceed Enlist products.

YGCB, HX1, LL, RR2 (Optimum® Intrasect®) – Contains a Bt trait and Herculex® I gene for resistance to corn borer.

AVBL,YGCB,HX1,LL,RR2 (Optimum® Leptra®) – Contains the Agrisure Viptera® trait, the Bt trait, the Herculex® I gene, the LibertyLink® gene, and the Roundup Ready® Corn 2 trait.

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

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