AGRONOMY

2022 Research Summary

PIONEER®

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INTRODUCTION

2021 GROWING SEASON IN REVIEW

Resilience, or lack thereof

If one had to choose a single word to define 2021, "resilience" would be a good contender. 2021 was a year in which the resilience of infrastructure and supply chains was put to the test by a seemingly endless succession of disruptions. The year started off with the effects of the ongoing COVID-19 pandemic continuing to cascade through global supply chains. Shortages of raw materials and computer chips, congestion at ports in the U.S. and China, and labor shortages all contributed to restrict the flow of goods and drive up costs throughout the economy. Crop producers were directly impacted by these disruptions, with machinery parts often in short supply and the season ending with a sharp run up in fertilizer prices and concerns over availability of nitrogen and other crop inputs for 2022.

Pandemic-related issues were compounded by a number of extreme weather events. In February, a southward migration of the polar vortex produced an extreme cold snap in Texas and overwhelmed an energy grid ill-equipped to handle the freezing temperatures. In June, Pacific Northwest areas of the U.S. and Canada experienced an unprecedented heat wave, causing agricultural losses, straining infrastructure, and fueling wildfires. Flooding driven by extreme rainfall impacted several areas in the U.S., as well as parts of China and Western Europe.

The grounding of the Ever Given container ship in the Suez Canal in March was emblematic of both the weather-related disruptions and supply chain fragility that characterized 2021. The ship was pushed off course by high winds, and the subsequent six-day blockage of a critical trade route resulted in a massive disruption to global shipping.

The container ship Ever Given stuck in the Suez Canal, March 27, 2021. NASA JSC ISS image library.

Mostly sunny with a chance of smoke

Resilience is always top of mind in crop production, as each year comes with its own set of conditions and challenges. The 2021 season got off to a relatively good start with timely planting in most areas. For some growers, 2021 was a welcome opportunity to get back on track after two planting seasons in a row were disrupted by the extreme wet conditions of 2019.

Fortunes diverged, as they often do, with summer weather. Summer of 2021 was the hottest on record for the contiguous U.S., due in large part to extreme heat in several western and northern states, and above average nighttime temperatures spanning almost the entire U.S. (Figure 1). Much of the northern Corn Belt and northern plains experienced above average daytime high temperatures as well (Figure 2). However, daytime highs were close to normal for much of the central Corn Belt and below average throughout the South.

Summer precipitation roughly corresponded to summer temperatures, with hotter areas generally being drier as well. Minnesota, the Dakotas, Nebraska, Kansas, and parts of Iowa all had below normal summer precipitation, while rainfall was above average in much of the eastern Corn Belt, and well above average in the South and the Northeast (Figure 3).

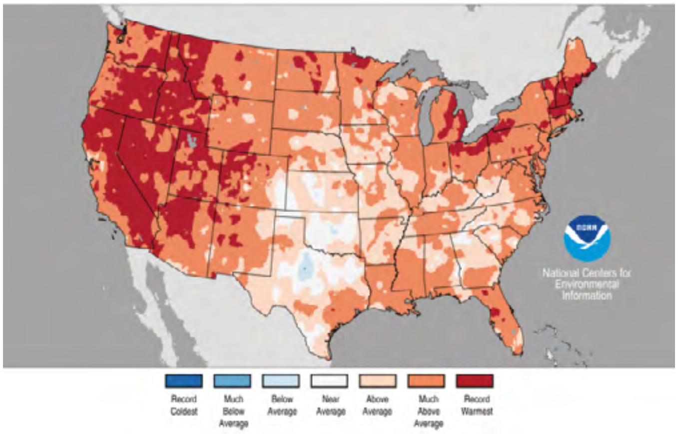


Figure 1. Minimum temperature percentiles June-Aug 2021.

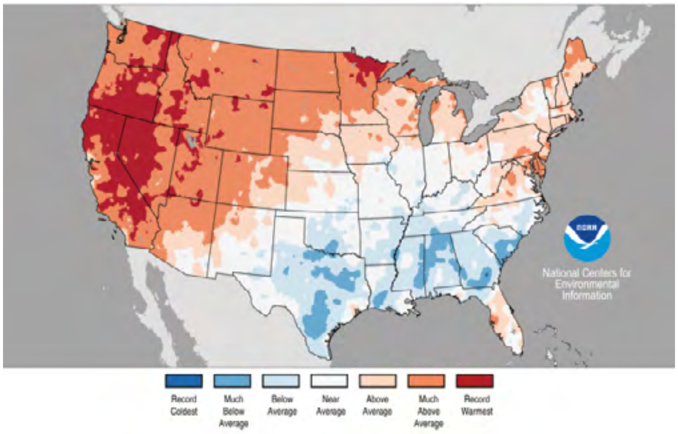


Figure 2. Maximum temperature percentiles June-Aug 2021.

Extreme heat and drought in the western U.S. and Canada drove another severe wildfire season, second only to the 2020 season in total area burned. Wildfire smoke in the atmosphere has now become a common enough feature to warrant questions as to its potential impact on crop productivity.

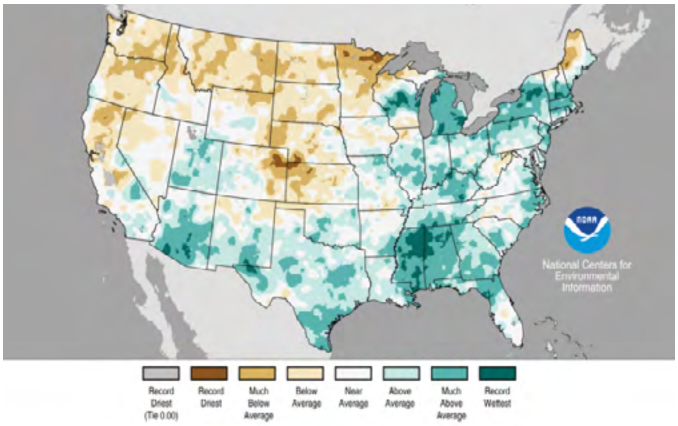


Figure 3. Total precipitation percentiles June-Aug 2021.

The 2021 season wound down with much of the western and northern U.S. under severe drought conditions, and some degree of drought affecting most of the U.S. west of the Mississippi (Figure 4). Further east, heavy late-season rains brought field work to a stop and caused harvest to lag behind normal pace in parts of the central and eastern Corn Belt.

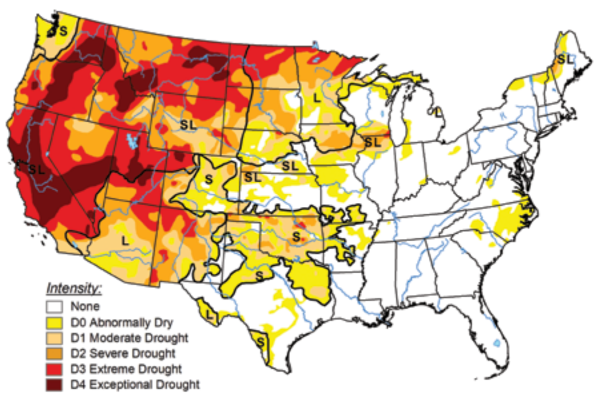


Figure 4. U.S. Drought Monitor map, October 5, 2021.

Disease and insect pressure

In addition to weather-related challenges, diseases and insect pests made an impact in 2021. Corn rootworm pressure was high in parts of the Corn Belt, likely due, in part, to soil conditions favorable for winter survival and spring hatch. In areas that received adequate summer precipitation, foliar diseases were often an issue. Southern rust continued its recent trend of pushing further up into the Corn Belt, appearing as far north as Wisconsin, Michigan, and Ontario. A widespread outbreak of tar spot proved that the 2018 outbreak was not a fluke and that this disease will be an ongoing challenge for corn production in the U.S. and Canada.

Rain makes grain

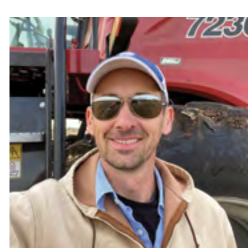
When all was said and done in 2021, yields were generally good where there was enough rain to keep the crop going. Corn yields were up over 2020 in most of the eastern U.S., with several states posting new records. Hot and dry conditions pushed yields down slightly in Minnesota and Wisconsin and down sharply in the Dakotas. Soybean yields followed similar trends, with record yields in a dozen states and generally good yields east of the Mississippi, while west of the river yields were flat or down everywhere except Iowa and Nebraska.

Takeaways from 2021

2021 demonstrated the importance of resilience in critical systems, as well as how far-reaching and interconnected those systems are. Plant breeders and agronomists have made great strides over the past century in improving crop genetics and agronomic management while increasing the resilience of cropping systems against a wide range of biotic and abiotic stresses. But those systems do not end at the farm gate; they encompass a vast web of supply chains that produce the inputs necessary for growing a crop and moving the finished product off the farm to buyers around the globe. Crop management systems need to be resilient to stress; energy and transportation systems must be resilient as well.

Many of the features of the 2021 growing season – severe heat and drought in the west, extreme rainfall events in the east, disruptions in the polar vortex, and expanding geographic ranges of pathogens and insects – are forecast to become more common as global temperatures continue to rise. Crop management systems that can endure changing and intensifying stresses will be increasingly important.

Pioneer Agronomy research is focused not only on continuing to drive top-line yield potential but also creating management systems that protect yield potential against an ever-evolving array of stress factors. This Agronomy Research Summary is the latest edition of an annual compilation of Pioneer agronomy information and research results. This summary provides insights on numerous crop production topics; however, it represents just a small portion of the vast array of resources available in the Pioneer agronomy library at www.pioneer.com. We hope that the resources available in this book and online will help you improve productivity and build resilience in 2022.



Mark Jeschke, Ph.D.

Agronomy Manager

Forward—thinking Farming

a webinar series powered by Pioneer® Agronomy

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

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2021 WEBINAR SERIES

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

FEEDING YOUR FIELD: NUTRIENT RATIOS IN CORN PRODUCTION

Identifying and understanding ideal nutrient ratios can help maximize your fertilizer investment, but which ratios should you be aiming for? Dr. Stephen Strachan, former Corteva Agriscience Research Scientist, reviews the science and physiology of the corn plant to help you identify nutrient ratios for your fields to potentially boost yield.

BEHIND THE SCENES IN THE SOILS LAB

What happens between pulling a soil sample on your farm and receiving your soil test report? Jamie Bultemeier from A&L Great Lakes Laboratories discusses soil analysis concepts, such as how different extractants used in various regions of the U.S. can impact soil test results, the difference between extractable and total nutrients, and how a lab generates a soil report.

FEEDING YOUR FIELD: HOW TO FORM YOUR NUTRIENT PLAN

A good nutrient management plan begins with a soil sample. In this webinar, Dr. Matt Clover, Pioneer Agronomy Manager, discusses how to use soil test results to develop your nutrient management strategy, the pros and cons of different nutrient programs, which fertilizers to use and why, and efficiencies of different application methods.

FEEDING YOUR FIELD: NUTRIENT UPTAKE FOR CORN PRODUCTION

Essential nutrients like nitrogen, phosphorus, and potassium are only valuable if they successfully travel from the soil to the corn roots. Dr. Stephen Strachan discusses how nutrients are stored in the soil and extracted by the corn root, facts about soil chemistry and plant physiology, and opportunities for farmers to increase corn yields through nutrient management.

FEEDING YOUR FIELD: CONNECTING CORN PHENOLOGY WITH HIGH YIELDS

Understanding the growth stages of a corn plant is an important factor when building your comprehensive nutrient plan. Dr. Brewer Blessitt, Pioneer Agronomy Manager, discusses nutrient needs during different growth stages and how to use plant tissue sampling to calculate nutrient uptake rates.

THE PIONEER® YIELD PYRAMID™ DECISION TOOL – REACHING NEW HEIGHTS

Dr. Matt Clover, Pioneer Agronomy Manager, and Troy Deutmeyer, Pioneer Field Agronomist, introduce the Pioneer Yield Pyramid decision tool, which uses advanced data science tools to help farmers prioritize their management decisions and increase yield potential.

OPTIMIZING YIELDS – THE IMPORTANT ROLE OF SULFUR

Dr. Matt Clover, Pioneer Agronomy Manager, and Dr. Shaun Casteel, Associate Professor of Agronomy at Purdue University, discuss the role of sulfur in building yield, best practices for fertilizer selection and application, and current research on sulfur applications for high-yielding soybeans.

SEED TREATMENTS – AN ANSWER TO CORN AND SOYBEAN NEMATODES

Nematodes – tiny, translucent, soil-dwelling pests – are known as silent yield-robbers of corn and soybeans, invisible to the naked eye with symptoms that can be easy to overlook. Ron Sabatka, Corteva Technical Marketing Manager, discusses the life cycles and distribution of key nematode species, impacts on crop yield, and seed protection options to maximize yield potential.

SOYBEAN WEED CONTROL: THE NEW ENLIST™ SYSTEM

Kevin Bradley, Professor and State Extension Weed Scientist at the University of Missouri; Nick Monnig, Pioneer Field Agronomist; Jaime Farmer, Pioneer Field Agronomist; and Ron Geis, Corteva Agriscience Market Development Specialist, discuss the Enlist™ system powered by Enlist herbicide, a new weed control option with broad application timing and tank mix flexibility.

BIOLOGICAL INNOVATION AND INTEGRATED MANAGEMENT SYSTEMS

Biological products offer cutting-edge, complementary solutions to the persistent challenges that growers face. Brooks Coetzee, Corteva Agriscience Laureate and Global Biologicals Leader, walks through examples of Corteva research, the importance of a holistic approach to management, and what can be expected from biologicals in the future.

Mark Jeschke, Ph.D.,
Agronomy Manager

MANAGING CORN FOR GREATER YIELD POTENTIAL:

4 LESSONS FROM 2020 NCGA WINNERS

KEY POINTS

- Improved hybrids and production practices are helping corn growers increase yields. Over the past 20 years, U.S. yields have increased by an average of 1.9 bu/acre/year.
- NCGA winners in the non-irrigated yield contest classes have increased their yields at more than double the rate of the national average. What are they doing differently?
- The NCGA National Corn Yield Contest provides a benchmark for yields that are attainable when conditions and management practices are optimized.
- The 2020 contest had 180 entries that exceeded 300 bu/acre, which was up from 130 entries in 2019 and second only to the record high of 224 entries in 2017.

4 LESSONS FOR INCREASING CORN YIELD

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

BENCHMARKING YOUR CORN YIELD

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

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

2020 NCGA National Corn Yield Contest Trends

The 2020 growing season was generally an improvement over the widespread challenges of the 2019 season. However, corn yield outcomes varied widely, with highly productive soils often yielding very well, while performance often dropped off on less productive and more drought-prone acres. Results of the 2020 NCGA National Corn Yield Contest reflected recent yield trends. The number of high-yield entries—defined for the purposes of this discussion as all entries yielding more than 300 bu/acre—increased considerably from 2019 but was still short of the all-time high set in 2017 (Figure 1).

The geographic distribution of high-yield entries in 2020 was, to some extent, an inversion of the pattern observed in 2019. In 2019, yield results were relatively poor in the central Corn Belt, while the Mid-Atlantic states of Pennsylvania, Delaware, New Jersey, and Virginia posted their best-ever results. In 2020, the central Corn Belt rebounded, with Illinois, Indiana, Nebraska, Ohio, Minnesota, and Wisconsin all showing strong results. No entries topping 300 bu/acre were recorded in either Pennsylvania or Virginia (Table 1).

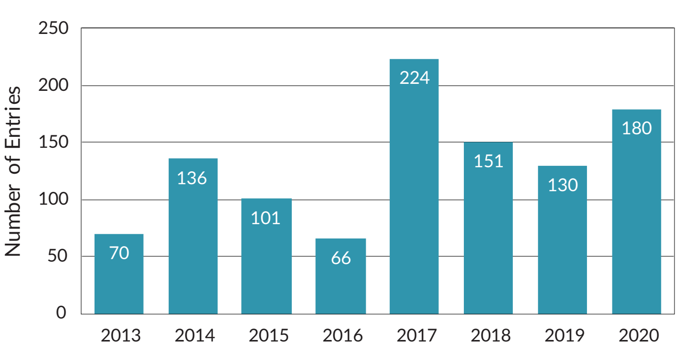

Figure 1. Total entries in the NCGA National Corn Yield Contest exceeding 300 bu/acre by year from 2013 to 2020.

Table 1. Number of NCGA National Corn Yield Contest entries over 300 bu/acre by state, 2016-2020.

State	2016	2017	2018	2019	2020
	number of entries				
AL	1	3	3	5	4
AR	1	2	1	0	1
CA	2	0	3	3	2
CO	2	4	1	0	1
DE	2	0	0	6	0
FL	0	0	0	0	0
GA	4	7	0	7	5
IA	7	16	8	3	6
ID	1	0	8	1	3
IL	5	25	18	6	19
IN	1	26	17	8	23
KS	1	2	3	2	6
KY	0	17	4	3	3
MA	1	1	2	4	1
MD	4	4	2	5	3
MI	1	7	1	4	3
MN	0	1	0	0	5
MO	1	12	4	3	11
NC	1	0	1	3	0
NE	1	41	39	7	37
NJ	0	1	1	9	9
NM	2	2	0	1	0
NY	0	4	0	0	0
OH	0	1	2	2	6
OK	3	2	2	0	2
OR	2	3	4	7	0
PA	0	0	0	15	0
SC	5	9	0	4	3
SD	0	2	0	0	2
TN	3	9	2	3	3
TX	4	3	7	1	2
UT	3	7	6	0	2
VA	3	5	2	9	0
WA	2	2	9	7	3
WI	1	6	1	1	13
WV	2	0	0	1	2
Total	**66**	**224**	**151**	**130**	**180**

The average yields among national winners tend to be skewed by a small number of very high yields, particularly in the irrigated classes. Therefore, as a yield performance benchmark, it can be useful to look at a larger set of contest entries. Table 2 shows the median yield of the top 100 yielding entries in the irrigated and non-irrigated classes. Median yields of top entries in both the irrigated and non-irrigated classes exceeded 300 bu/acre for the fourth year in a row, which is about 75% greater than the current U.S. average. Median yields of the top 100 non-irrigated entries and irrigated entries in 2020 were both short of the highs achieved in 2017.

Table 2. Median yields of the top 100 irrigated and non-irrigated NCGA National Corn Yield Contest entries and the USDA average U.S. corn yields, 2014-2020.

Year	Non-Irrigated	Irrigated	U.S. Average
	bu/acre		
2014	299	306	171
2015	292	288	168
2016	283	294	175
2017	312	317	177
2018	300	315	176
2019	302	311	168
2020	307	310	172

SELECT THE RIGHT HYBRID

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

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

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

Pioneer® brand products were used in 13 national winning entries (Table 3), as well as 219 state-level winning entries—more than any other seed brand. State-level winners included a total of 79 different Pioneer brand products from 53 different hybrid families ranging from 70 to 120 CRM.

Table 3. 2020 NCGA National Corn Yield Contest national winning entries using Pioneer brand products.

Category	Rank	State	Hybrid/Brand[1]
A: Conv. Non-Irrigated	2nd	SC	**P1847VYHR** (AVBL, YGCB, HX1, LL, RR2)
A: Conv. Non-Irrigated	3rd	NJ	**P1197**
C: NT Non-Irrigated	1st	SC	**P1847VYHR** (AVBL, YGCB, HX1, LL, RR2)
C: NT Non-Irrigated	2nd	NJ	**P1464AML™** (AML, LL, RR2)
C: NT Non-Irrigated	3rd	WV	**P1197**
D: NT Non-Irrigated	3rd	IA	**P1563AM™** (AM, LL, RR2)
E: Strip-, Min-, Mulch-, Ridge-Till Non-Irrigated	1st	NJ	**P1197AMT™** (AMT, LL, RR2)
G: No-Till Irrigated	1st	NE	**P1138AML™** (AML, LL, RR2)
G: No-Till Irrigated	2nd	NE	**P1138AML™** (AML, LL, RR2)
H: Strip-, Min-, Mulch-, Ridge-Till Irrigated	2nd	NE	**P1828AM™** (AM, LL, RR2)
I: Conventional Irrigated	1st	MI	**P0720AM™** (AM, LL, RR2)
I: Conventional Irrigated	2nd	WI	**P0720Q™** (Q, LL, RR2)
I: Conventional Irrigated	3rd	NE	**P1563AML™** (AML, LL, RR2)

The brands of seed corn used in the highest yielding contest entries in 2015 through 2020 are shown in Figure 2. In all years, Pioneer brand products were used in more entries exceeding 300 bu/acre than any other individual seed brand.

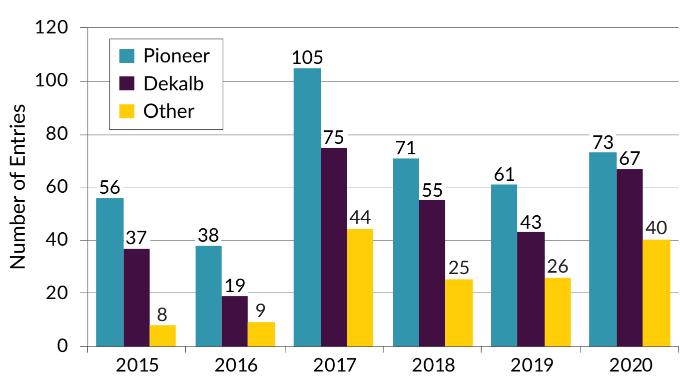

Figure 2. Seed brand planted in National Corn Yield Contest entries exceeding 300 bu/acre from 2015 to 2020.

Yields exceeding 300 bu/acre have been achieved using Pioneer® brand products from 66 different hybrid families over the past 6 years, ranging from 91 to 121 CRM. The top-performing Pioneer hybrid families in the National Corn Yield Contest are shown in Table 4. The Pioneer brand P1197 family of products has had the best performance in the contest by far, topping 300 bu/acre 84 times since its debut in the contest in 2014. Pioneer brand P1185 and P1563 families of products were top performers in the 2020 yield contest.

Table 4. Pioneer hybrid families with the most entries over 300 bu/acre in the NCGA National Corn Yield Contest over the past six years.

Hybrid Family	2015	2016	2017	2018	2019	2020	Total
	number of entries						
P1197	13	10	33	11	11	**6**	**84**
P2088	7	5	14	5	1		**32**
P1366			8	10	9	**3**	**30**
P1828				8	4	**6**	**18**
P0801	1	1	9	5	1		**17**
P1563				3	1	**11**	**15**
P1870			4	1	9	**1**	**15**
P1151	5	1	3	1	1		**11**
P0157	2	1	3	2	2	**1**	**11**
P1185						**10**	**10**
P1311	1	5	3			**1**	**10**
P1370			1	5		**2**	**8**
P0574			3	2	2		**7**
P1751	1	3	2	1			**7**
P9840		1	1	2	2		**6**

HIGH-YIELD MANAGEMENT PRACTICES

Top performers in the NCGA National Corn Yield Contest not only have produced yields much higher than the current U.S. average, they have also achieved a higher rate of yield gain over time. Over the past 20 years, U.S. corn yields have increased at a rate of 1.9 bu/acre/year while winning yields in the non-irrigated yield contest classes have increased by 5.1 bu/acre/year.

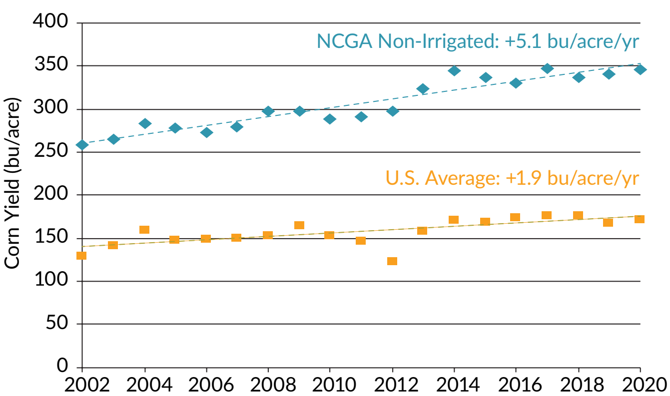

Figure 3. Average yields of NCGA National Corn Yield Contest non-irrigated class national winners and U.S. average corn yields, 2002-2020.

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.

OPTIMIZE PLANTING PRACTICES

Establish Sufficient Population Density

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

Harvest populations in irrigated and non-irrigated National Corn Yield Contest entries over 300 bu/acre from 2016 through 2020 are shown in Figure 4. The average harvest population of irrigated entries (36,720 plants/acre) was slightly greater than that of non-irrigated entries (36,550 plants/acre) over five years. However, yields over 300 bu/acre were achieved over a wide range of populations—from 28,000 to 56,000 plants/acre—demonstrating that exceptionally high populations are not necessarily a prerequisite for high yields. Although population density is important in establishing the yield potential of a corn crop, it is just one of many factors that determine yield.

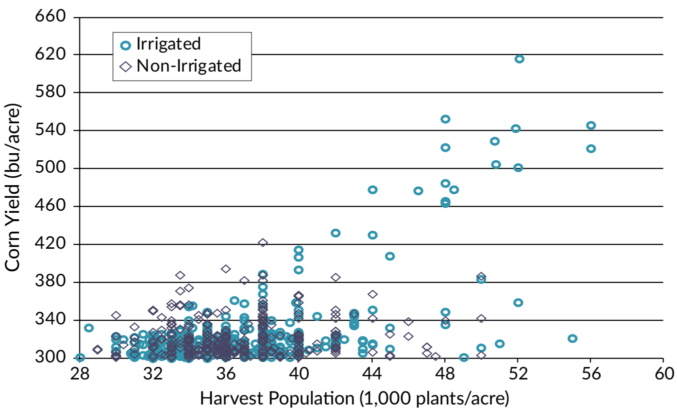

Figure 4. Harvest populations and corn yield of irrigated and non-irrigated NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2016-2020.

Plant Early

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

Planting dates for entries exceeding 300 bu/acre ranged from March 15 to June 3 in 2020. Mid-April to early-May planting dates have typically been the most common for high-yields in the central Corn Belt. The 2020 contest had several high-yield entries planted in mid- to late-May (21 entries over 300 bu/acre were planted after May 15), demonstrating that high yields can still be achieved under favorable conditions if planting is not delayed for too long.

Determine Row Width

The vast majority of corn acres in the U.S. are currently planted in 30-inch rows, accounting for more than 85% of corn production. **A majority of 300 bu/acre contest entries over the past five years have been planted in 30-inch rows** (Figure 5). This proportion has increased slightly in recent years as wider row configurations (most commonly 36-inch or 38-inch) have declined and narrower row configurations (15-inch, 20-inch, 22-inch or 30-inch twin) have largely remained steady.

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).

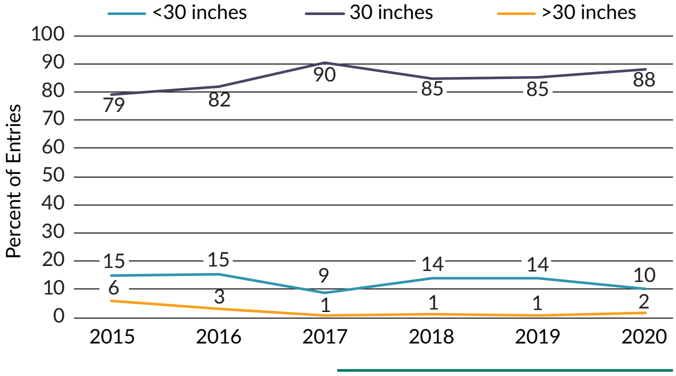

Figure 5. Row width used in NCGA National Corn Yield Contest entries exceeding 300 bu/acre, 2015-2020.

ROTATE CROPS

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

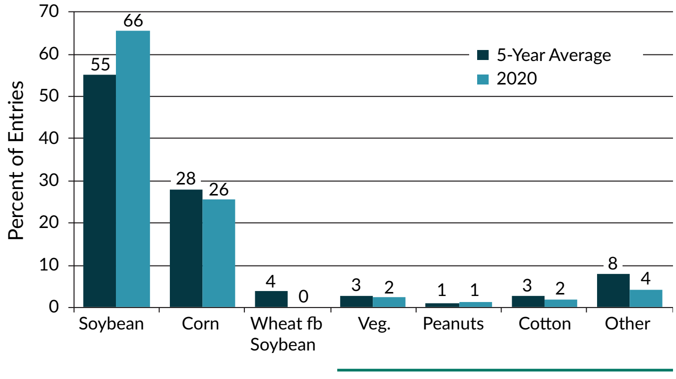

Figure 6. Previous crop in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2020 and 5-year averages.

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% in research studies but has generally been lower 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, close to half of the high-yield entries in the NCGA National Corn Yield Contest have used conventional tillage, with the other half using no-till or some form of reduced tillage (Figure 7). The proportion of high-yield entries using conventional tillage has declined over time, offset by increases in no-till and strip-till.

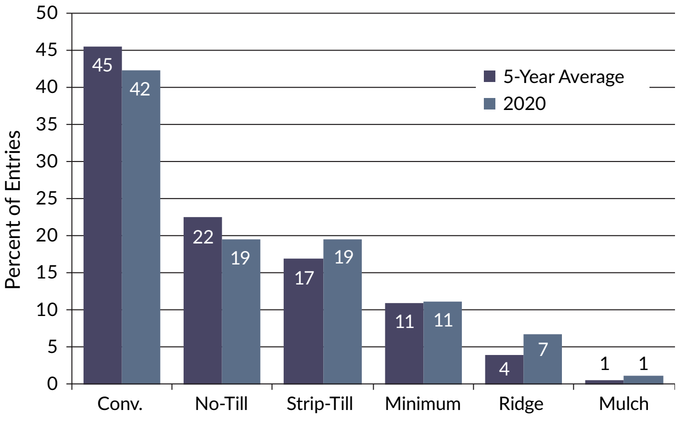

Figure 7. Tillage practices in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2020 and 5-year averages.

OPTIMIZE NUTRIENT MANAGEMENT

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

Nitrogen

Corn grain removes approximately 0.67 lbs of nitrogen (N) 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, as 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 crops, manure applications, and N in irrigation water. Nitrogen application rates of entries exceeding 300 bu/acre are shown in Figure 8.

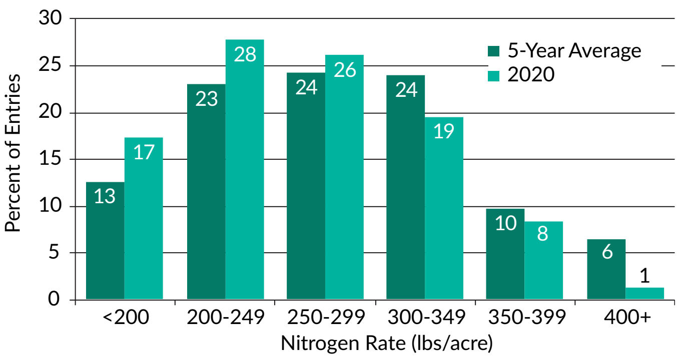

Figure 8. Nitrogen rates (total lbs/acre N applied) of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2020 and 5-year averages.

The N application rates of 300 bu/acre entries varied greatly in 2020, but over half were in the range of 200 to 300 lbs/acre. Some entries with lower N rates were supplemented with N from manure applications. 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 yields 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.

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, 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. Around 90% of 300 bu/acre entries included some form of in-season N, either side-dressed or applied with irrigation. Multiple N applications were also used in around 90% of high-yield entries.

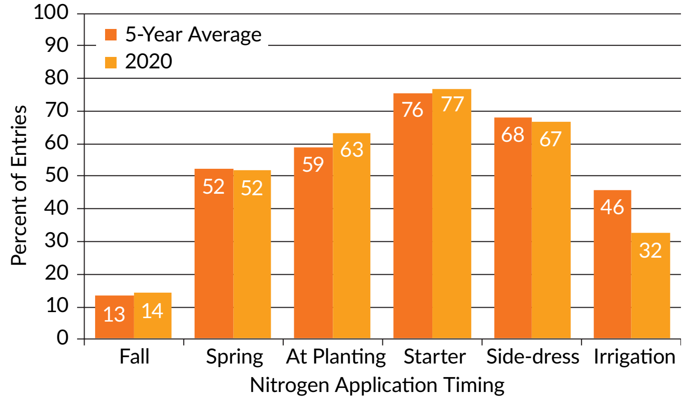

Figure 9. Nitrogen fertilizer application timing of NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2020 and 5-year averages.

Micronutrients

Micronutrients were applied on nearly half of the 300 bu/acre entries (Figure 10). The nutrients most commonly applied were sulfur (S) and zinc (Zn), with some entries including boron (B), magnesium (Mg), manganese (Mn), or copper (Cu). Micronutrients are sufficient to meet crop needs in many soils. However, some sandy soils and other low organic matter soils are naturally deficient in micronutrients, and high pH soils may make some micronutrients less available (Butzen, 2010). Additionally, as yields increase, micronutrient removal increases as well, potentially causing deficiencies.

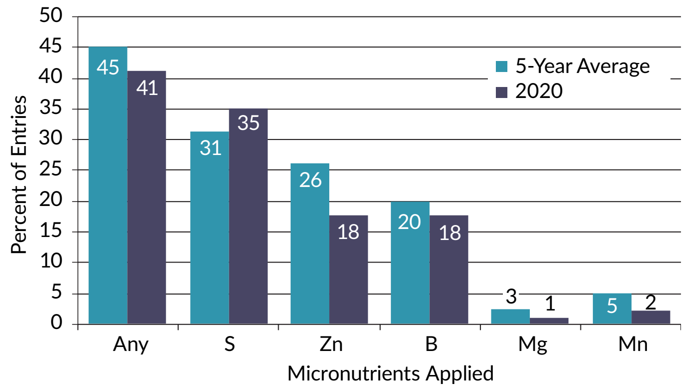

Figure 10. Micronutrients applied in NCGA National Corn Yield Contest entries exceeding 300 bu/acre in 2020 and 5-year averages.

Mark Jeschke, Ph.D.,
Agronomy Manager

WHY DO CORN PLANTS DEVELOP MULTIPLE EARS ON THE SAME SHANK?

KEY POINTS

- Modern corn hybrids generally produce one ear per plant but may produce a second ear on the node below the primary ear if sunlight and resources are abundant.
- In rare cases, plants will produce multiple ears at the same stalk node.
- The phenomenon of multiple ears on the same shank is associated with a disruption in the hormonal apical dominance of the primary ear, and often occurs when the primary ear fails to develop properly.
- In many cases, the primary ear remains dominant and develops normally, with smaller secondary ears that will often fail to pollinate.
- “Bouquet ears” refers to a form of multiple ear development in which a plant forms a cluster of several ears, none of which develop normally.

MORE EARS, MORE PROBLEMS

Modern corn hybrids grown at plant populations that optimize yield generally produce one main ear per stalk. However, in areas of the field where plants experience less competition with their neighbors for sunlight and resources, such as along field edges or adjacent to gaps, it's not unusual to find two ears per plant. The second ear typically grows from the node below the primary ear and is almost always smaller.

A much less common phenomenon is the development of multiple ears on the same node. In many cases, this amounts to little more than an agronomic curiosity if there is still a dominant primary ear that is able to develop normally. Secondary side ears will often be much smaller and cease development after they fail to pollinate. However, in cases where multiple ears develop on a node where there is no dominant ear, all of the ears can exhibit stunted, abnormal growth. If a lot of plants in a field are affected, this can have a negative impact on yield.

Figure 1. Corn ear with a primary ear and multiple secondary ears growing from the same ear shank.

CORN EAR GROWTH AND DEVELOPMENT

Corn ear development is a highly organized function in the corn plant. Ear shoot initiation begins early in the life of the plant—around the V6-V7 growth stage—long before any ear is visible on the plant. Ear shoots initiate at all ear nodes from the first to approximately the 14th leaf node; however, hormonal apical dominance in the plant ensures that it is the uppermost ear shoot that fully develops (Figure 2). A second ear can develop on the node below the primary ear if resources are abundant and may produce harvestable grain.

Just as apical dominance in the plant suppresses development of ears at additional stalk nodes, hormonal apical dominance expressed by the primary ear suppresses the initiation of any other ears along the ear shank. This normally prevents the development of multiple ears at the same stalk node.

Figure 2. Dissected corn plant at the V12 growth stage. A total of 8 ear shoots are visible with the lowest at node 7 and the primary ear shoot at node 14. *Image courtesy of Iowa State University Extension.*

The ear shank is essentially a miniature version of the main stalk, with multiple nodes and internodes. Leaves emerge from the nodes and an inflorescence is produced at the terminal node. In this case of the ear shank though, the inflorescence at the terminal node is the ear rather than the tassel and the leaves on the shank enclose the ear, forming the husk (Figure 3).

In some cases, additional ears do initiate on the same ear shank, which suggests the normal apical dominance has been disrupted somehow. This phenomenon has been noted in scientific literature dating back to at least the 1960s and was dubbed MESS (Multiple Ears on Same Shank) syndrome by Purdue University Extension agronomist Dr. Bob Nielsen in 1998 (Nielsen, 1999).

Figure 3. Removing the husk leaves reveals the nodes and internodes of the ear shank.

EXPRESSION OF MULTIPLE CORN EARS

Expression of multiple ears on the same shank can vary, both in terms of the number of ears and the extent to which one ear is dominant. Both of these factors will determine the potential impact on yield. In general, a greater number of ears and the lack of a dominant ear are both likely to be detrimental to yield. Manifestations of multiple ears on the same shank can be broken out into a few general categories.

Dominant Primary Ear

The most common form of multiple ears on the same shank is a dominant primary ear at the terminal node of the ear shank with one or two side ears emerging from lower nodes on the shank. Sometimes, the side ears will be wrapped in the husk with the primary ear and only become noticeable when silks begin emerging from the side of the husk. In other cases, secondary ears are visibly separate from the primary ear.

Figure 4. Multiple ears on the same shank with the secondary ear(s) separate from the main husk (left) and contained in the main husk (right).

In this scenario, yield is unlikely to be affected as long as the dominant ear is able to develop normally. Side ears often silk late and fail to pollinate, so they don't compete with the primary ear for resources during grain fill. This form of multiple ears on the same shank often shows up in areas where plants have received more abundant sunlight and resources—near gaps, in end rows, and in more productive areas of the field.

Figure 5. Corn plant with a well-developed primary ear and two secondary ears growing from lower nodes on the ear shank. Neither of the secondary ears have pollinated.

Often, multiple ears on the same shank occur alongside plants with a normal second ear below the primary ear node. This suggests that resource availability plays a role, in addition to disruption in normal apical dominance of primary ear in some plants. Plants set extra ears because they have the resources to do so but instead of setting a second ear on the lower node, some plants will set more ears on the primary node.

Failed Primary Ear

In some cases, multiple ears on the same shank occur following the development failure of the primary ear (Figure 6). Secondary ears may form on the same node as the failed primary ear, or they may form on the node below it. In this scenario, normal apical dominance has clearly been disrupted by the loss of the primary ear. Yield impact will depend on the extent to which one or two ears are able to develop normally.

Figure 6. Corn plant with a primary ear that has failed to produce silks. The plant has compensated for the failed primary ear by producing two more ears at the same node. *Image courtesy of Rachel Veenstra, Ph.D. student, Department of Agronomy, Kansas State University.*

Bouquet Ears

The term "bouquet ears" is commonly used to refer to the most extreme form of multiple ears on a shank, in which a cluster of multiple ears emerges close together on a shank (Figure 7). This commonly includes three to five ears on the same shank but clusters of up to eight ears have been observed (Elmore and Abendroth, 2006). The crowding of the ears causes them to splay out in multiple directions, forming a "bouquet."

Bouquet ears also appear to be associated with the failure of the primary ear. Often, none of the ears will develop properly, and the total yield of the plant ends up being less than what would have been achieved by a single normal ear. The potential to negatively impact yield makes bouquet ears particularly concerning compared to other, less extreme forms of multiple ears on the same shank. In some cases, bouquet ears have been observed throughout a field, affecting the majority of plants. The potential for significant reductions in yield makes it important to try to determine the factor or factors causing bouquet ears, in the instances when they occur.

Figure 7. Corn plant showing a cluster of ears at a single leaf node, a condition referred to as "bouquet ears." *Image courtesy of the University of Illinois.*

POSSIBLE CAUSES OF MULTIPLE CORN EARS

Iowa State Observations

In 2006, bouquet ears appeared at a higher-than-normal frequency in corn fields from Iowa to Indiana. Iowa State University researchers recorded the following observations that year (Elmore and Abendroth, 2006):

- Incidence reports from fields expressing bouquet ears ranged from 20% to 100% of plants.
- In extreme cases, clusters contained up to eight small ears.
- Different hybrids from different seed companies were affected.
- Several different herbicides (pre and post) were used.
- Some locations were affected by early-season drought.
- Some had mid-season fungicide applications, others did not.
- In the end, no single cause could be identified.

University of Illinois Observations

When bouquet ears occurred in Illinois in 2007, the following observations were made (Nafziger, 2007):

- Some hybrids were more likely than others to produce "side" ears. In some fields, up to five or six ears developed.
- The side ears were well developed, though many likely failed to form kernels due to late silking and lack of pollen.
- In general, the larger and more numerous the side ears, the more likely that the main ear was damaged in some way or had low kernel numbers.

Nafziger concluded that secondary ears were likely able to grow faster when the primary ear either showed less dominance or just used less plant sugar, leaving more for the other ears. He also surmised that the causes of damage to the main ear might have been different in different fields.

Corteva Agriscience Observations

Corteva Agrisicence corn breeders place an ear shoot bag over the small ear shoot of a corn plant prior to silk emergence to protect silks from pollen contamination prior to making a controlled pollination. These researchers have long noted that when such plants are not pollinated, multiple ears often develop at the same stalk node as the non-pollinated ear. This suggests that the failure of the primary ear is the stimulus for the development of the secondary ears. Other observations by Corteva Agriscience researchers and agronomists confirm this conclusion. When extreme silk feeding by corn rootworm beetles or Japanese beetles prevents or limits pollination of some ears, the formation of multiple ears often results.

Multiple ears on the same shank may also result from stress to the plant earlier in its development. Stress during primary ear formation—around the V6 stage—can cause disruption of ear development and the loss of apical dominance. Pioneer agronomists have observed multiple ears on the same shank associated with stress caused by high winds, extreme temperatures, and wide swings in temperature during ear development.

Pioneer agronomists have also observed bouquet ears resulting from a disease commonly referred to as crazy top. This disease is caused by a fungal pathogen (*Sclerophthora macrospora*) spread by flooding. Crazy top may result not only in a proliferation of leaves in the tassel of the plant (from which it draws its name), but also a proliferation of ears at a single node (Figure 8). Other diseases have been implicated in the expression of bouquet ears, but a direct cause and effect relationship has not been conclusively established. Likewise, no conclusive relationship has been established between herbicide, fungicide, or insecticide application and bouquet ears.

It has often been difficult to definitively pinpoint a single cause or interaction of causes that results in multiple ears on the same shank, but a common thread in many cases seems to be some sort of disruption in development of the main ear that weakens its apical dominance and allows other ears to develop on the same node.

Figure 8. Bouquet ears resulting from crazy top of corn.

MANAGEMENT CONSIDERATIONS

Multiple ears that occur due to poor pollination of the primary ear can be avoided by addressing insect feeding on the silks. Corn rootworm beetles, and in some areas, Japanese beetles, are the primary silk-feeders that can prevent or limit normal pollination.

If hybrid differences are observed, growers should note them for future reference when selecting hybrids. However, if maturities also differ, silk timing may have been more important than hybrid performance per se. In previous cases where multiple ears on the same shank have been observed over a wide area, it generally has not been limited to a single hybrid or brand.

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Former Senior Research Scientist

HOW CORN PLANTS REGULATE NUTRIENT UPTAKE

SUMMARY

- Thirteen of the 16 nutrients essential for corn growth are taken up from the soil.
- As corn roots extract nutrients from soil, regulatory proteins determine essential quantities and ratios of nutrients to support yield.
- High affinity transport system (HATS) proteins supply sufficient nutrients to keep the plant alive if the concentration of a nutrient in the soil is very low, while low affinity transport system (LATS) proteins are most efficient when nutrient concentrations are relatively high.
- Ideal nutrient ratios within the corn plant change as the growing season progresses.
- A profitable and sustainable fertility program replaces nutrients removed by harvested grain and increases the nutrient reserve in the soil as monetary resources allow.

NUTRIENT NEEDS IN CORN PRODUCTION

The yield potential of modern corn hybrids continues to increase, as does the quantity of nutrients removed from the soil as grain leaves the field. A long-term, sustainable fertility program maintains current and future high grain yields. Fertility management decisions include what nutrients to apply, how much of each nutrient to apply, and when to apply these nutrients. Fertilizers must be applied appropriately to support high grain yield, create a profit, and responsibly steward the land to minimize nutrient loss to neighboring waterways and other non-target land areas. The process starts with proper soil testing to determine quantities of available nutrients and then adding fertility to support desired grain yields.

This article will view nutrient uptake from a corn plant's perspective, exploring how the corn plant regulates nutrient uptake to maintain nutritional balance during the corn plant's life cycle. Ideal nutrient ratios change as corn growth progresses from germination to maturity. It will also consider nutrient removal as grain leaves the field and suggest a starting point for a fertility program to sustainably maintain high grain yields in future years.

SOURCES AND QUANTITIES OF NUTRIENTS

Sixteen nutrients are essential for corn growth (Table 1). Two of these nutrients, carbon and oxygen, are extracted from the air. Hydrogen is extracted from soil water. Corn plants split water molecules into hydrogen and oxygen. Hydrogen is consumed and incorporated into organic compounds such as sugars, starch, proteins, and cell wall materials. Oxygen is either consumed by mitochondrial respiration in the corn plant or is released as molecular oxygen into the atmosphere.

The remaining 13 nutrients are extracted from soil. These nutrients must be considered as part of a fertility management program. The three primary macronutrients – nitrogen, phosphorus, and potassium – are called primary macronutrients because the corn plant requires hundreds of pounds of these nutrients per acre for maximum yield. The three secondary macronutrients – sulfur, calcium, and magnesium – are called secondary macronutrients because the corn plant consumes tens of pounds of each of these nutrients per acre to maximize yield. The seven micronutrients – boron, chlorine, copper, iron, manganese, molybdenum, and zinc – are consumed at rates of ounces per acre for corn grain production.

Table 1. Sources of 16 nutrients essential for corn production.

Atmosphere	Carbon	Oxygen
Water	Hydrogen	
Soil	**Primary Macronutrients**	**Secondary Macronutrients**
	Nitrogen Phosphorus Potassium	Sulfur Calcium Magnesium
	Micronutrients	
	Boron Chlorine Copper Iron	Manganese Molybdenum Zinc

Corn ears contain all 13 of the soil-supplied nutrients in harvested grain (Heckman et al., 2003) (Table 2). The second column in Table 2 shows nutrient contents on a per bushel basis. Although grain yields vary widely across different environments, nutrient concentrations change very little on a pound/bushel basis. The third column shows amounts of nutrients that leave the field when a 300 bu/acre yield is harvested and transported for grain. To figure removal rates for other yields, multiply nutrient contents in pounds/bushel times the bu/acre of grain yield. The fourth column shows nutrient ratios with copper as the base unit of one. For example, for every pound of copper removed in grain, 4,100 pounds of nitrogen are also removed.

Table 2. Nutrient content per bushel of corn grain, removal by a 300 bu/acre crop, and nutrient amounts in corn grain as a ratio relative to copper (Heckman et al., 2003).

Nutrient	Content per Bushel (15.5% moisture)	Total Removal 300 bu/acre	Ratio Relative to Cu
	lbs/bu	*lbs*	*lbs*
Nitrogen	0.615	184.5	4,100
Phosphorus	0.428	128.4	2,850
Potassium	0.273	81.9	1,820
Sulfur	0.0506	15.18	337
Magnesium	0.0733	21.99	489
Calcium	0.0132	3.96	88
Iron	0.00168	0.504	11.2
Zinc	0.00126	0.378	8.4
Boron	0.00028	0.084	1.86
Manganese	0.00023	0.069	1.53
Copper	0.00015	0.045	1.0
Molybdenum	Trace	Trace	Trace
Chlorine	Unknown	Unknown	Unknown

The remaining three essential nutrients – carbon, oxygen, and hydrogen – are also present in grain. The corn plant's chemical composition consists of 44% carbon, 45% oxygen, and 6% hydrogen, along with the 13 soil-supplied nutrients (Latesha and Miller, 1924). For a 300 bu/acre yield, approximately 6,300 pounds of carbon, 6,400 pounds of oxygen, and 850 pounds of hydrogen are transported as grain. The organic matter composition of this amount of grain contributes about 25.9 million calories of energy to food and feed chains as this grain is consumed in different feed, fuel, and industrial products.

REGULATION OF NUTRIENT UPTAKE IN CORN

In order to understand how the corn plant regulates nutrient uptake, it is necessary to first understand some basic corn anatomy. Figure 1 shows two different views of a corn root.

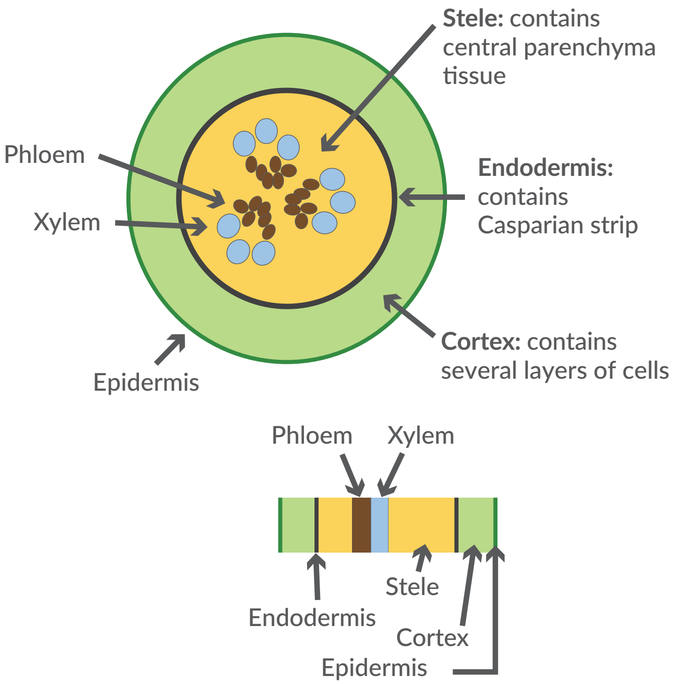


Figure 1. Two different views of a corn root cross section.

The outermost layer of cells – the epidermis – is in direct contact with surrounding soil. Just inside the epidermis, represented by the green ring, is the cortex, which is several cell layers thick. One of its functions is to temporarily store nutrients as these nutrients move from soil to corn roots. Initially, when nutrients enter corn roots, these nutrients are retained in "non-living" spaces between cortical and epidermal cells. Nutrients enter the "living portion" of the corn root when they cross a cell plasma membrane (represented by the black circle). These nutrients are now in the central core, or stele, of the corn root. Once inside the stele, nutrients move into xylem vascular tissue and translocate as needed to all parts of the corn plant, such as the stalk, leaves, ears, and grain.

The plasma membrane (plasmalemma) and Casparian strip (represented by the black line in Figure 2) are impermeable to water and nutrient penetration. Holes in the plasma membrane, called plasmodesmata, allow the transport of water and nutrients across the plasma membrane. Regulatory proteins located in the plasmodesmata determine how much of each nutrient crosses the plasma membrane.

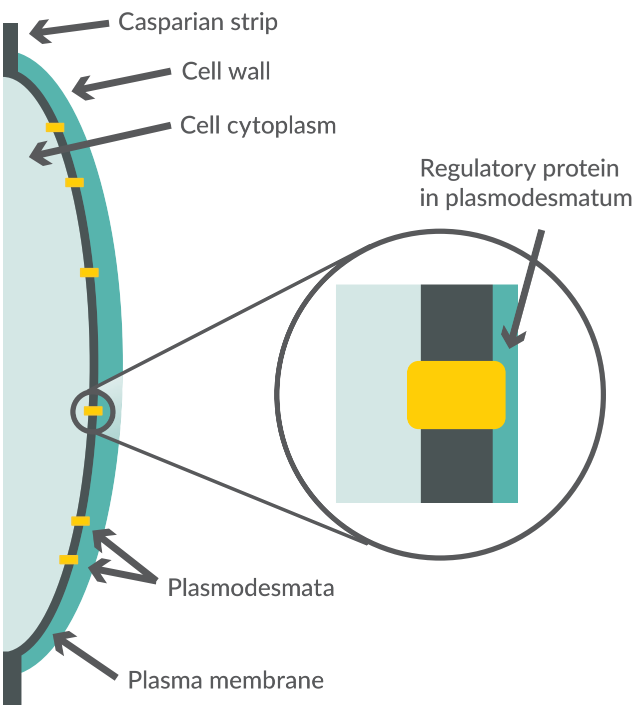


Figure 2. The Casparian strip, plasma membrane, plasmodesmata, and regulatory proteins form a system to regulate water and nutrient uptake.

The two types of regulatory proteins—high affinity transport systems (HATS) and low affinity transport systems (LATS)—are located in the plasmodesmata (Figure 3) (Glass, 2002). HATS proteins select nutrients that are present in very low concentrations in the outer portion of the corn root and transport these nutrients across the plasma membrane. HATS proteins supply sufficient nutrients to keep the plant alive if the concentration of a nutrient in the soil is very low. However, HATS proteins cannot transport enough nutrients to meet demands for high grain yields. Corn plants stay alive but may still show nutrient deficiency and potential yield loss because nutrient supply does not meet nutrient demand. LATS proteins supply the biochemical power to transport sufficient nutrients across plasma membranes to meet demands for high grain yields. LATS proteins are most efficient when nutrient concentrations are relatively high in the soil.

According to our current knowledge, specific HATS and LATS proteins tend to bind selectively to particular nutrients. There is a specific type of protein that matches each of the nutrients; however, not all proteins are entirely nutrient specific. For example, the chemical structure of a regulatory protein binds semi-selectively to calcium (Ca^{2+}). However, other divalent cations, such as magnesium (Mg^{2+}) or zinc (Zn^{2+}), may also bind to and be transported by this same regulatory protein. This lack of complete specificity may partly explain why nutrient concentrations tend to have a range of values in harvested grain or why some nutrients are present in "luxury quantities" in the corn plant.

Uptake of each nutrient is regulated independently. If a soil has high nitrogen fertility but is low in sulfur, LATS proteins will efficiently take up and transport all of the nitrogen needed to support grain yield. However, in a low sulfur soil, there is insufficient sulfur for the LATS to work efficiently. HATS proteins therefore conduct the majority of sulfur uptake and transport. These HATS proteins supply whatever sulfur they can to support growth, but they cannot meet the high demand to support maximum growth. The end result is the expression of sulfur deficiency in the corn plant.

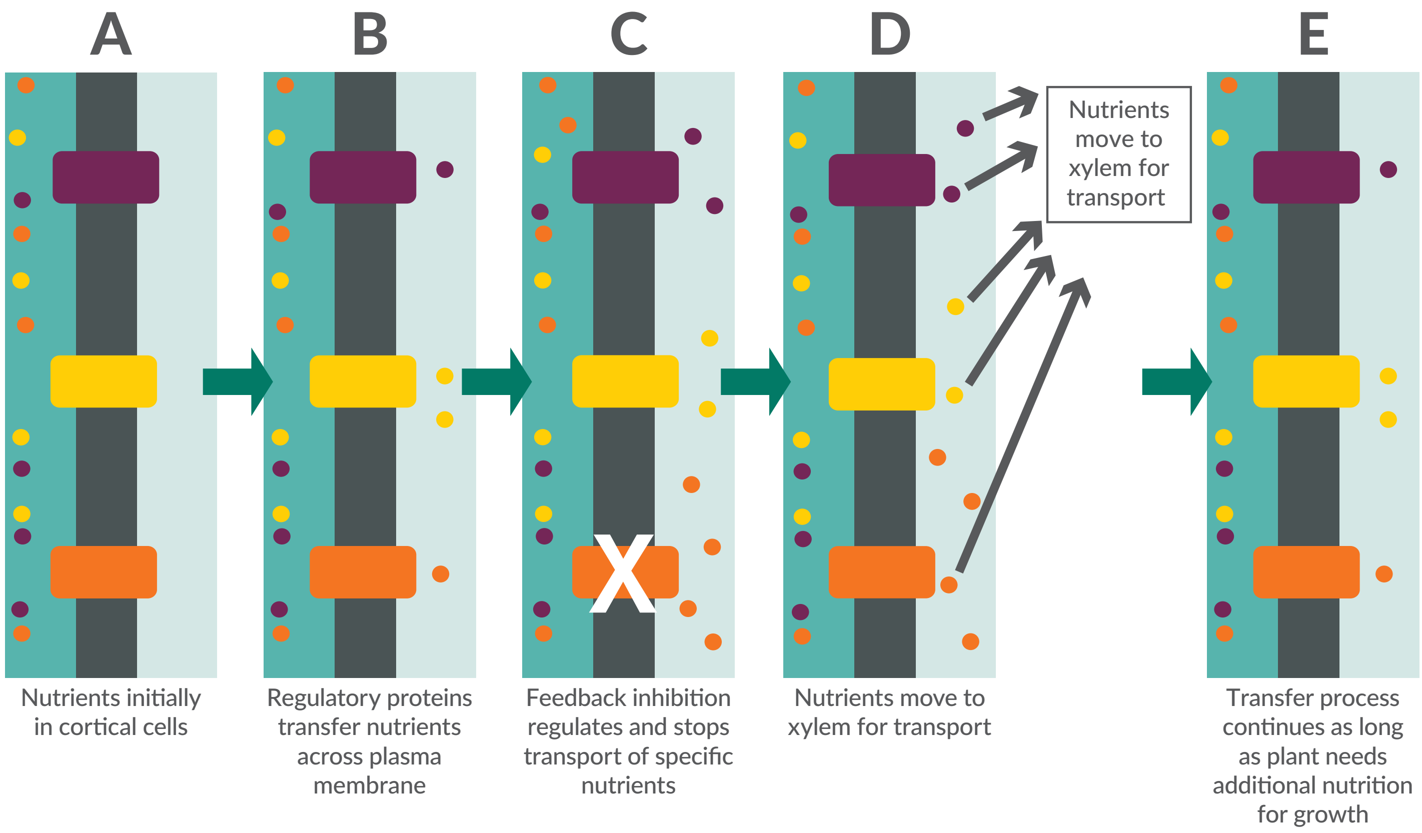
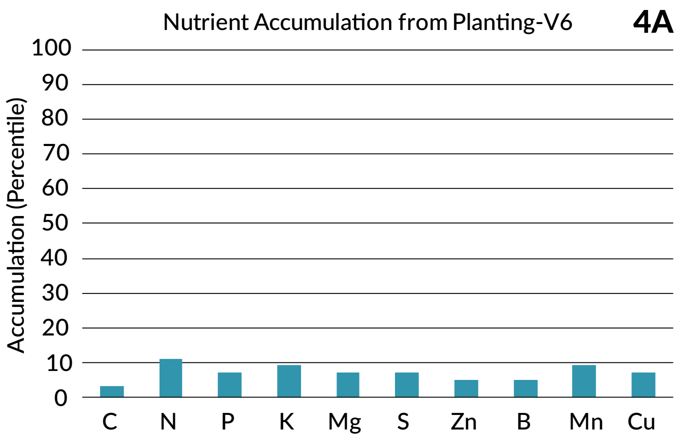
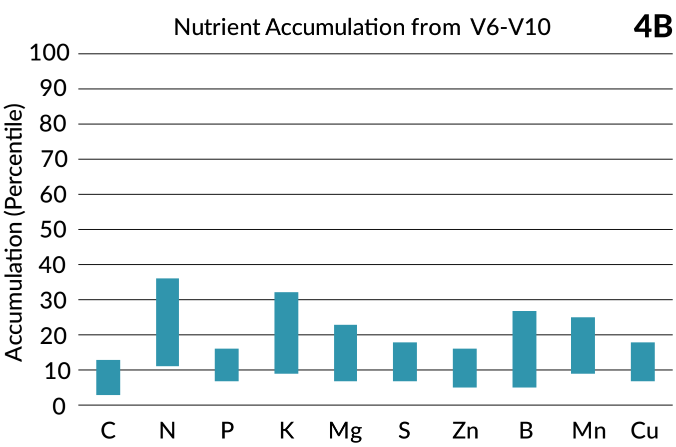


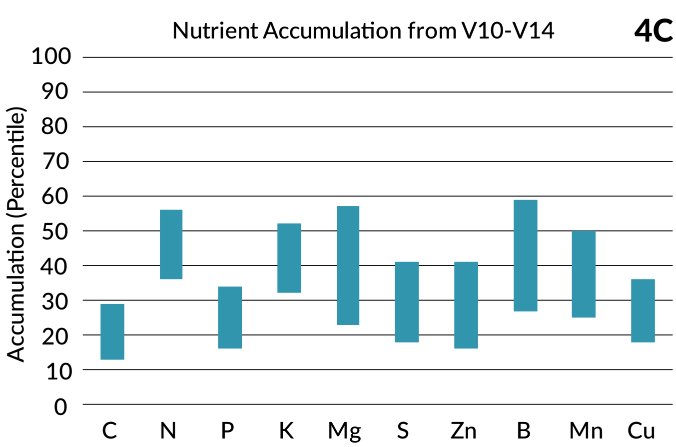
Figure 3. Regulatory process for nutrient uptake to support corn growth. **A:** Nutrients (colored circles) leave the soil solution and enter into "non-living tissues" surrounding cortical cells. **B:** Regulatory HATS and LATS proteins (colored rectangles) selectively transport nutrients (correspondingly colored circles) across the plasma membrane. **C:** Transport processes of regulatory proteins stop if nutrient concentrations in the center of the corn root become too high (feedback inhibition). **D:** Once inside the central portion of the corn root, nutrients are transported via the xylem to wherever they are needed in the corn plant. **E:** The process continues until corn growth is complete.

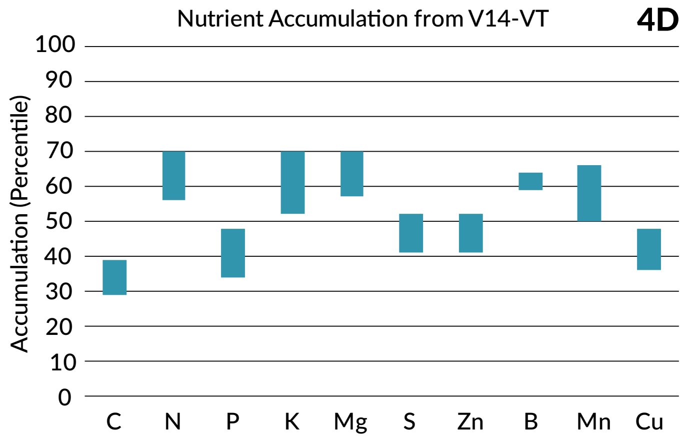
RATIOS OF NUTRIENT UPTAKE CHANGE DURING THE GROWING SEASON

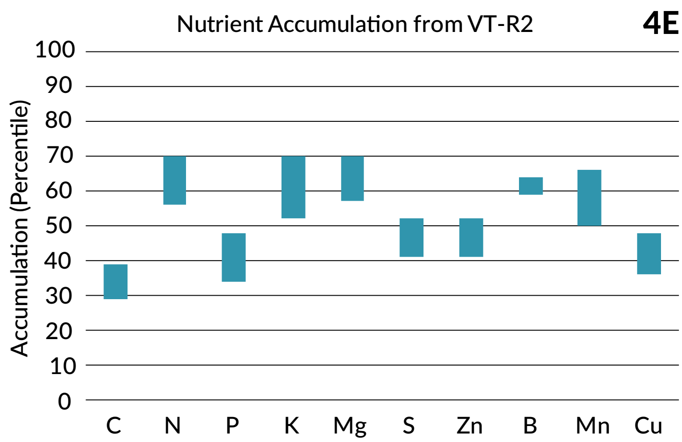
High affinity transport systems (HATS) and low affinity transport systems (LATS) regulatory proteins adjust amounts of nutrient uptake and nutrient ratios during the entire growing season. As the corn plant matures, rates of uptake of some nutrients are faster than for other nutrients, thus changing the ideal nutrient ratio for corn growth at different growth stages. Scientists at the University of Illinois have published research showing how nutrients accumulate during the corn life cycle (Bender et al., 2013) (Figure 4A-4G).

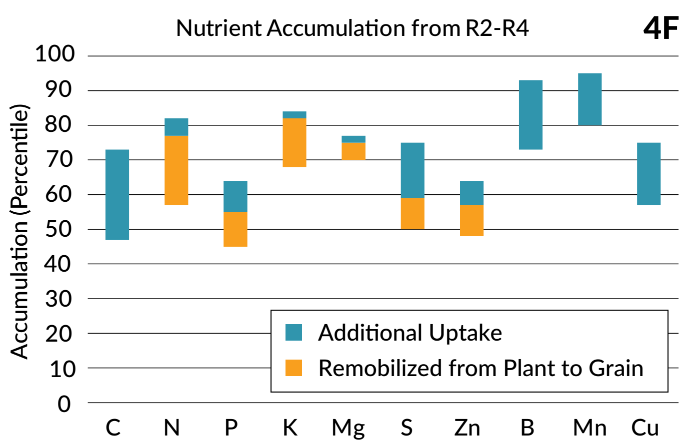












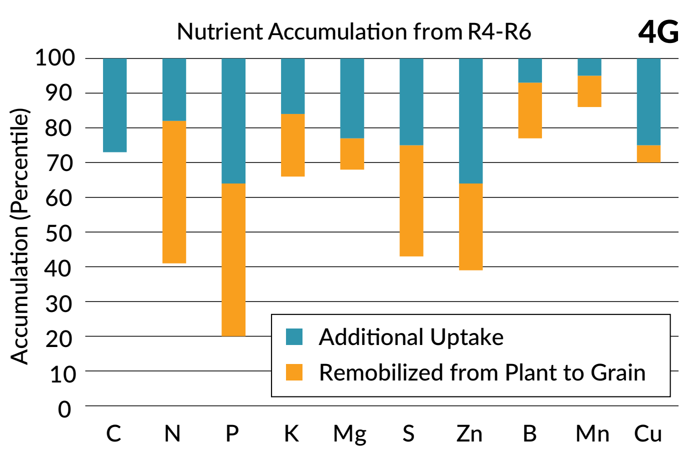


Figure 4. Relative amounts of nutrients acquired by the corn plant at different growth stages.

The corn plant accumulates up to approximately 11% of its total nutrient uptake between germination and V6. Between V6 and V10, nitrogen, potassium, and boron uptake increase more rapidly than other nutrients. Nutrient uptake during vegetative growth is most rapid during V10 to V14. At V14, the corn plant has accumulated approximately ⅔ of the total nitrogen, potassium, magnesium, boron, and manganese. By VT, the corn plant has acquired approximately 70% of its total uptake of these five nutrients while acquiring only 40% of total carbon. At VT, the corn plant has achieved maximum vegetative growth. Additional nutrient uptake after VT supports ear growth. Today's corn hybrids devote about 50-60% of total dry matter accumulation to ear growth.

The corn plant acquires very few nutrients during pollination, probably because the corn plant is devoting the majority of its resources to support successful pollination and fertilization of embryos. Nutrient uptake during reproductive growth is most active between R2 and R4. The corn plant accumulates a substantial portion of its total carbon, sulfur, boron, manganese, and copper during this growth phase. In addition, the corn plant moves some of the nitrogen, phosphorus, potassium, magnesium, sulfur, and zinc from vegetative leaf and stalk matter to the developing grain.

Between R4 and R6 (maturity) the corn plant acquires nearly 20% to almost 40% of the total carbon, nitrogen, phosphorus, potassium, magnesium, sulfur, zinc, and copper during late-season grain fill. Accumulated carbon during R4 to R6 is deposited in the kernels. Grain fill during R4 to R6 accounts for approximately 25% of the increase in total weight of the corn plant at maturity. Figure 4G also illustrates what percent of the total nutrient acquired by a corn plant during the growing season is present in the grain. As this grain leaves the field, approximately 80% of phosphorus, 62% of zinc, 58% of nitrogen, 57% of sulfur, 34% of potassium, 32% of magnesium, and 30% of copper also leaves the field and is no longer part of your future soil fertility program.

BUILDING A NUTRIENT MANAGEMENT PLAN

A successful nutrient management plan is one that assures there is enough of every nutrient in the soil to support corn growth at each developmental stage to meet the targeted grain yield. Maintaining adequate fertility levels of all nutrients during the entire growing season is more important than fertilizing for specific nutrient ratios because HATS and LATS regulatory proteins continuously adjust nutrient uptake to provide maximum yields allowed by the growing environment.

The optimal fertility management program will depend, in part, on soil type. High cation exchange capacity (CEC) soils may require relatively few fertilizer applications with greater amounts of fertilizer applied at each application, while low CEC soils may need substantially more applications to "spoon-feed" specific nutrients depending on the corn growth stage.

Additionally, a successful nutrient management plan needs to be sustainable and consistently support high yields in future years. A fertility program will include replacement amounts of nutrients that leave the field as the crop is harvested and will also include additional fertility to increase soil reserve fertility levels as your budget allows. A place to start when calculating replacement amounts of nutrients is to multiply the nutrient contents listed in pounds per bushel (Table 2) by the most recent corn yield. This information, in combination with soil test values, helps to define a profitable and sustainable fertility program.

Nutrients most likely to show deficiency first are the macronutrients – nitrogen, potassium, and phosphorus – followed by the secondary macronutrients – sulfur and magnesium – and then followed by the micronutrients, zinc and copper, because corn grain removes relatively large amounts of these nutrients as grain leaves the field. Other nutrients may show deficiency under specific soil environments.

SOIL AND TISSUE SAMPLING FOR CORN NUTRIENT MANAGEMENT *IN ONTARIO*

Paul Hermans,
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KEY FINDINGS:

- **Keep soil potassium (K) levels up.** Tissue K concentrations were generally lower than ideal. Soil K levels have been shown to correlate to tissue concentrations and corn yield.
- **Consider adding sulfur (S).** Tissue samples showed low sulfur concentrations. Soil tests do not provide a reliable measure of sulfur levels.
- **Use both soil and tissue sampling.** The combination of both sampling methods provides guidance for pre- and in-season fertilization.

STUDY OBJECTIVES

- Soil and plant tissue samples were collected from numerous corn fields in southeastern Ontario in 2020 to evaluate:
  - » Overall nutrient levels.
  - » Correlations between soil and tissue sample results.
  - » Changes in tissue nutrient levels during the growing season.

STUDY DESCRIPTION

- Samples were collected from 34 locations in southeastern Ontario planted to corn in 2020.
- Soil samples were collected at two points in each field early in the growing season.
- Tissue samples were collected at V6, R1, and R3 growth stages and analyzed by A&L Canada.

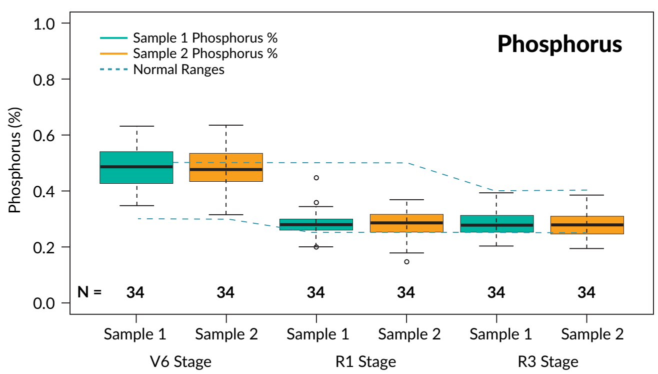

Figure 1. Average phosphorus tissue sample levels across all locations at the V6, R1, and R3 growth stages. Blue lines signify the upper and lower bounds of the optimum range.

KEY RESULTS

- Tissue levels of phosphorous (P), K, and S generally were in the lower end of the optimum ranges (Figures 1-3).
- Nitrogen to sulfur (N:S) and nitrogen to potassium (N:K) ratios were generally higher than desired (Figures 4 and 5).
  - » N:S ratio should be 10 to 15.
  - » N:K ratio should be less than 1.4.
- Soil test K saturation correlated with tissue K, particularly earlier in the season (Figures 6 and 7).
- Tissue N levels did not correlate strongly across growth stages (Figures 8 and 9).

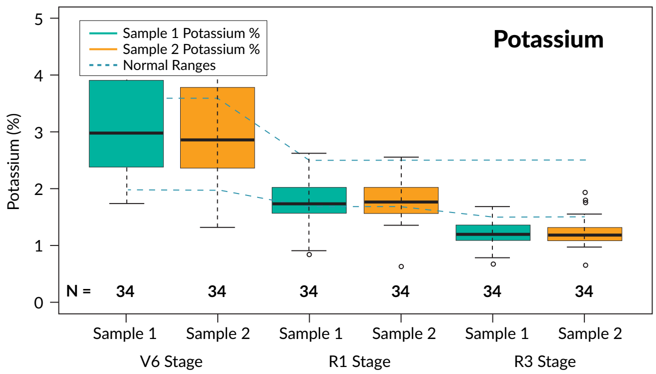

Figure 2. Average potassium tissue sample levels across all locations at the V6, R1, and R3 growth stages. Blue lines signify the upper and lower bounds of the optimum range.

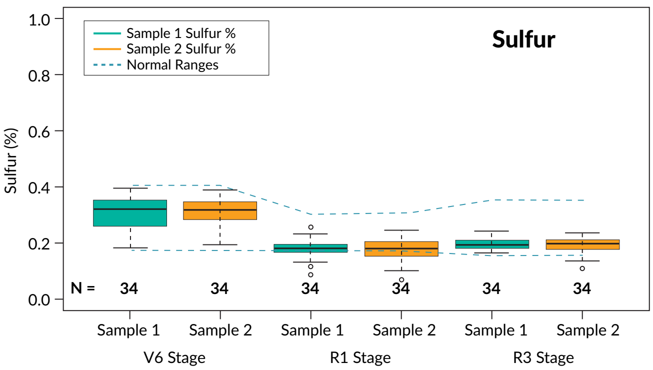

Figure 3. Average sulfur tissue sample levels across all locations at the V6, R1, and R3 growth stages. Blue lines signify the upper and lower bounds of the optimum range.

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NUTRIENT RATIOS

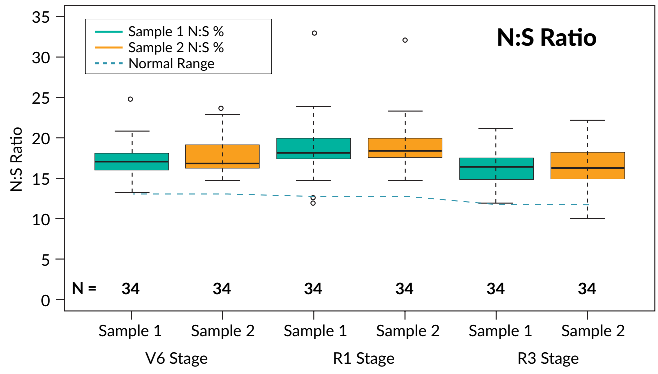

Figure 4. Average nitrogen : sulfur ratio across all locations at the V6, R1, and R3 growth stages. Blue line signifies the optimum ratio.

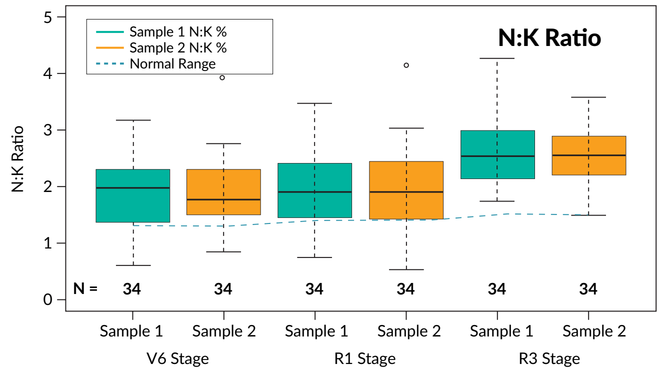

Figure 5. Average nitrogen : potassium ratio across all locations at the V6, R1, and R3 growth stages. Blue line signifies the optimum ratio.

POTASSIUM SOIL AND TISSUE CORRELATIONS

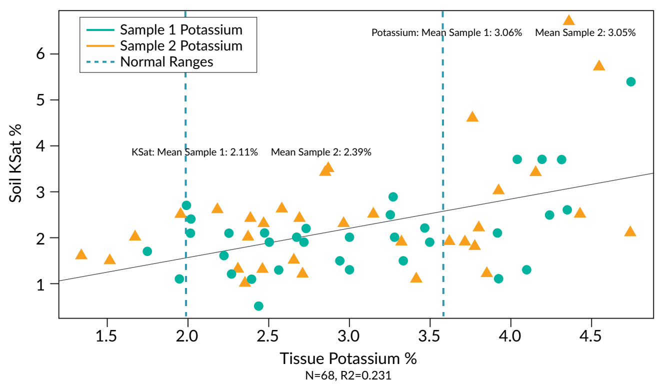

Figure 6. Soil potassium levels early in the season and tissue potassium concentrations at the V6 growth stage.

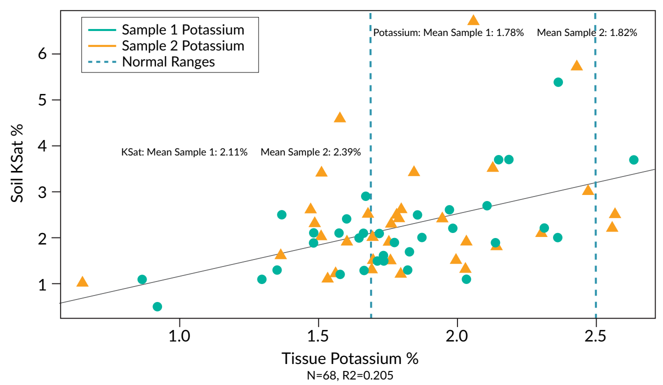

Figure 7. Soil potassium levels early in the season and tissue potassium concentrations at the R1 growth stage

NITROGEN TISSUE CONCENTRATIONS

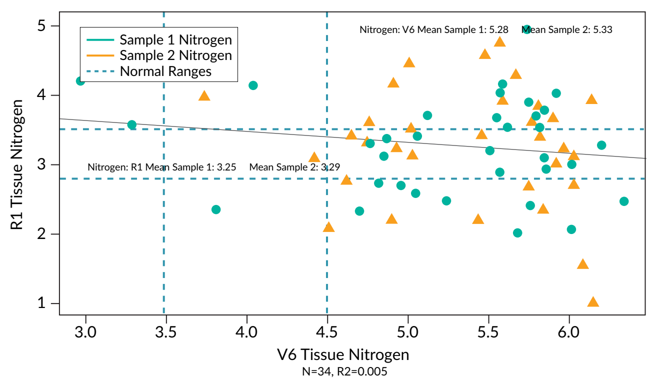

Figure 8. Tissue nitrogen concentrations at the V6 and R1 growth stages.

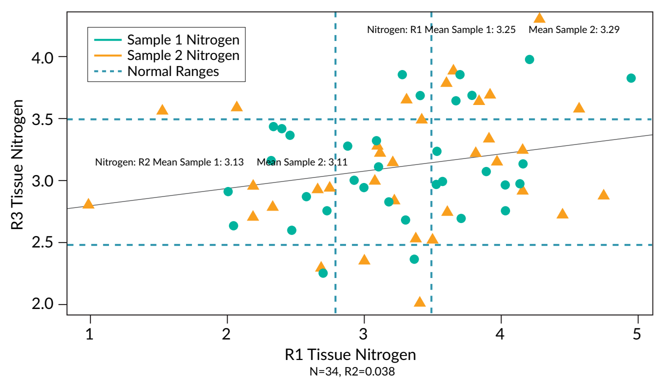

Figure 9. Tissue nitrogen concentrations at the R1 and R3 growth stages.

DISCUSSION

- Soil and tissue samples are valuable for understanding crop nutrient levels, but are not currently utilized on many farms.
- Granular Agronomy Fertility Management utilizes soil sample data along with local fertility guidelines to generate fertility management recommendations.
- Custom prescriptions make the most of every nutrient to meet yield targets and stay on budget.

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CORN MATURITY AND DRY DOWN
IN ONTARIO

KEY FINDINGS:

- Trial locations accumulated an average of 104 growing degree units (GDUs) over the 3-week study period and lost an average of 7.7 points of grain moisture.
- 88 to 96 comparative relative maturity (CRM) hybrids all dried down to within a point of each other, while 98 CRM hybrids were still approximately 4 pts wetter on the final sampling date.
- For each week delay in planting, grain moisture increased by an average of 1.7 pts.

2020 CORN DRY DOWN FIELD RESEARCH

- Corn ear samples were collected from 14 field trial locations to measure the rate of in-field drying prior to harvest in 2020.
- Each field trial included at least four different hybrids ranging in comparative relative maturity (CRM) from 84 to 101 (Table 1).
- Planting dates of field trials ranged from April 25 to May 21.
- Representative ears were sampled from each hybrid in the trial four times: Sept. 28, Oct. 5, Oct. 13, and Oct. 19.
- Sampled ears were hand-shelled and grain moisture was measured using benchtop moisture testing equipment or a calibrated moisture tester.
- Accumulated growing degree units (GDUs) for each trial location were estimated using the GDU calculator at https://www.pioneer.com/us/tools-services/growing-degree-unit.html

Table 1. Planting dates and comparative relative maturity of hybrids planted at dry down study locations in 2020.

Planting Date	Hybrid Comparative Relative Maturity													
	84	85	87	88	89	91	92	93	94	95	96	98	99	101
	number of hybrids													
May 13	1	1	1	1										
May 21				1		1	1	1	1	1				
May 10				1	1	1	1	1	2	1	1			
May 6				1		1	1	1	1		2	1		
May 18				1		1	2	1	1	1	2	1		
May 6				1				1	1	1	1	1		
May 12						1	1	1	2	1				
May 12						1	1	1	2	1				
May 6						1	1	1	1	1				
May 14						1	1	1	1		1			
April 25						1	1	1		1	1	1		
May 12						1	2	1	1	1	2	1		
May 1								1	1	1	1	1	1	
May 16										1	1	1	1	1

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RESULTS

- Trial locations accumulated an average of 104 growing degree units (GDUs) over the course of the study period: 40 in week 1, 39 in week 2, and 25 in week 3 (Figure 1).
- Average grain moisture across all locations and hybrids was 30.9% at the start of the study and 23.2% at the end of the study, meaning that grain dried down an average of 1 point per 13.6 GDUs (Figure 2).

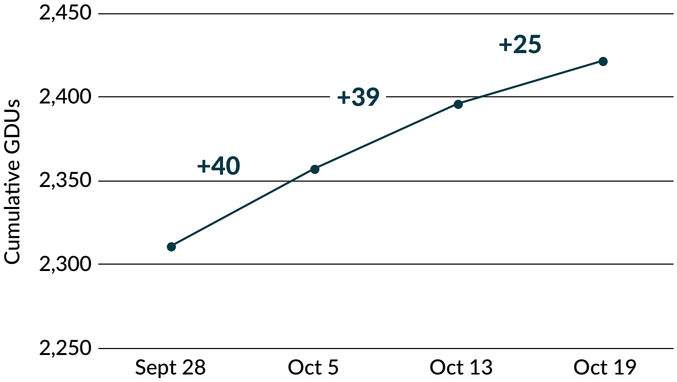

Figure 1. Average cumulative GDUs since planting across trial locations on the four moisture sampling dates.

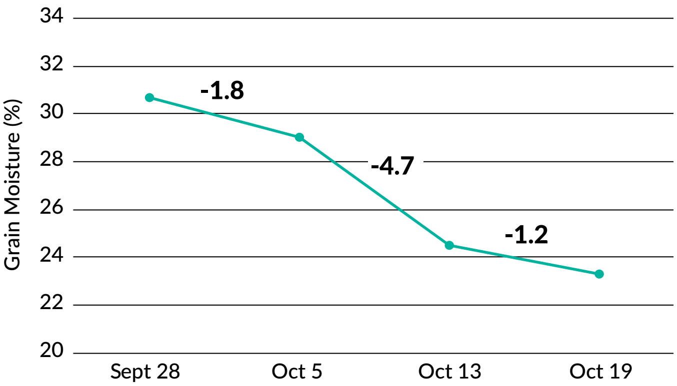

Figure 2. Average grain moisture across all trial locations and hybrids on the four moisture sampling dates.

- Average dry down rate was much more rapid during the second week of the study (4.7 pts) than the first week (1.8 pts) even though average GDU accumulation was no greater, illustrating the fact that drying rate is affected by more than just temperature (Figure 2).
- Killing frost timing and above average wind speeds may have contributed to the rapid dry down observed during the second week.

Hybrid Maturity Effect

- Grain drying dynamics were affected by hybrid comparative relative maturity (CRM).
- Shorter CRM hybrids dried earlier than longer CRM hybrids, as would be expected (Figure 3).
- Longer CRM hybrids lost more moisture over the course of the study period, presumably due to the fact that they had more moisture left to lose at the start of the study.
- At the end of the study period, 88 to 96 CRM hybrids had all dried down to within a point of each other, while 98 CRM hybrids averaged approximately 4 pts wetter.

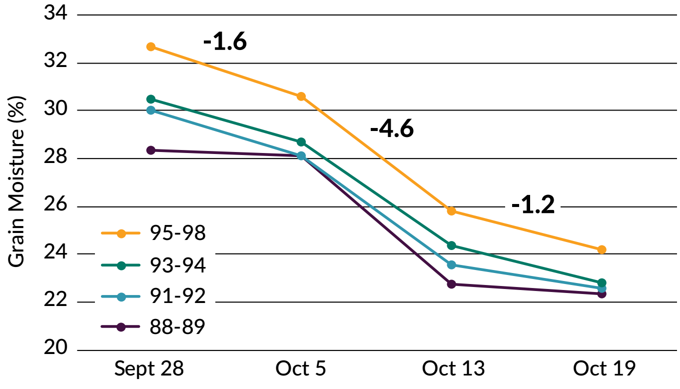

Figure 3. Average grain moisture by hybrid comparative relative maturity (CRM) on the four moisture sampling dates.

Planting Date Effect

- Total GDU accumulation and corn grain dry down timing were both influenced by planting date.
- Total GDU accumulation was reduced by an average of 47 GDUs for each week delay in planting, (Figure 4).
- For each week delay in planting, the average moisture of 93-94 CRM hybrids (which were planted at 12 of the 14 locations) increased by an average of 1.7 pts (Figure 5).

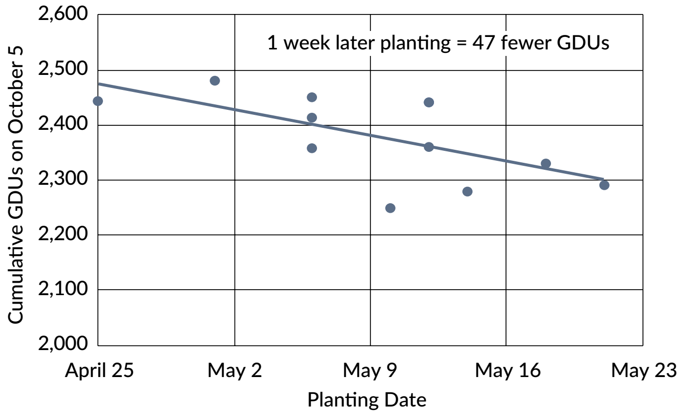

Figure 4. Effect of planting date on cumulative GDUs through October 5 at trial locations.

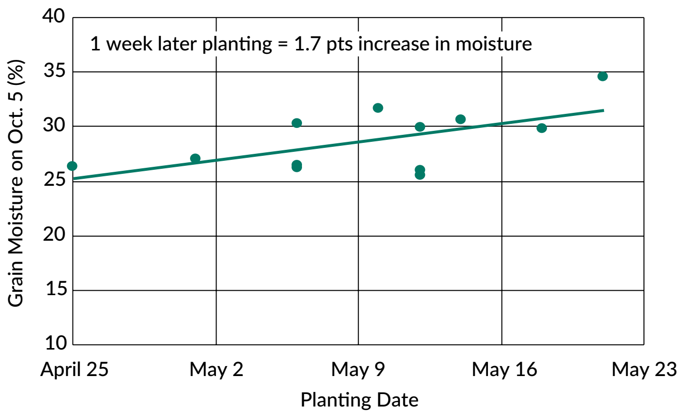

Figure 5. Effect of planting date on average moisture of 93 and 94 CRM hybrids measured on October 5 across 12 locations.

Mark Jeschke, Ph.D.,
Agronomy Manager

IS SMOKE FROM WILDFIRES AFFECTING CROP YIELDS?

KEY POINTS

- Wildfires in western North America have gotten worse in recent years and will almost certainly continue to increase in frequency and intensity.
- In the Corn Belt region, noticeable levels of smoke in the air during summer and fall have now become commonplace.
- The potential impact of wildfire smoke on crop growth is complex and involves competing effects that can both enhance and suppress photosynthesis.
- There are three primary factors associated with wildfire smoke with the capability to directly impact crops: reduced total solar radiation and elevated ozone, which are both negative, and increased diffusion of solar radiation, which could potentially be positive.
- Based on what is known about the effects of reduced solar radiation and ozone on crops, it's very plausible that wildfire smoke could cause reductions in crop yields.
- The effects of wildfire smoke on both agricultural and natural ecosystems are likely to be an active area of research in coming years, as smoky days become more common.

WILDFIRE SMOKE BECOMING MORE COMMON

The past several years have been marked by an increase in the frequency and severity of wildfires in the western U.S. and Canada. The effects of these fires have been devastating on the areas directly impacted, and smoke from the fires has been a frequent health concern in nearby population centers. It has also become increasingly apparent that the impact of these wildfires can extend far beyond the immediate area. Wildfire smoke can and does impact air quality throughout the entire continental U.S.

In the Corn Belt region, noticeable levels of smoke in the air during summer and fall have now become commonplace. Wildfire smoke is often most noticeable in the evenings, with hazy red sunsets resulting from the filtering of sunlight through the particulate matter suspended in the atmosphere. During the day, the smoke creates a persistent cloudy haze in the air, reducing the intensity of direct sunlight and making it more diffuse.

The increased frequency of smoky days in agricultural areas raises the question of what impact the smoke might be having on crop productivity. Ample sunlight is critical for maximizing plant photosynthesis and crop yield, and lower than normal solar radiation during grain fill can be detrimental. Corn, in particular, is susceptible to reduced yields and reduced standability if the plants need to remobilize carbohydrates from the stalk to make up for a deficit in photosynthesis. This weakens the stalks and opens the door for stalk rot pathogens.

WHY ARE WILDFIRES GETTING WORSE?

Wildfires in western North America have gotten considerably worse in recent years. Over the past 40 years, the total burned area from wildfires in the U.S. has approximately quadrupled, from around 2 million acres annually to more than 8 million acres (Figure 1).

The increase in fire risk has been driven by two major factors: increased fuel load in forested areas resulting from decades of fire management practices focused on fire suppression, and increased fuel aridity due to a hotter and drier climate.

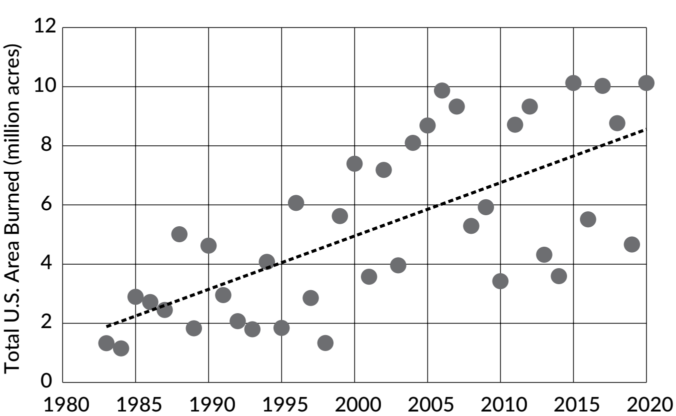

Figure 1. Total acres burned by wildland fires in the U.S., 1983-2020. Source: NIFC Wildland Fire Statistics, 2021.

Forest Management

Fire is a natural feature of many forest ecosystems in western North America and controlled burns were common practice across the landscape for generations. In the early 20th Century though, focus started to shift away from forest management in favor of fire suppression after a devastating fire in 1910 known as the "Big Burn" consumed more than 3 million acres across Washington, Idaho, and Montana and killed at least 85 people. This event had a long-term impact on the policy direction of the U.S. Forest Service, which had been founded five years prior (Tidwell, 2010).

The outcome of decades of policy focused on fire suppression has been a buildup of fuel in many forested areas. Even though the importance of prescribed burning for fire risk mitigation is now well-understood, doing it has become more difficult due to the expansion of residential development in the wildland urban interface and the diversion of limited fire management resources into protecting homes and businesses from increasingly frequent and intense wildfires. A massive increase in tree mortality following an extended period of drought in California has further increased the supply of combustible fuel (Stephens et al., 2018), dramatically increasing the near-term risk of devastating fires in affected areas.

Smoky sunset in central Iowa. July 31, 2021.

Climate Change

The risk posed by increased fuel loads in western forests has been exacerbated by climate change, which has manifested though increased temperatures and lower precipitation during the fire season, a lengthening of the fire season due to higher spring and fall temperatures, earlier snowmelt, and reduced river flows. All these factors have contributed to make fuel loads in forests drier and more combustible (Overpeck and Udall, 2020).

The increase in fire activity over the past 20 years has largely been driven by climate change, with hotter, drier conditions leading to larger and more frequent fires (Abatzoglou and Kolden 2013). The six worst wildfire years in California – years in which more than 1 million acres burned – have all been years with above-average temperature and below-average precipitation during the July to November fire season (Figure 2). This set of conditions is occurring with increasing frequency. Average fire season temperatures have exceeded the 20th Century average every year since 2004, with the 2020 season setting a new high of over 4°F above average as well as a new record of more than 3 million acres burned.

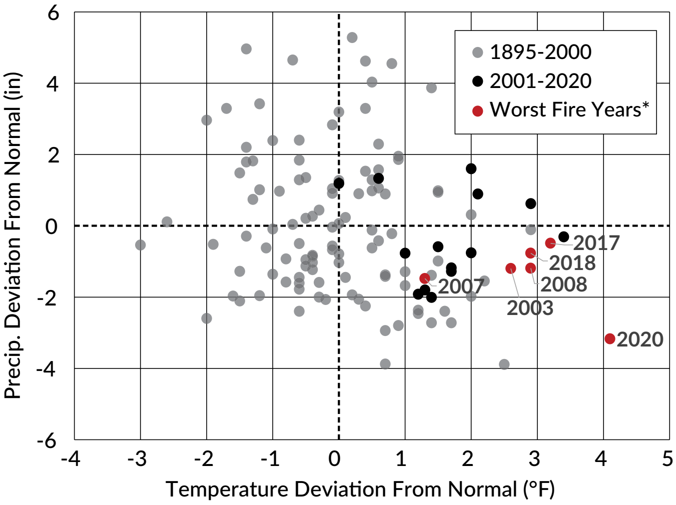

Figure 2. California temperature and precipitation deviation from average from July-November of each year, 1895-2020.

**More than 1 million acres burned.*
Source: NOAA National Centers for Environmental Information

Impact of Wildfire Smoke

The increase in wildfire activity has led to a substantial increase in the number of days each year impacted by smoke in the air. Effects of wildfire smoke extend far beyond the west coast, with increases observed throughout the U.S. (Burke et al., 2021). The heat generated by active fires lifts smoke high into the atmosphere. At high altitudes, the smoke can travel with jet stream winds across the continent (NASA, 2017). Pockets of concentrated smoke can sometimes occur far from the fires that generated it (Figure 3). Smoke is most noticeable and poses the greatest human health threat when it descends to the surface; however, smoke at any altitude has the potential to affect crop growth by reflecting and scattering incoming sunlight.

Given what is known about the factors that have led to increased wildfire activity, it's a virtual certainty that wildfire smoke in the atmosphere will continue to increase in frequency and concentration for the foreseeable future, making it important to understand how crop growth and productivity might be affected.

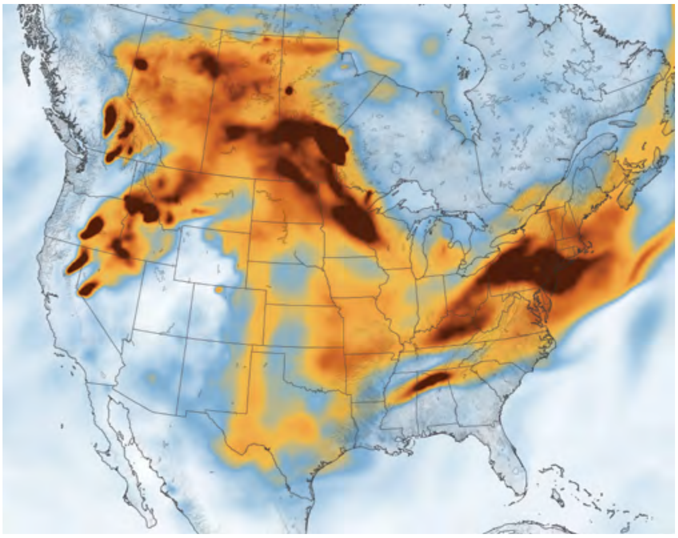

Figure 3. Smoke concentration in the atmosphere over North America, July 21, 2021. Source: NASA Earth Observatory.

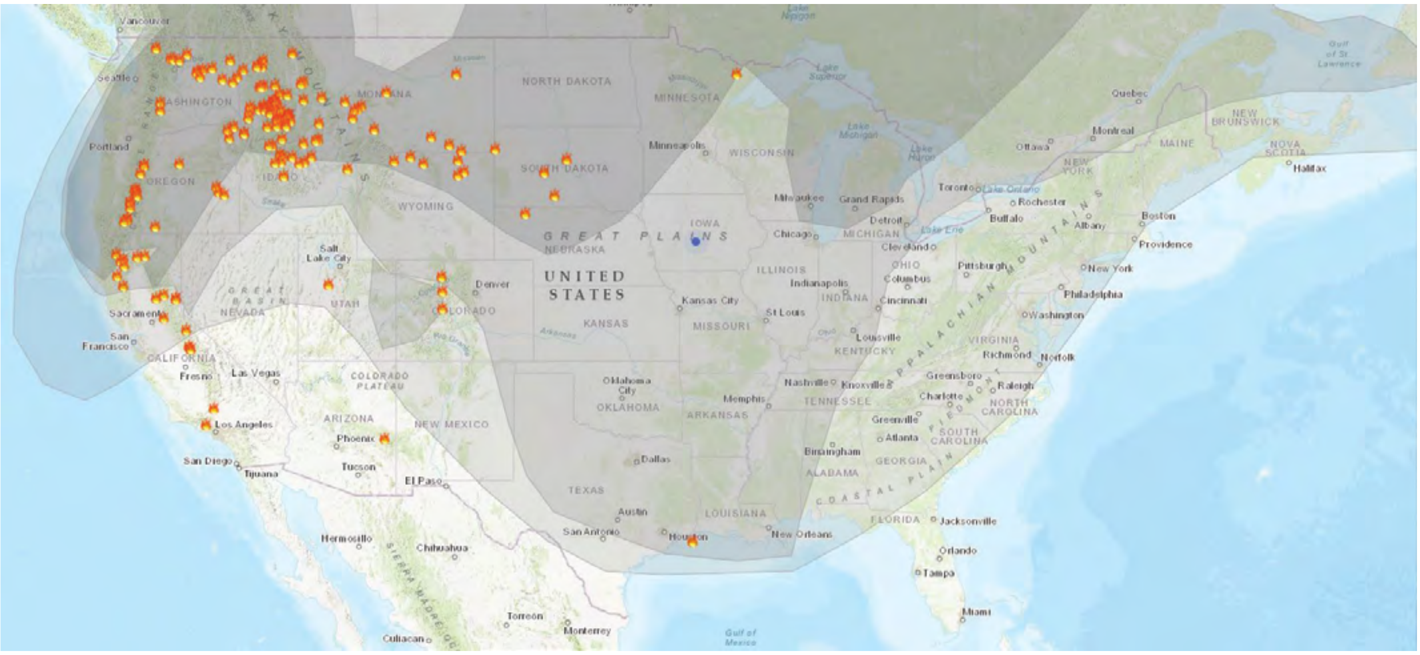

Figure 4. Map showing active wildfires and areas impacted by smoke across the U.S. on August 6, 2021.
Real-time maps and air quality indicators are available at https://www.airnow.gov.

POTENTIAL EFFECTS OF SMOKE ON CROPS

The impact of wildfire smoke on crop growth is complex and involves competing effects that can both enhance and suppress photosynthesis. Among the many potential effects on crop growth are three primary factors with the capability to directly impact photosynthesis: reduced sunlight intensity, increased sunlight diffusion, and increased ozone (O_3) levels.

Problem: Reduced Sunlight Intensity

The most obvious effect of wildfire smoke in the atmosphere is a reduction in total solar radiation. Much like a hazy cloud cover, smoke reflects a portion of incoming sunlight, reducing the amount of light available to plants. Since plants depend on sunlight to carry out photosynthesis, any reduction in light is potentially detrimental to crop productivity. Plants with the C4 carbon fixation pathway, such as corn, have a higher light saturation point, making them more susceptible to reductions in solar radiation than C3 plants such as soybeans.

Potential Benefit: Increased Diffusion of Sunlight

In addition to reflecting a portion of incoming light, smoke also scatters it, making the light available to plants more diffuse. Wildfire smoke can significantly increase the diffuse fraction of photosynthetically active radiation (PAR), which can actually benefit plants by increasing their light use efficiency. The potential effect of more diffuse light on plant growth depends on the characteristics of the plant canopy, with taller, higher leaf area index, and multilayer canopies likely to benefit more from diffuse radiation than shorter plants.

Problem: Increased Ozone Levels

Ozone (O_3) is most commonly known for the naturally occurring ozone layer in the upper atmosphere that shields Earth from harmful ultraviolet radiation. Ground-level ozone, however, is a damaging air pollutant that is harmful both to human health and plant growth. Ozone is formed when pollutants, mainly nitrogen oxides and volatile organic compounds, react in the atmosphere in the presence of sunlight. Wildfires emit large quantities of these precursor compounds. Nitrogen oxides and organic carbons produced by wildfires can be transported long distances by regional weather patterns before they react to create ozone in the atmosphere, where it can persist for several weeks.

Ground-level ozone is very harmful to plants, causing more damage to plants than all other air pollutants combined (USDA ARS, 2016). Ozone is a strong oxidant and damages plants by entering stomata and oxidizing (burning) plant tissue during respiration. Elevated ozone levels have the potential to significantly reduce crop yields. Dicot species, such as soybean ,are generally thought to be more susceptible to yield reduction than monocot species, such as corn (Heagle, 1989), although research has shown that corn and soybean are both susceptible to yield loss from ozone pollution (McGrath et al., 2015).

Complex and Interacting Effects

Of the three primary effects of wildfire smoke on crop growth, two of them – reduced total solar radiation and elevated ozone – are clearly negative, while increased diffusion of solar radiation could potentially be positive for crop growth. The ultimate effect on crop growth and yield will depend on the relative impact of each of these factors. For example, any benefit derived from increased diffuse radiation could be negated if the reduction in total solar radiation is too great. Interaction between effects is possible as well. For example, reduced solar radiation from smoke could suppress the formation of ozone from precursor compounds, a process that is dependent on sunlight. Additional effects could come into play as well. Reduction in solar radiation can reduce surface temperatures, which may be good, bad, or neutral depending on the timing and circumstances.

SOLAR RADIATION AND CROP PRODUCTION

Numerous experiments over the years have studied the impact of reduced solar radiation on corn yields using shade cloths that cover a portion of the crop canopy and reduce the intensity of incident solar radiation by a certain amount. These studies have provided some important insights on the effects of reduced solar radiation on corn.

Reductions in yield can be dramatic. Studies that have included shade treatments that reduce light by 50% or more during grain fill have seen corn yield drop by more than half (Table 1) (Yang et al., 2019).

Table 1. Percent corn yield reduction associated with three different levels of shading (15%, 30%, and 50%) for two hybrids at three different plant densities (Yang et al., 2019).

Density (plants/acre)	Hybrid 1			Hybrid 2		
	15%	30%	50%	15%	30%	50%
	yield reduction (%)					
30,400	NS*	NS	34.7	13.3	19.3	50.1
42,500	NS	19.2	41.8	14.8	25.2	54.7
48,500	NS	23.6	51.3	13.7	28.7	63.5

** Not significant at α=0.05*

Timing and intensity matter. Studies that have included multiple degrees of shading have found, not surprisingly, that the more solar radiation is reduced, the greater the effect on yield. Yang et al. (2019) found that impact on yield more than doubled when shading was increased from 30% to 50% (Table 1). The timing of shading is also of critical importance in corn. Reductions in solar radiation during silking and grain fill have a much greater impact than the same level of reduction prior to silking (Table 2) (Liu and Tollenaar, 2009; Reed et al., 1988).

Table 2. Effect of shade treatment timing on corn yield (Liu and Tollenaar, 2009.)

Shade Period*	Yield Reduction (%)
4 weeks pre-silking[a]	3.2% NS
3 weeks at silking[b]	12.6% **
3 weeks post-silking[c]	21.4% **

** Weeks relative to silking: [a] -5 to -1, [b] -1 to +2, [c] +2 to +5. Shading treatments reduced solar radiation by 55%*

*NS=not significant, **= highly significant, (α=0.05)*

Effects can vary by hybrid and plant density. Yang et al. (2019) compared effects of shading during grain fill on two different hybrids at three different plant densities. When solar radiation was only reduced by 15%, yield impacts were similar across plant densities. As the degree of shading was increased, however, yield reductions were greater at higher plant densities. The two hybrids compared in the study also differed in their response to reduced light levels, with one hybrid consistently affected more than the other. At the 15% level of shading, yield of the more sensitive hybrid was reduced by 13-15% while the more tolerant hybrid did not have a significant reduction in yield (Table 1).

Reduced solar radiation can also affect stalk quality. In addition to direct effects on corn yield, reduced solar radiation can lower harvestable yield by negatively affecting stalk quality and standability. Upon successful pollination, ear development places a great demand on the plant for carbohydrates. When the demands of the developing kernels exceed the supply produced by the leaves, stalk and root storage reserves are utilized. Environmental stresses that decrease the amount of photosynthate produced by the plant can force plants to extract even greater percentages of stalk carbohydrates, which preserves grain fill rates at the expense of stalk quality. As carbohydrates stored in the roots and stalk are mobilized to the ear, these structures begin to decline and soon lose their resistance to soil-borne pathogens. Instances of severe stalk rots and lodging have often been observed in association with prolonged periods of low solar radiation during grain fill (Figures 5 and 6).

Figure 5. A Pioneer hybrid plot in 2018 in which poor stalk quality was associated with below average solar radiation throughout the grain fill period. (September 28, 2018; Stephenson County, IL)

How Much Does Wildfire Smoke Reduce Solar Radiation?

Shading studies in corn have often involved treatments that reduced solar radiation by large percentages, similar to reductions that would be caused by moderate to heavy cloud cover. Data collected in Johnston, IA, found that solar radiation reductions from cloud cover ranged from 23 to 62% (Figure 7). So how much does wildfire smoke reduce solar radiation?

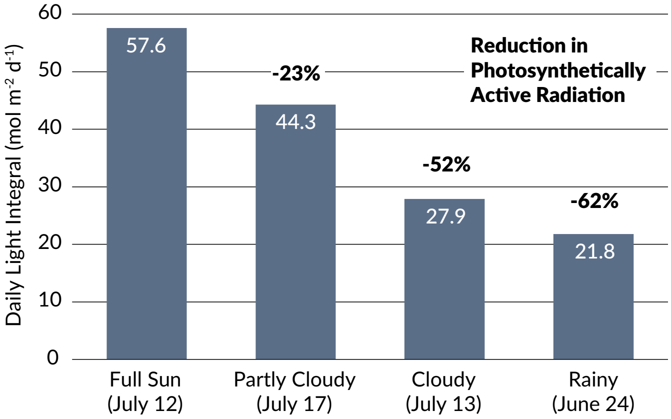

Figure 7. Daily PAR received in Johnston, IA, under sunny, cloudy, and rainy conditions on four different days during the summer of 2015.

A study conducted in 2018 in the California Central Valley found that total PAR was only reduced by 3.6% on average due to wildfire smoke, while the diffuse fraction increased by over 34% during the study period from mid-July to the end of August (Hemes et al., 2020). The predicted effect on corn was a 2.5% increase in photosynthesis, as the positive effect of more diffuse PAR exceeded the negative effect of reduced total PAR. However, under the smokiest conditions observed during the study period, photosynthesis was predicted to decline by more than 8%. The authors of the study noted that it focused on ecosystem productivity, not crop yield, and that yield may not respond to increased diffuse PAR in the same way.

Another study in California focused on lake ecosystems found that wildfire smoke over a 55-day period in 2018 reduced PAR by 11% compared to the 2014-2017 average (Scordo et al., 2021). Ohio State University researchers compared photosynthetic

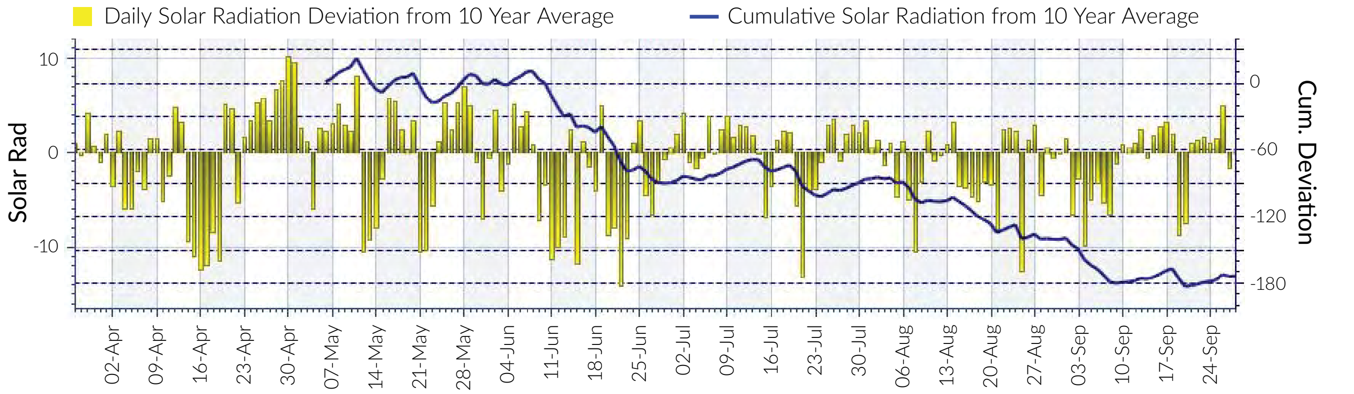

Figure 6. Daily and cumulative solar radiation for the Pioneer hybrid plot shown in Figure 5. Cumulative solar radiation fell below average by mid-June and continued to decline throughout the entire grain fill period.

photon flux density in June and July of 2021, a period marked by frequent smoke in the atmosphere, with the average of the previous 4 years and found that levels were reduced by 6-7% (Table 3).

Table 3. Daily average photosynthetic photon flux density in Wood County, Ohio (Lindsey et al., 2021).

Year	June	July
	μmol/m²/s	
2021	679	694
2017 to 2020	730	738
Difference	**-7%**	**-6%**

WILDFIRE SMOKE EFFECT ON CROP YIELDS

Determining the actual impact of wildfire smoke on crop yields is extremely difficult for a number of reasons, including the multiple, competing effects involved and the difficulty in isolating the effects of smoke from other influences. Conducting controlled experiments on wildfire smoke is impractical, so research has often focused on measuring the effects of smoke events as they occur. Experiments such as shading studies can provide important insights into the possible impact of specific aspects of smoke cover on crop yield but cannot replicate the full suite of effects.

Based on what is known about the effects of reduced solar radiation and elevated ozone on crops, it seems very plausible that wildfire smoke could cause reductions in crop yields. The scope of possible outcomes likely ranges from slightly beneficial to significantly harmful. The study by Hemes et al. (2020) probably represents something close to a best-case scenario, where the benefit of increased diffuse PAR exceeded the negative effects of slightly lower total PAR and elevated ozone. The heavier the smoke, the more likely reduction in total PAR will be the dominant factor.

In general, corn is likely to be more susceptible to the effects of wildfire smoke than soybeans. Corn has a higher light saturation point due to its C4 photosynthetic pathway, so is more likely to be impacted by reductions in total PAR. Corn may also experience reduced standability if lower solar radiation during grain fill forces plants to remobilize more carbohydrates from the stalk. The risk of yield loss and reduced stalk health is likely greater when smoke imposes an additional stress upon a crop that is already experiencing the effect other stresses, like disease or drought stress. Clearly identifying all contributing stresses can be very difficult, much less being able to precisely quantify the impact each of the those compounding factors may have had on the crop.

Corn and soybean can both be harmed by elevated ozone levels; however, both the production of ozone from wildfire smoke and the intake of ozone through plant stomata can be influenced by a number of different factors. Corn and soybean already experience wide scale reductions in yield from ozone associated with other sources of air pollution (McGrath et al., 2015), so the additional effect of ozone specifically associated with wildfire smoke could be difficult to determine.

Wildfire smoke is not a problem that's going away anytime soon. Based on what we know about the contributing factors, wildfires in western North America are likely to increase in frequency and intensity in the coming years. The effects on wildfire smoke on both agricultural and natural ecosystems will likely continue to be an active area of research.

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SOLAR RADIATION IN CORN PRODUCTION

KEY POINTS:

- Cloudy, rainy periods that limit the amount of solar radiation available to a corn crop during susceptible stages of development can have significant effects on yield.
- Several experiments have used shade cloth to reduce the amount of solar radiation on a portion of the crop canopy.
- Shade studies have found that corn is most susceptible to yield loss during flowering and grain fill and effects can vary by plant density.

SOLAR RADIATION AND CROP NEEDS

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

CLOUD EFFECTS ON SOLAR RADIATION

- Plants are able to use only a portion of the solar radiation spectrum. This portion is known as photosynthetically active radiation (PAR) and is estimated to be about 43% to 50% of total radiation.
- The amount of PAR available to a crop is reduced proportionately to cloud cover (Figure 1).
- As Figure 1 shows, PAR was reduced by 25% to 50% on partly cloudy to cloudy days, and by more than 60% on rainy days.
- It is not surprising, then, that cloudy, rainy periods during susceptible stages of crop development can have significant effects on yield.

EFFECT OF SHADE ON CORN YIELD

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

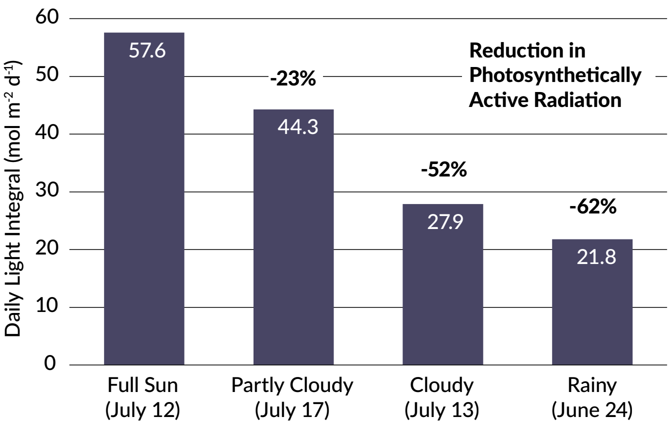

Figure 1. Daily PAR received in Johnston, IA, under rainy, cloudy and sunny conditions on four different days in summer.

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

Shade period*	Yield reduction (%)
4 weeks pre-silking[a]	3.2% NS
3 weeks at silking[b]	12.6% **
3 weeks post-silking[c]	21.4% **

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

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

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

Shade period	% Yield Reduction	Change in kernels/row	Change in kernel wt.
Vegetative	12%	-5%	+1%
Flowering	20%	-21%	+9%
Grain fill	19%	-5%	-13%
LSD (.05)	7%	4.5%	6%

- Studies that have included multiple degrees of shading have found, not surprisingly, that the more solar radiation is reduced, that greater the effect on yield.
- Yang et al. (2019) found that impact on yield more than doubled when shading was increased from 30% to 50% (Table 3).
- When solar radiation was only reduced by 15%, yield impacts were similar across plant densities. However, as the degree of shading was increased, yield reductions were greater at higher plant densities.

Table 3. Percent corn yield reduction associated with three different levels of shading (15%, 30%, and 50%) for two hybrids at three different plant densities (Yang et al., 2019).

Density (plants/acre)	Hybrid 1			Hybrid 2		
	15%	30%	50%	15%	30%	50%
	yield reduction (%)					
30,400	NS	NS	34.7	13.3	19.3	50.1
42,500	NS	19.2	41.8	14.8	25.2	54.7
48,500	NS	23.6	51.3	13.7	28.7	63.5

NS=not significant,

AVERAGE U.S. SOLAR RADIATION

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

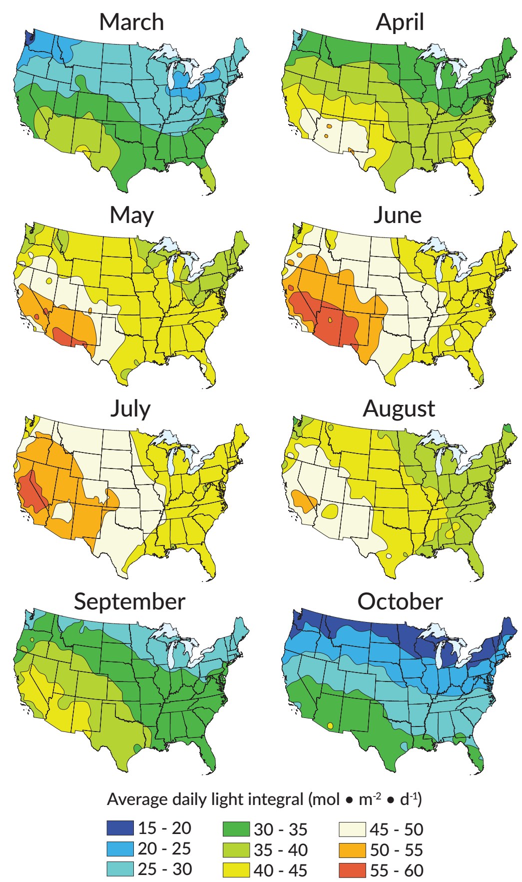

Figure 2. Average U.S. daily light integral (DLI) by month (Korczynski, et al., 2002).

Dan Emmert,
Pioneer Field Agronomist

EFFECTS OF REDUCED SOLAR RADIATION ON CORN GROWTH AND YIELD

KEY FINDINGS:

- Reduced solar radiation had a large impact on corn yield and stalk quality. Specific effects differed depending on when the reduction occurred.
- Corn was most susceptible to yield loss when reduced solar radiation occurred during pollination.
- Reduced solar radiation during grain fill resulted in lower kernel weight and stalk strength.

RATIONALE AND OBJECTIVES

- Along with water and nutrients, solar radiation (sunlight) is an essential input for crop growth and yield.
- Photosynthetically active radiation (PAR) can be reduced by more than 60% on cloudy and rainy days compared to full sunlight.
- Extended periods of low solar radiation during grain fill can reduce yield and cause stalk quality issues as corn plants remobilize stalk carbohydrates to the ear.
- A field demonstration was conducted in 2021 to show how a reduction in solar radiation at various stages of corn growth impacts corn ear development and final yield.

Figure 1. Shade structure that was used to apply reduced solar radiation treatments.

STUDY DESCRIPTION

- The field demonstration was conducted near Montgomery, Indiana.
- Two-row plots of four different Pioneer® brand corn products, ranging from 109 to 113 comparative relative maturity (CRM) were planted on April 24.
- A shade structure that reduced solar radiation by approximately 70% was installed over a portion of the plot area beginning at the V13 growth stage (Figure 1).
- The shade structure was rolled down the row to shade a different portion of the plot area after the accumulation of approximately 320 growing degree units (GDUs).
- A total of five different shade timings were applied as part of the demonstration (Table 1).
- Kernels per row, kernel weight, corn yield, and stalk strength were measured for each hybrid and shade treatment.
- Stalk strength was assessed using a standard push test, in which plants were pushed 30 degrees from vertical and either snapped back to vertical or crimped and fell over.

Table 1. Shade treatment timings.

Treatment	Date Initiated	Date Ended	GDUs*
V13-VT	June 17	July 3	407
VT-R2	July 3	July 15	313
R2-R3	July 15	July 29†	313
R4	July 30	Aug 14	363
R5	Aug 14	Aug 28	325

* Source: https://mrcc.purdue.edu/U2U/gdd/
† Canopy was temporarily removed July 22 and 23

RESULTS

- The number of kernels per row was reduced when plants were shaded prior to R3 (Figure 2).
- A 70% reduction in solar radiation during pollination resulted in near-total pollination failure.
- Shade during R2 and early R3 caused kernels that had successfully pollinated at the tip of the ear to abort.
- Shade during R4 and R5 did not reduce the number of kernels per row but did reduce kernel weight (Figure 3).
- Maximum kernel weights occurred when pre-pollination shading reduced the total number of kernels, but solar radiation was not reduced at any point during grain fill.
- Reducing solar radiation during R4 and R5 reduced available photosynthate for grain fill, resulting in reduced kernel weights, stalk cannibalization, and weaker stalks (Figure 5).

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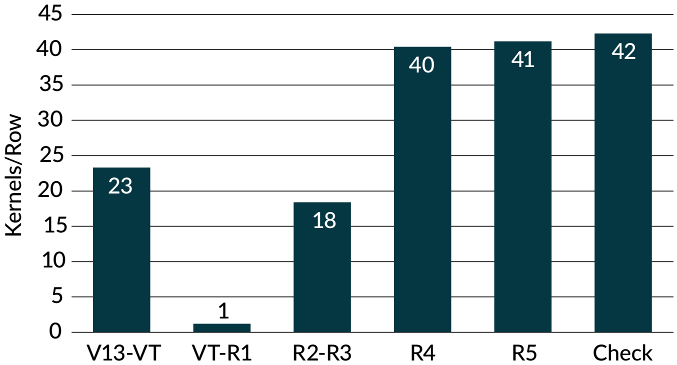

Figure 2. Shade treatment effects on kernels per row.

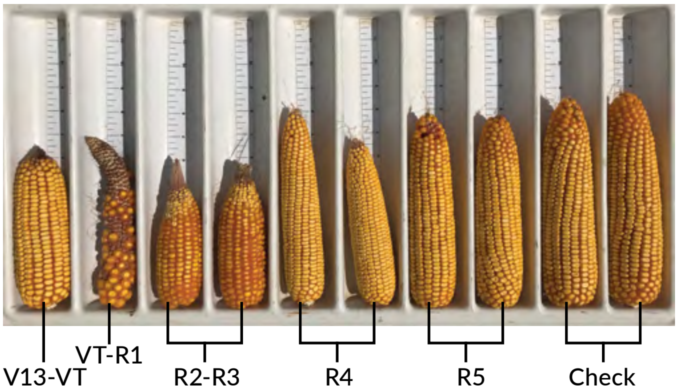

Figure 6. Shade treatment effects on pollination and ear length.

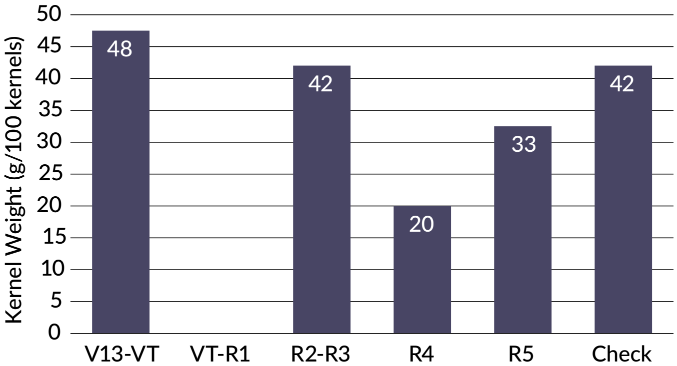

Figure 3. Shade treatment effects on kernel weight.

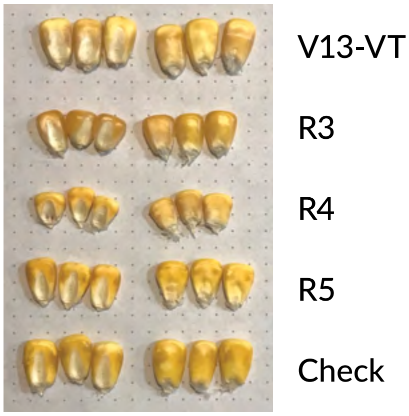

Figure 7. Shade treatment effects on kernel size.

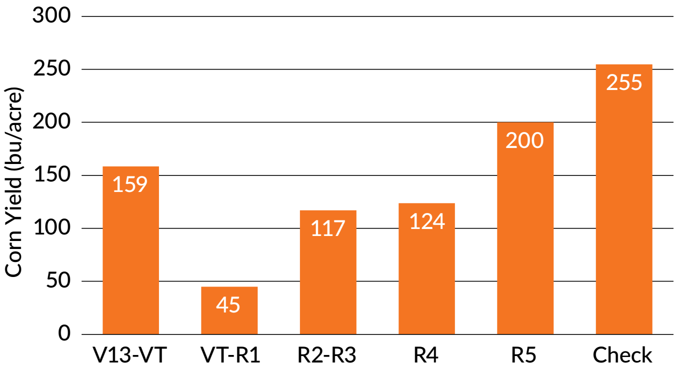

Figure 4. Shade treatment effects on corn yield.

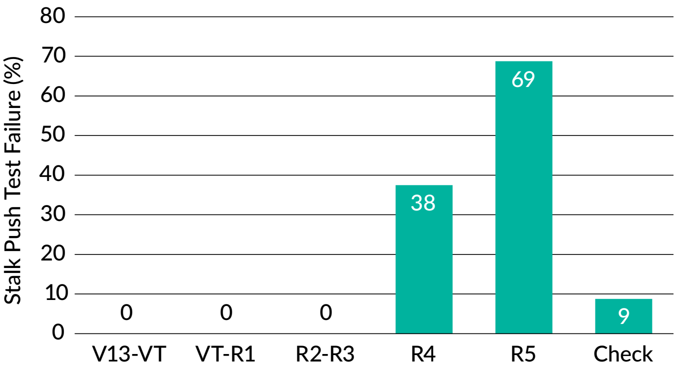

Figure 5. Shade treatment effects on stalk strength.

Corn Growth Stage	Effect of 70% Reduced Solar Radiation on Growth and Yield
V13-VT	• Additional set of brace roots. • Reduced internode length. • Smaller leaves at final nodes. • Decreased tassel size. • Reduced kernels per row. • **Yield loss = 38%.**
VT-R1	• Delayed ear development and silk emergence. • Near-total pollination failure. • **Yield loss = 82%.**
R2-R3	• Increased kernel abortion at ear tips. • Kernels per row reduced by more than 50%. • **Yield loss = 54%.**
R4	• Kernel weight reduced by more than 50%. • Reduction in stalk strength. • **Yield loss = 51%.**
R5	• Reduced kernel weight. • Dramatic reduction in stalk strength. • **Yield loss = 21%.**

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Agronomy Manager

HEAT STRESS EFFECTS ON CORN

SUMMARY

- Research has shown a negative response of corn yield to the accumulation of temperatures above 86°F (30°C).
- Heat stress during flowering can reduce yield by inhibiting successful pollination and by reducing net photosynthesis, although negative effects on pollination are relatively rare.
- The greatest impact of extreme heat stress on corn likely comes through intensification of water stress rather than the direct effect of heat itself.
- Higher temperatures cause the transpiration rate of plants to increase, placing a greater demand on soil water supply and potentially accelerating the onset of drought stress.
- Corn plants respond to water stress by closing their stomata, which helps preserve water but also reduces the rate at which plants are able to take in CO_2 needed for photosynthesis.
- Damage caused by extreme heat can be partially mitigated by irrigation or increased precipitation, but not eliminated.
- Future increases in the number of extreme heat days during the growing season could limit corn productivity.

HOW HOT IS TOO HOT FOR CORN?

Heat stress is defined as the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development (Wahid et al., 2007). It is generally understood among corn growers that excessive heat can be detrimental to yield, but how hot is too hot, and what is the risk of yield losses due to excessive heat now and in the future?

Multiple statistical studies have shown negative correlations between above average seasonal temperatures and corn yield (Lobell and Field, 2007; Sakurai et al., 2011; Tao et al., 2008). As average temperatures increase above a certain point, corn yields decrease. Further analysis of yield and weather data has found that the main driver of this negative association is the sensitivity of corn to temperatures above 86°F (30°C) (Schlenker and Roberts, 2009). Researchers have begun using the terms extreme degree days (EDD) or extreme heat degree days (HDD) to quantify the accumulation of temperatures above this level (Lobell et al., 2013; Roberts et al., 2013). Corn yields tend to increase with temperatures up to this threshold and then drop off sharply when temperatures exceed it.

Concerns regarding the direct effects of extreme heat on corn have often focused on reproductive success; specifically, the potential for high heat to desiccate silks and reduce pollen viability, negatively affecting pollination. However, in corn production areas of North America, it is relatively rare for temperatures to reach the threshold necessary to impact pollination. And yet, studies have shown that high temperatures are having a negative impact on corn yields. This suggests other heat stress mechanisms are involved.

Increasing global temperatures mean that corn crops will likely experience more frequent heat stress in many areas, making it important to understand how high heat affects corn growth and yield.

HEAT STRESS EFFECTS ARE COMPLEX

Heat stress effects on corn are complex and often difficult to quantify. Heat stress is not just a function of temperature, but also depends on the duration and timing of high temperatures, as well as the rate of temperature change (Wahid et al., 2007). Some forms of heat stress can create visual injury symptoms while other are more subtle.

Heat stress is also often accompanied by drought, which can make it challenging to disentangle the individual impacts of temperature and water stress on corn growth and yield. Research has shown that the direct effect of heat stress is important, but the greater impact likely comes from the effect of heat on intensifying water stress.

WARM DURING THE DAY, COOL AT NIGHT

When examining the effects of temperature on corn yield, it is useful to consider the predominant conditions to which corn was adapted in its area of origin. The genetic lineage of corn can be traced back the Central Highlands of Mexico (Galinat, 1988), specifically the Tehuacán Valley and Balsas River Valley. Summer climate in this region is characterized by relatively mild daytime high temperatures, cool nights, and abundant sunshine. Average summer temperatures in much of the Corn Belt are commonly warmer during the day and much warmer during the night than those to which corn was originally adapted in its native region (Figure 1).

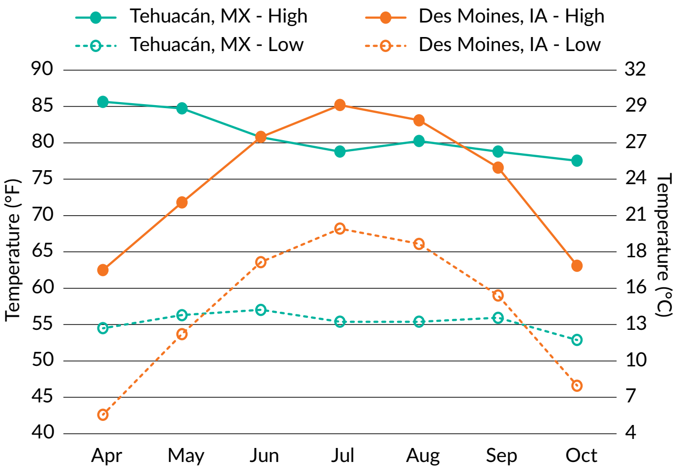


Figure 1. Average daily high and low temperatures for Tehuacán, Puebla, in the Central Highlands of Mexico near where corn was first cultivated, and for Des Moines, IA, in the heart of the modern U.S. Corn Belt.

DIRECT HEAT STRESS EFFECTS ON CORN

Kernel Set is Critical

Corn yield reduction from heat stress can be associated with reductions in both source and sink capacity. Impact on yield depends on the growth stage of the corn at the time stress occurs. The most critical period for corn yield determination is the roughly four- to five-week window bracketing silking when kernel number is set. Approximately 85% of total grain yield is related to the total number of kernels produced per acre (Otegui et al., 1995). Any stress during this time that reduces the number of kernels a plant is able to set will negatively impact yield. Even if the stress is temporary and the plant recovers, the damage to yield will be done.

Heat stress during this timeframe can reduce yield in a couple of ways: by inhibiting successful pollination and by reducing net photosynthesis, which can lead to an increase in kernel abortion. Both mechanisms can reduce the number of kernels on the ear. Heat stress can continue to impact yield through grain fill by reducing kernel weight, much like any other form of stress that inhibits photosynthetic carbon assimilation. Stalk quality can also be impacted if the stress forces the plant to increase its reliance on remobilized carbohydrates to complete grain fill.

Heat Stress Effects on Pollination

Temperatures above 90°F (32°C) have the potential to negatively impact pollination. Prolonged exposure to temperatures above 90°F (32°C) has been shown to dramatically reduce pollen germination (Herrero and Johnson, 1980). Temperatures above 95°F (35°C) depresses pollen production and can desiccate exposed silks, especially when accompanied by low relative humidity (Hoegemeyer, 2011). High temperatures and low humidity can similarly desiccate pollen grains once they are released from the anthers. Temperatures above 100°F (38°C) can kill pollen (Nielsen, 2020).

Corn tassel branches showing anthers extruded.

Peak pollen shed usually occurs in mid-morning. A second period of pollen shed can occur in late afternoon or evening as temperatures cool.

Under cool, cloudy conditions, pollen shed may continue throughout most of the day.

However, research suggests that yield loss due to heat stress effects on pollination is relatively rare in North America (Lobell et al., 2013). Daily maximum temperatures in the Corn Belt commonly reach the mid or upper 90s but pollination is usually not severely affected. Pollen shed typically occurs during early to mid-morning hours before temperatures climb to potentially harmful levels. The daily high temperature would likely need to be well above 100°F to reach dangerous levels during mid-morning, when most pollen shed occurs. For example, July 25, 2012, was the hottest day of a notoriously hot summer in central Iowa. The maximum temperature in Des Moines hit 106°F (41°C) at 5:00 pm, but temperatures between 9:00 and 10:00 am were only 90-95°F (30-35°C), just barely reaching the threshold for pollen and silk desiccation (Figure 2). Furthermore, pollination occurs over a period of several days, providing multiple opportunities for viable pollen to reach exposed silks.

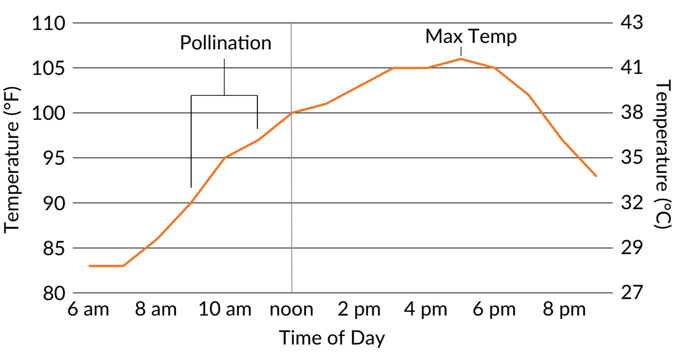


Figure 2. Temperature over the course of the day on July 25, 2012, showing timing of peak pollination and maximum daily temperature.

LEAF TEMPERATURE VS. AIR TEMPERATURE

Temperature effects on crop physiology are often characterized based on ambient air temperature; however, the temperature that photosynthesizing cells inside corn leaves actually experience can differ somewhat from that of the surrounding air. Leaves often have a lower temperature than the air around them because the evaporation of water transpired through the leaves cools them. The drier the air, the cooler the leaf of a well-watered plant will be compared to the surrounding air.

Figure 3. A live leaf and a dead leaf in the upper canopy. The surface temperature of the live leaf is 94°F (34°C), while the temperature of the dead leaf is 102°F (39°C).

This cooling effect is illustrated by comparing the surface temperatures of living leaf tissue vs. dead leaf tissue, shown in Figure 3. The temperatures of a live and dead leaf adjacent to each other in the upper canopy of a corn field differed by more than 7°F. The temperature of the living leaf was 94.4°F (34°C), a few degrees above the ambient air temperature of 91°F (33°C), while the dead leaf was well-above the ambient temperature at 102°F (39°C).

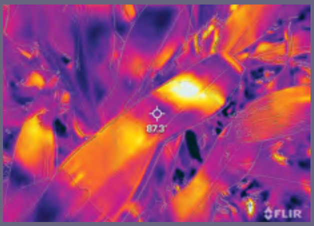


Figure 4. Leaf temperature differences due to partial shading in the canopy. A shaded portion of the leaf is 87°F (31°C), while a sunlit portion only a few inches away is nearly 95°F (35°C).

Temperature can also vary depending on the level of sun exposure and the position of the leaf relative to the angle of the incoming sunlight. Figure 4 shows a partially shaded leaf in the corn canopy, with the shading from other leaves creating a banded appearance in the infrared imagery. The temperature of a shaded portion of the leaf was 87.3°F (31°C), a few degrees below air temperature, while a portion of the leaf a few inches away exposed to direct sunlight was more than 7°F higher. Shaded and exposed areas will shift over the course of the day, so a given spot on a leaf may experience a range of different temperatures, even if the surrounding air temperature is relatively constant.

HEAT STRESS EFFECTS ON PHOTOSYNTHESIS

Heat stress can also impact corn yield through reduced net photosynthesis. Decreased net photosynthesis can cause large reductions in yield if it occurs during the critical period for kernel number determination. When stress occurs during this interval, the corn plant typically starts to abort kernels at the tip of the ear and moves toward the base of the ear until it reaches a point that the remaining viable kernels can be sustained by the plant.

Temperature dependent biological reactions, such as photosynthesis and respiration, generally have an optimum temperature (Topt) for operation (Figure 5). Photosynthesis and respiration are slow at cooler temperatures, increase as the temperature increases, and decline and eventually cease when the temperature gets too high. The optimum temperature for respiration is greater than that for photosynthesis. Net photosynthesis is a measure of carbon assimilated through photosynthesis (sugar produced) minus carbon expended through respiration (sugar consumed). Net photosynthesis has a Topt lower than that of gross photosynthesis due to the offsetting effect of the higher respiration rate (Figure 5).

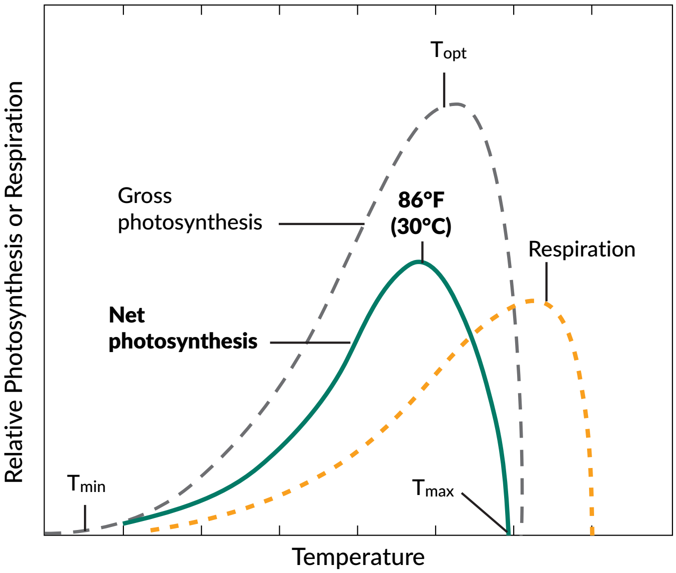


Figure 5. Generalized model of temperature effects on rates of gross photosynthesis, respiration, and net photosynthesis. Net photosynthesis in corn is optimized at 86°F. (Figure adapted from Hopkins, 1999)

Plant species with the C4 photosynthetic pathway, such as corn, generally have a higher optimum temperature for photosynthesis than C3 plants. In C3 plants, net photosynthesis is reduced at higher temperatures due to an increase in photorespiration caused by higher oxygenase activity of ribulose-1,5-bisphosphate carboxylase-oxygenase (rubisco), an enzyme involved in the first major step of photosynthetic carbon fixation. As temperatures increase, the ratio of dissolved O_2/CO_2 and the specificity of rubisco for O_2 increase, favoring oxygenase activity. C4 plants possess a mechanism to eliminate this inefficiency by locally increasing the concentration of CO_2 available to rubisco enzymes and, as such, are not constrained by temperature in the same way.

Reduced net photosynthesis in corn under heat stress has also been shown to be associated with rubisco activity, but it is due to the inactivation of the enzyme at high temperatures. A daytime temperature of 86°F (30°C) is ideal for corn growth (Miedema et al., 1987). At temperatures above this level, net photosynthesis declines due to the loss of rubisco activation (Crafts-Brandner and Salvucci, 2002).

The degree to which net photosynthesis is reduced at high temperatures can depend on how quickly temperatures increase. The faster the increase, the greater the reduction in photosynthesis. Crafts-Brandner and Salvucci (2002) found that a rapid increase to 113°F (45°C) reduced net photosynthesis by 95%, but a gradual increase to the same level reduced it by only 50%.

The level of solar radiation has also been shown to play a role in heat stress effects on corn by influencing the optimum temperature for net photosynthesis. Under light-limited conditions, the optimum temperature shifts lower due to the fact that respiration continues to increase with higher temperatures, whereas gross photosynthesis does not increase due to light limitation (Rainguez, 1979).

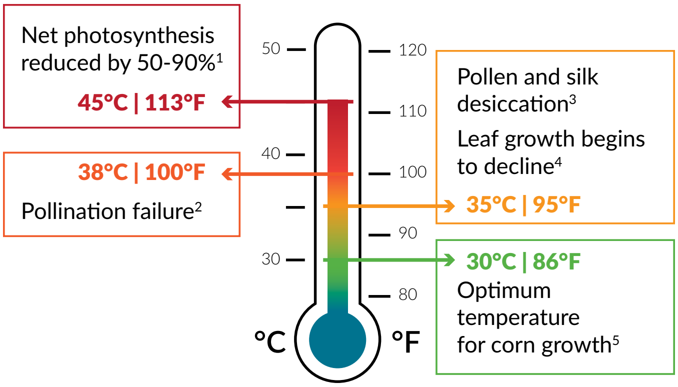


Figure 6. Key temperature thresholds for heat stress effects on corn pollination and growth.

[1] Crafts-Brandner and Salvucci (2002), [2] Nielsen (2020), [3] Hoegemeyer (2011), [4] Waqas et al. (2021), [5] Miedema et al. (1987).

HEAT AND WATER STRESS

High temperatures can impact corn yield directly, by reducing pollination and net photosynthesis, but field research and crop modeling studies indicate that a greater impact likely comes through the interaction of heat and water stress. Higher temperatures create a higher vapor pressure deficit (VPD) between the saturated leaf interior and the ambient air. This causes the transpiration rate of plants to increase, placing a greater demand on soil water supply and potentially accelerating the onset of drought stress.

What is Vapor Pressure Deficit?

VPD is the difference between how much water the air can hold when it is saturated and how much water it currently holds. It combines relative humidity (RH) and temperature into a single variable to describe the evaporative potential of the atmosphere. Air space in the interior of living plant tissue is essentially fully saturated with water (100% RH). Water vapor will tend to move from an area of higher concentration to an area of lower concentration, so if the ambient air is less than 100% humidity, it will pull water out of plant leaves, driving transpiration of water through the plant.

The greater the vapor pressure deficit between the leaf interior and the surrounding air, the faster the rate at which water will be pulled out of the plant and evaporated. Temperature is important to this equation because VPD increases exponentially with increasing temperature, even if RH stays constant. For example, if the RH of ambient air is 30%, the vapor pressure deficit (VPD) will be much greater at 100°F (38°C) than at 77°F (25°C) (Figure 7), creating a much higher evaporative demand at the higher temperature.

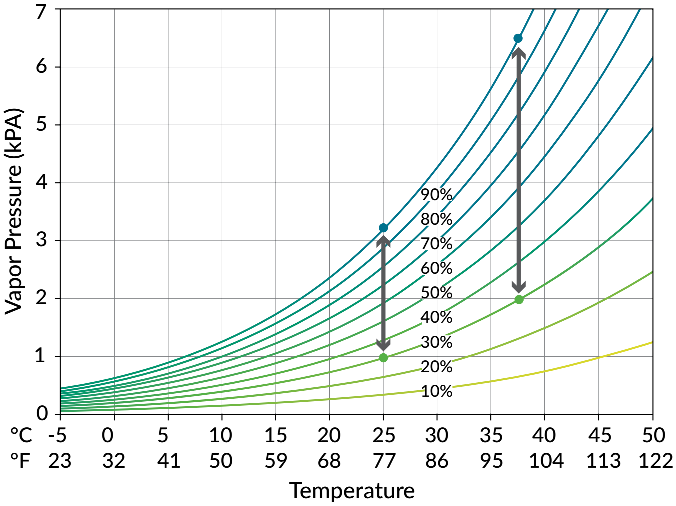


Figure 7. Vapor pressure for water by relative humidity and temperature.

SUNSCALD IN CORN

Heat and water stress can result in visible injury to corn in the form of sunscald. This occurs when the increase in evaporative demand exceeds the plant's ability to respond. The plant is unable to transpire water rapidly enough to cool heat-stressed leaf tissue, causing leaf tissue to die. Younger leaves and leaves with direct orientation to the sun are typically most affected.

Corn canopy with severe sunscald injury

Corn Response to High Vapor Pressure Deficit

Corn plants respond to higher VPD by closing their stomata, which helps preserve water for periods when evaporative demand is lower. However, reduced stomatal conductance also reduces the rate at which plants are able to take in CO_2, which lowers the rate of photosynthetic carbon fixation during high-VPD portions of the day.

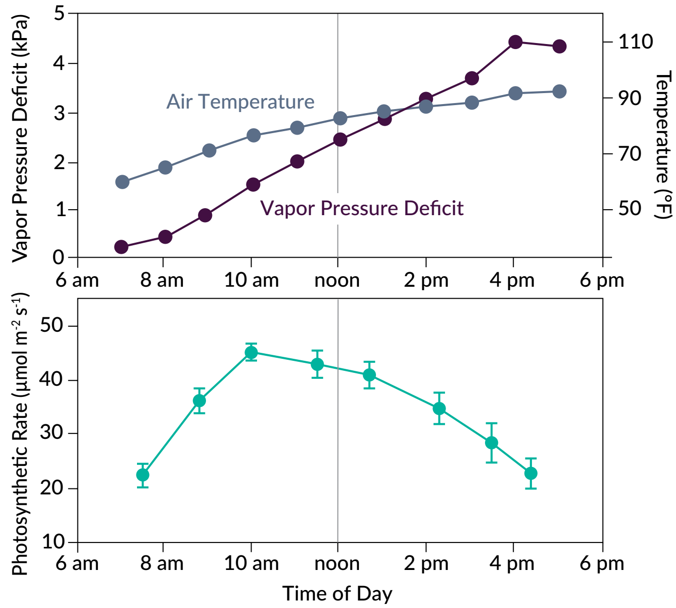


Figure 8. Air temperature, atmospheric vapor pressure deficit, and leaf photosynthetic rate in irrigated corn over the course of a day (Hirasawa and Hsiao, 1999).

Field experiments conducted in an environment in which temperatures reached daily highs in the mid-90s showed reduced photosynthesis and growth of corn associated with high VPD (Hirasawa and Hsiao, 1999). On days with high atmospheric VPD, photosynthetic rate and stomatal conductance peaked during late-morning and then declined throughout the afternoon as temperature and VPD continued to climb (Figure 8). Even in irrigated plots where soil water was ample, this afternoon depression in photosynthetic rate was apparent, although decline was much greater in non-irrigated plots (Figure 9).

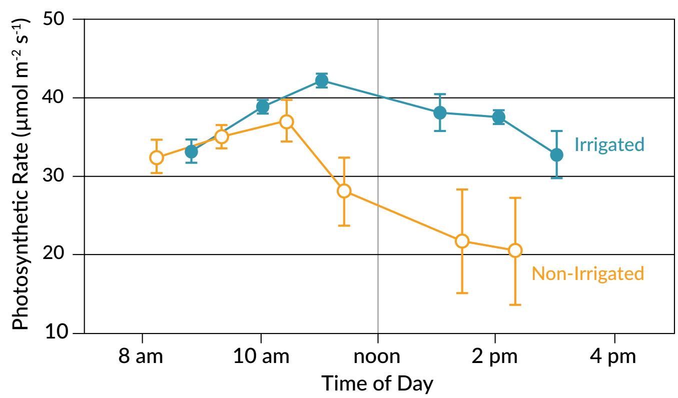


Figure 9. Leaf photosynthetic rate by time of day for irrigated and non-irrigated corn (Hirasawa and Hsiao, 1999).

Extreme Temperatures Drive VPD

A recent analysis showed a strong correlation between VPD and extreme degree days (EDD) accumulation in rainfed corn production in the U.S. Corn Belt (Roberts et al., 2013). Extreme heat contributes to water stress in two ways: by increasing demand for soil water to sustain carbon assimilation, and by depleting water from the soil, thus reducing future water supply. The increased water demand under extreme heat is substantial—raising temperatures from 80°F to 95°F (27°C to 35°C) causes water demand to double (Lobell et al., 2013). Research indicates that the damage caused by extreme heat can be partially mitigated by increased precipitation, but not completely eliminated (Roberts et al., 2013).

Lobell et al. (2013) compared the water stress effect caused by a 20% reduction in precipitation over month-long period with that caused by a 2°C increase in temperature over the same time period and found that increased temperature had a greater impact on water stress than reduced precipitation. Total seasonal rainfall was found to have a relatively weak relationship with corn yield, indicating that water demand can matter as much or more than water supply.

High Winds Can Make Heat and Water Stress Worse

Wind can exacerbate heat stress by increasing the vapor pressure deficit (VPD) between the leaves and the air immediately surrounding them. When water is evaporated from plant leaves, the air above the surface gradually becomes more saturated with water vapor. If winds are low, this layer of saturated air stays in place around the crop canopy, causing the evapotranspiration rate to decrease. When winds are high, this layer of saturated air is constantly being removed and replaced with drier air (Allen et al., 1998).

The higher the relative humidity, the less wind speed will matter, as the wind will only be able to replace the saturated air with slightly less saturated air. Under arid conditions though, small variations in wind speed may result in larger variations in VPD and evapotranspiration rate.

The impact of wind can be seen in the "field edge effect" in corn, where corn burns up and yields less along an edge of the field exposed to wind, commonly on the western or southern side (Figure 10). This phenomenon is commonly observed in hot and dry summers. The more severe stress along the field edge is likely due to the fact that the air is driest when it encounters the leading edge of field and picks up moisture as it moves across the crop canopy (White and Licht, 2020; Westgate and Vittetoe, 2017). Consequently, the effect of wind on VPD is greatest for plants near the field edge and lower for plants in the rest of the field.

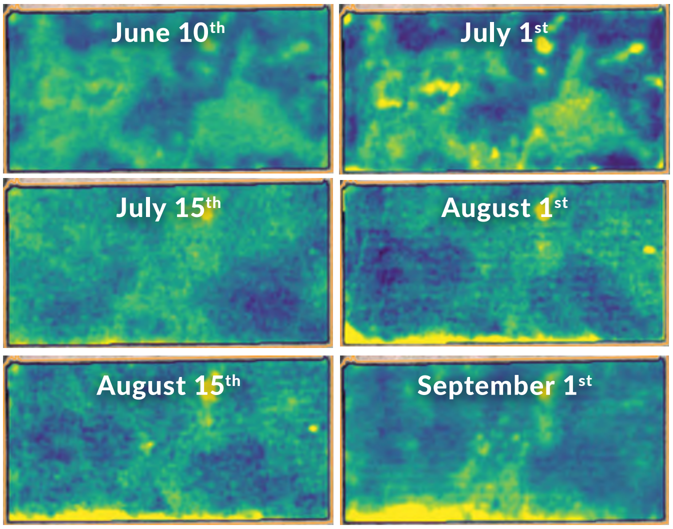
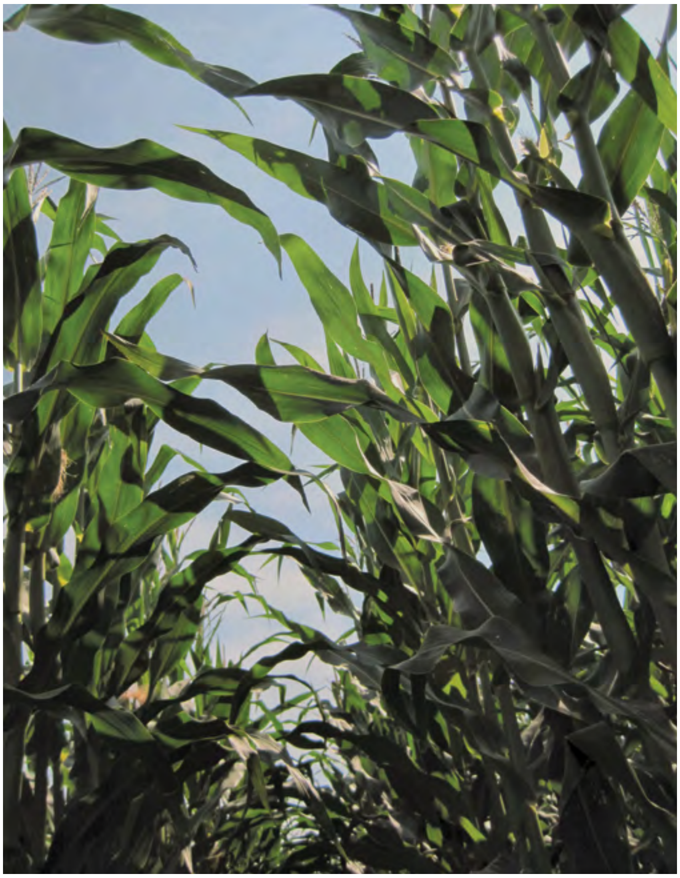


Figure 10. Sequence of Vegetation Index maps showing progression of crop damage along the southern edge of a corn field from June 10 to September 1, 2017.



IMPACT OF RISING TEMPERATURES

Research has shown that extreme heat can and does negatively affect corn yield, and that the greater impact likely comes through intensification of water stress rather than the direct effect of heat itself. Yields of rainfed corn show a clear negative response to the accumulation of temperatures above 86°F (30°C). An increase in the number of days during the growing season that surpass this threshold could constrain future gains in corn productivity.

Outside of North America, nearly every major crop production area of the world is already experiencing a greater frequency of extreme heat during the growing season, with global corn yields estimated to be 3.8% lower than they would be without recent warming trends (Lobell et al., 2011). Corn-producing areas of the U.S. and Canada have been relatively unaffected so far, as summer temperatures have not increased to the degree that they have elsewhere (Angel et al., 2018). This anomaly has even been given a name—the U.S. "warming hole"—because of the distinct lack of summer warming compared to most of the rest of the world (Partridge et al., 2018). Annual average temperatures in this area have increased, but mostly due to warmer winters and higher night temperatures. Extreme summer heat has stayed steady or declined in much of this area.

This reprieve from rising summer temperatures is not expected to last indefinitely, however. Summer temperatures are projected to increase more in the Midwest than any other region of the United States by mid-century (Vose et al., 2017). Extreme heat is therefore likely to become a more frequent and more severe constraint on corn yields in North America, much as it already is in most other crop-producing regions.

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REDUCTION IN CORN YIELD DUE TO HIGH NIGHT TEMPERATURES

NIGHT TEMPERATURES AND CORN YIELD

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

YIELD REDUCTIONS FROM WARM NIGHTS

2010 Growing Season

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

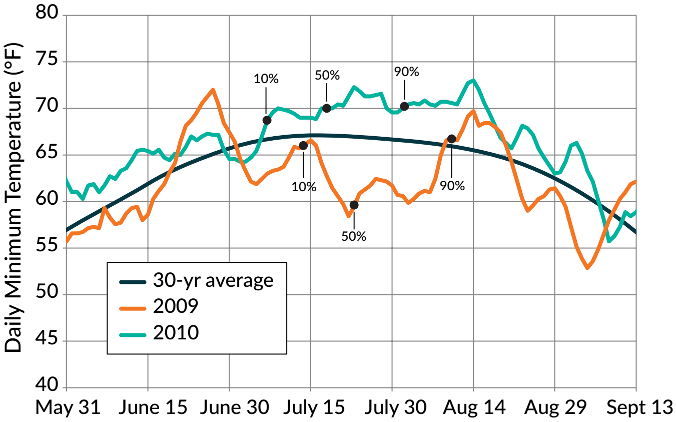


Figure 1. Daily minimum temperatures (7-day moving average) for Des Moines, IA, in 2009 and 2010 and 30-yr average minimum daily temperatures (1981-2010). Approximate dates of 10%, 50%, and 90% silking in Iowa in 2009 and 2010 based on USDA crop progress reports.

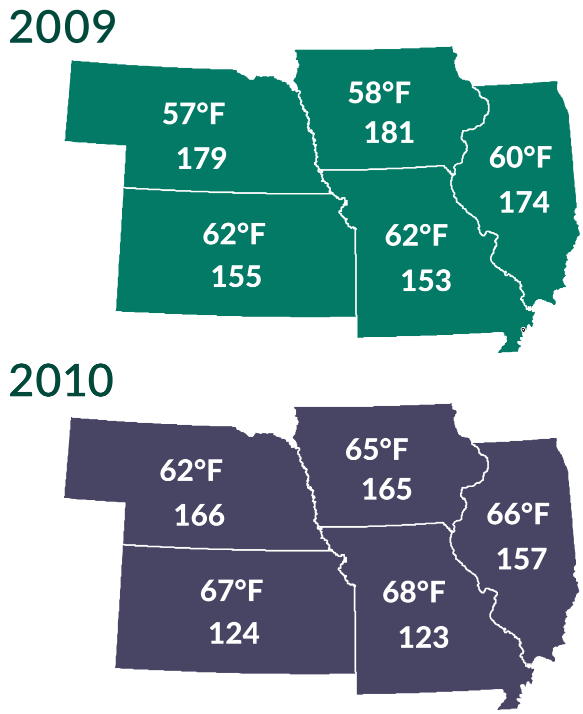


Figure 2. Average minimum temperatures experienced in July-August of 2009 **(top)** and 2010 **(bottom)** and average yields (bu/acre) in Iowa, Illinois, Missouri, Kansas, and Nebraska. *Data from NCEI NOAA, USDA NASS.*

University of Illinois Study

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

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

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

Further Research on Temperature Effects

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

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

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

WHY DO WARM NIGHTS REDUCE YIELD?

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

Higher Rate of Respiration

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

Accelerated Phenological Development

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

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

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

Mark Jeschke, Ph.D.,
Agronomy Manager

SUNSCALD IN CORN AND SOYBEANS

KEY POINTS:

- **Extreme heat and moisture stress can lead to tissue damage on the leaf surface of corn and soybeans.**
- **Sunscald can occur in irrigated as well as non-irrigated fields.**
- **Sunscald causes tissue damage that generally is not yield limiting unless foliar diseases infect and spread from the damaged tissue.**

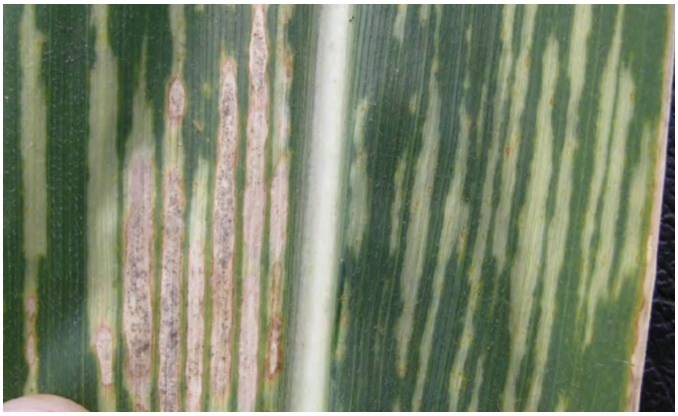
SUNSCALD IN CORN

- Sunscald occurs when the rate of water movement up to and through the leaf cells cannot keep up with the rate of evapotranspiration from these leaf cells.
- Younger leaves and leaves with direct orientation to the sun are most affected.
- Tissue can have a silver/gray cast initially and then turn brown and necrotic in a few days.
- If no additional disease is present, stalk tissue will look normal.
- Sunscald damage will not progress on the leaves.
- Injury can occur while leaves are still in the whorl.

Sunscald injury on a corn leaf.

Sunscald injury to a corn leaf tip.

- Water in the form of dew or from irrigation can injure tissue as high temperatures heat water on the leaf surface.
- Injury to the tassel can occur, but typically will not decrease pollination as damage is usually isolated within the field.
- Susceptibility to sunscald differs by hybrid genetics.



Closeup of sunscald injury on a corn leaf, showing injured tissue between the leaf veins.

Sunscald injury to a corn leaf tip.

SUNSCALD IN SOYBEANS

- Sunscald in soybeans occurs in the same manner as corn, with water heating on the leaf surface.
- Typical sunscald injury is usually found on the underside of the leaf, since soybean leaves flip upside down during the warmer part of the day.
- Sunscald in soybeans may be mistaken for herbicide injury, disease, or spider mite damage.
- If no additional disease is present, stem tissue will look normal.
- Spider mite damage may accompany sunscald. Be sure to check the underside of the leaf for insect feeding.

Comparison of sunscald injury and spider mite damage. Injury caused by spider mite feeding can be distinguished by the stippling pattern on the leaves.

Sunscald injury visible on the underside of a soybean leaf.

FIELD EDGE EFFECTS IN CORN

Mark Jeschke, Ph.D.,
Agronomy Manager

Photos courtesy of Alex Woodall, Pioneer Field Agronomist

KEY POINTS:

- Reduced corn yield along field edges can be associated with the effect of incoming winds on the microclimate within the field.
- Hot, dry air hitting the leading edge of a field increases evaporative demand and amplifies heat and drought stress along the field edge.
- The air picks up more moisture as it moves across the field, so plants in the interior experience less stress than those on the edge.

LOWER PERFORMANCE ALONG FIELD EDGES

- There are a number of factors that can cause corn yields to be lower along the edges of a field:
  - » Insect populations that move in from fence rows.
  - » Herbicide drift from neighboring fields.
  - » Soil compaction in the end rows, especially in areas that have heavy traffic during harvest.
- In some cases, poor performance is specifically associated with exposure of the field edge to wind.
  - » Edges adjacent to a road or a shorter crop, such as soybeans, that are directly exposed to wind fare worse than edges along another corn field that have a greater degree of protection.
  - » Poor performance is more frequently observed on the southern and western edges of fields (Figure 1).
- In cases where herbicide drift can be ruled out, the edge effect is likely associated with the effect of incoming winds on the microclimate within the field.
- Particularly in hot and dry summers, arid winds can amplify heat and drought stress along exposed edges of the field.

Figure 1. Corn field showing stress symptoms along the western edge of the field, with soybeans in the neighboring field (September 2021).

HEAT AND DROUGHT STRESS

- Vapor pressure deficit (VPD) is the difference between how much water the air can hold when it is saturated and how much water it currently holds.
- Higher temperatures increase crop water demand by creating a higher VPD between the saturated leaf interior and the ambient air.
- Air space in the interior of living plant tissue is essentially fully saturated with water.
- The greater the vapor pressure deficit between the leaf interior and the surrounding air, the faster the rate at which water will be pulled out of the plant and evaporated.
- Extreme heat dramatically increases water demand – raising temperatures from 80°F to 95°F (27°C to 35°C) causes water demand to double (Lobell et al., 2013).

Vapor Pressure Deficit and Temperature

- Extreme heat dramatically increases water demand because VPD increases exponentially with increasing temperatures, even as relative humidity (RH) stays constant.
- For example, if the RH of ambient air is 30%, the VPD will be much greater at 100°F (38°C) than at 77°F (25°C), creating a much higher evaporative demand at the higher temperature (Figure 2).

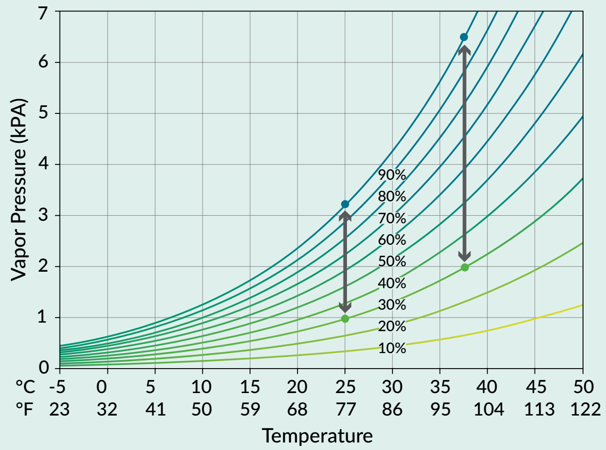


Figure 2. Vapor pressure for water by relative humidity and temperature.

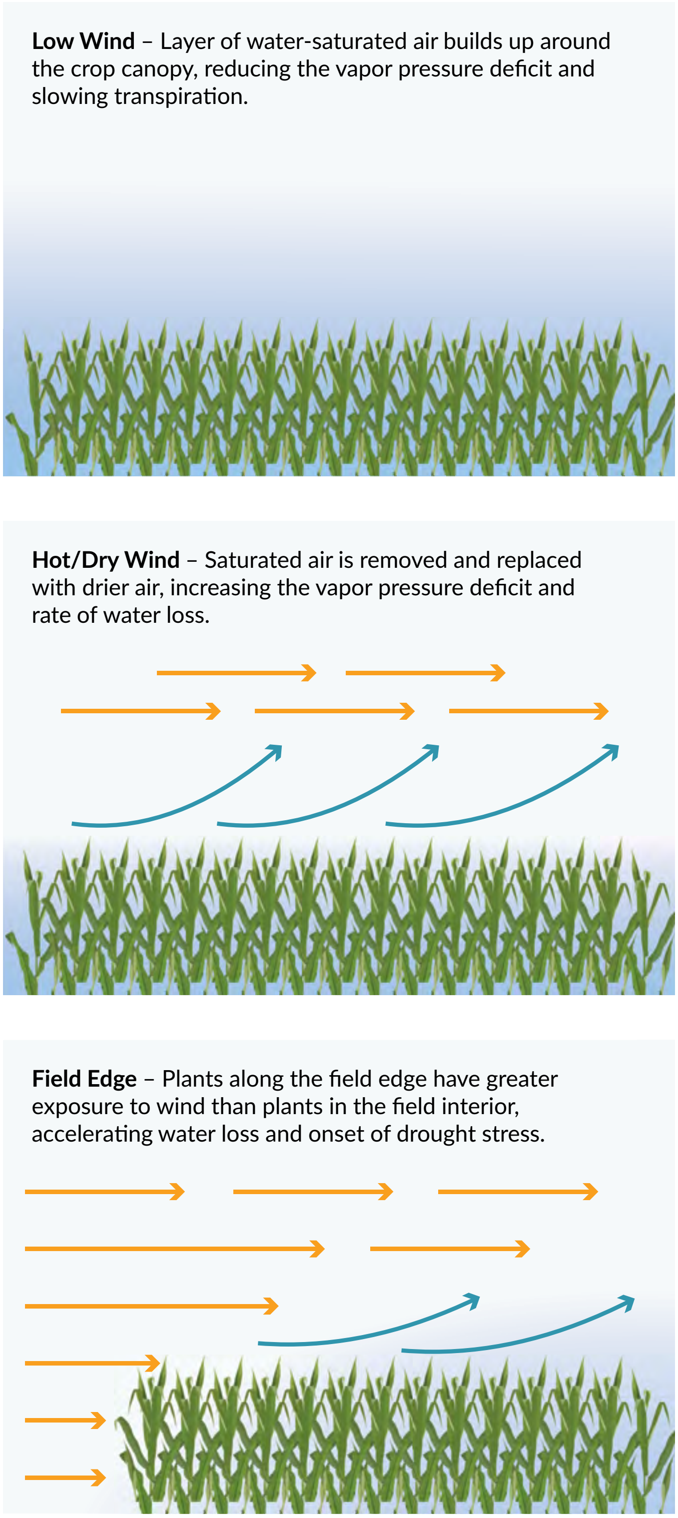


Figure 3. Illustration of the effect of arid wind on the microclimate of the crop canopy

WIND INCREASES STRESS

- Wind can exacerbate heat stress by increasing the vapor pressure deficit (VPD) between the leaves and the air immediately surrounding them.
- When water is evaporated from plant leaves, the air above the surface gradually becomes more saturated with water vapor.
  - If winds are low, this layer of saturated air stays in place around the crop canopy, causing the evapotranspiration rate to decrease (Figure 3).
  - When winds are high, this layer of saturated air is constantly being removed and replaced with drier air (Allen et al., 1998).
- At high relative humidity, wind speed will matter less, as the wind will only be able to replace the saturated air with slightly less saturated air.
- Under arid conditions though, small variations in wind speed may result in large variations in VPD and evapotranspiration.
- The more severe stress along the field edge is likely due to the fact that the air is driest when it encounters the leading edge of the field and picks up moisture as it moves across the crop canopy (White and Licht, 2020; Westgate and Vittetoe, 2017).
- Consequently, the effect of wind on VPD is greatest for plants near the field edge and lower for plants in the rest of the field (Figure 3).

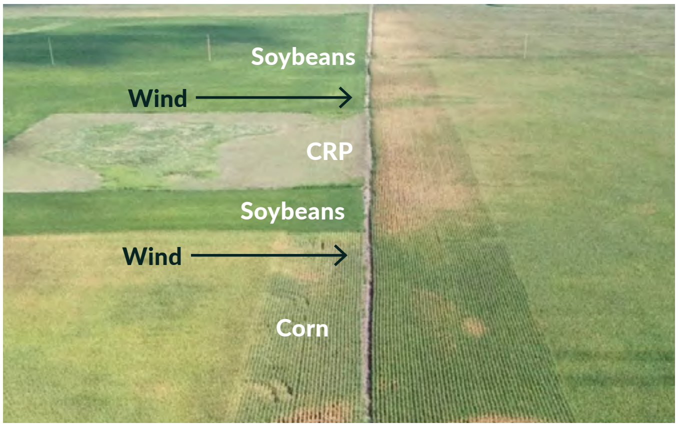


Figure 4. Corn field showing stress symptoms along the edge of the field where it is bordered by soybeans and conservation reserve program land (CRP), but no symptoms where it is bordered by corn (September 2021).

IMPACT ON CORN PLANTS

- Corn plants respond to higher VPD by closing their stomata, which helps preserve water, but also reduces the rate at which plants take in CO_2, which lowers the rate of photosynthesis and decreases yield.
- Greater evaporative demand also increases the rate at which the soil water supply is depleted, which can cause longer-term stress on the crop.
- Plants on field edges may be at greater risk for sunscald, which occurs when evaporative demand increases faster than the plant is able to respond, causing leaf tissue to die.

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Mark Jeschke, Ph.D.,
Agronomy Manager

EARLY SEASON DROUGHT EFFECTS ON CORN

- Corn is less susceptible to drought during vegetative growth than during pollination and grain fill, but severe early-season drought can significantly reduce yield.
- Drought stress during the vegetative stages can reduce corn plant size and leaf area and limit the number of kernels on the ear.
- Development of nodal roots and brace roots can be inhibited by dry soil.

EARLY-SEASON DROUGHT

- Water availability is the most common yield-limiting factor in corn production.
- In North America, drought stress most often occurs during the latter half of the growing season, during pollination and grain fill, when crop demand for water is greatest (Table 1).
- Drought stress early in the season is less common and generally less detrimental to corn yield, but can negatively impact the crop depending on the severity and duration of the stress.

CORN GERMINATION AND EMERGENCE

- Corn seeds need to imbibe 30-35% of their weight in water to initiate the germination process.
- If the soil surrounding the seed is too dry to supply the necessary moisture, germination will be delayed.
- Dry soils at planting often lead to uneven emergence, as some seeds germinate more quickly than others due to variations in the soil microenvironment.
- Shallow planting can exacerbate the problem, as soil near the surface dries more quickly.
- Poor seed to soil contact and residue in the seed furrow can also compound the effects of dry soil, by reducing the ability of water to move from the soil to the seed.
- Fertilizers placed in the seed furrow may also inhibit germination due to the salt effect being more pronounced in drier soil. Salts have an affinity to water and can draw moisture away from or out of the germinating seed or root tissues.

Table 1. Average daily corn water use, and water use per growth stage over the course of the growing season.

Growth Stage	Daily Water Use Rate (in)	Water Use Per Stage (in)
Emergence (VE)	0.08	0.8
4-leaf (V4)	0.10	1.8
8-leaf (V8)	0.18	2.9
12-leaf (V12)	0.26	1.8
Early tassel (R1)	0.32	3.8
Silking (R2)	0.35	4.1
Blister Kernel (R3)	0.32	1.9
Beginning Dent (R4.7)	0.24	3.8
Full Dent (R5.5)	0.20	3.8
Maturity (R6)	0.10	1.4

CORN DEVELOPMENT DURING VEGETATIVE STAGES

- **Emergence-V3** – Corn seedling depends on resources from the seed and the seminal root system, which ceases growth around V3.
- **V3-V6** – Nodal root system begins development, becoming the primary source of soil resources by V6.
- **V5-V7** – Number of kernel rows on the ear is established.
- **V7-V11** – Maximum number of potential kernels on the ear is established.

CORN RESPONSE TO DROUGHT STRESS

- Reduced water uptake under drought conditions can limit the rate of photosynthesis in the plant.
- Corn plants respond to drought stress by closing stomates and rolling leaves to reduce the volume of water transpired through the plant. This response benefits the plant by protecting it through short bouts of drought stress.
- However, closing the stomates also reduces the ability of the plant to take in carbon dioxide, which slows down photosynthesis and plant growth.
- The eventual impact on yield is determined by the severity and duration of stress. Drought stress lasting four or more days is likely to reduce yield (Table 2).

Table 2. Estimated corn yield loss when drought stress persists for four or more consecutive days. (Drought stress indicated when the uppermost, fully expanded leaf was visibly wilted.)

Corn Growth Stage	Estimated Yield Loss per Day of Stress (%)
Early vegetative (VE - V12)	1 – 3
Late vegetative (V12 to VT)	2 – 5
Pollination to Blister (R2)	3 – 9
Milk (R3)	3 – 6
Dough (R4)	3 – 5
Dent (R5)	2 – 4
Maturity (R6)	0

EFFECTS ON CORN GROWTH AND DEVELOPMENT

- Although not outwardly visible, there is a lot of physiological development happening inside corn plants during the early to mid-vegetative growth stages.
  - By V6, all aboveground plant parts have been initiated, including all leaves, ear shoots, and the tassel.
  - Development during this time establishes the size of the overall plant and the size of each leaf.
- Drought stress during this time can impact the eventual yield potential of the plant by reducing:
  - The number of kernel rows on the ear.
  - The number of kernels per row.
  - Total leaf area and photosynthetic capacity of the plant.

Figure 1. Corn plants at the V3-V4 stage showing severe stress during the drought of 2012. Drought symptoms at this stage may include leaf rolling, reduced growth, leaf death, and, in severe cases, plant death.

DROUGHT EFFECTS ON ROOT DEVELOPMENT

- Some degree of soil dryness early in the season can actually be beneficial, as it facilitates deeper initial rooting.
- However, excessive dryness can limit root growth and eventually lead to root desiccation and death.
- Extreme dryness and high soil surface temperatures can kill developing nodal roots, resulting in a condition known as "rootless" or "floppy" corn, where the plant is supported solely by the seminal root system and is prone to falling over (Figure 2).
  - Shallow planting can exacerbate the risk of rootless corn by placing developing nodal roots closer to the soil surface.
- Drought conditions can also inhibit brace root development, causing the roots to grow out horizontally over the surface of the hard, dry soil instead of penetrating the soil (Figure 2), making the plant more susceptible to lodging.

Figure 2. Rootless corn caused by shallow planting followed by dry soil conditions, which inhibited nodal root development (left). Underdeveloped and callused brace roots resulting from hot, dry conditions during brace root development (right).

DROUGHT EFFECTS ON NUTRIENT UPTAKE

- Reduction in water uptake by a corn plant can also mean a reduction in nutrient uptake.
- The nutrient most likely to become deficient under drought stress is potassium.
  - Potassium exists as a cation in the soil solution.
  - As soil water is depleted, potassium ions become more tightly bound to the negatively charged surfaces of soil colloids, making them less available for plant uptake.
- Potassium deficiency can exacerbate the effect of drought stress on the plant.
  - Potassium plays a key role in regulating the opening and closing of stomata.
  - Plants with insufficient potassium can be slower to close their stomates in response to the onset of drought stress.

HOW TO IMPROVE CORN RESILIENCE TO DROUGHT

- Five management practices can help make the crop more resilient to early-season drought stress when it occurs:
  1. Ensure adequate potassium fertility.
  2. Reduce or eliminate spring tillage, if possible, to help preserve soil moisture.
  3. Avoid planting too shallow – target a depth of around two inches in most situations.
  4. Ensure good seed to soil contact at planting.
  5. Manage soils to improve structure and water-holding capacity, and minimize compaction.

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CORN WATER USE

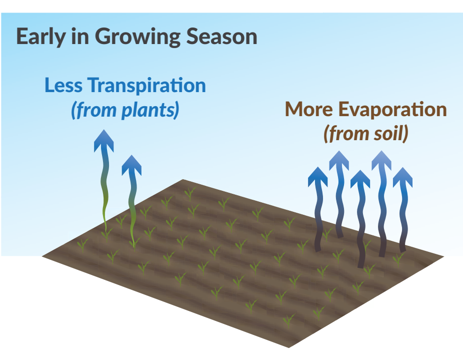
KEY POINTS:

- Crop water use, often referred to as evapotranspiration (ET) is composed of two components: 1) soil evaporation (E) and 2) crop transpiration (T).
- Daily ET increases through the vegetative growth stages, peaks around silking, and declines through grain fill.
- Corn is most sensitive to water deficits from flowering through grain fill.
- Seasonal corn water use can range from 21 to 28 inches during the growing season, depending on the local ET rates.

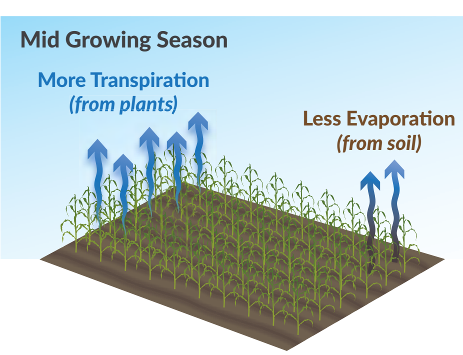
EVAPOTRANSPIRATION

Evaporation

- Early in the growing season, water loss from the soil occurs primarily through evaporation from the soil surface.
- As the crop grows and more leaf area shades the soil, evaporation will decline as transpiration increases.
- Crop residue on the soil surface can significantly reduce the amount of water lost through evaporation by reflecting solar radiation and protecting the soil from wind.



Early in the growing season, more water leaves the soil through evaporation compared to the small amount transpired by the small plants.



By mid-season, leaf area is much larger than the exposed soil surface and transpiration accounts for 90 to 98% of ET.

Transpiration

- In the process of transpiration, plants take up water from the soil and transport it to the leaves. Small openings in the leaves (stomata) allow water vapor to pass from the plant into the atmosphere, cooling the plant.
- The rate of transpiration depends on climatic conditions – primarily air temperature, wind, humidity, and solar radiation.
- The rate of transpiration increases with higher air temperature, solar radiation, and wind speed.
- High humidity levels reduce transpiration by decreasing the difference in water potential between the leaf airspace and the ambient air.

Table 1. Average daily corn water use, water use per growth stage, and cumulative water use over the course of the growth season.

Growth Stage	Daily Water Use Rate	Water Use Per Stage	Cumulative Water Use
	inches		
Emergence (VE)	0.08	0.8	0.8
4-leaf (V4)	0.10	1.8	2.6
8-leaf (V8)	0.18	2.9	5.5
12-leaf (V12)	0.26	1.8	7.3
Early tassel (R1)	0.32	3.8	11.1
Silking (R2)	0.35	4.1	15.2
Blister Kernel (R3)	0.32	1.9	17.1
Beginning Dent (R4.7)	0.24	3.8	20.9
Full Dent (R5.5)	0.20	3.8	24.7
Maturity (R6)	0.10	1.4	26.1

CORN ET DURING THE GROWING SEASON

- Evaporation often accounts for 20 to 30% and transpiration 70 to 80% of total ET over the course of a growing season (Kranz et al. 2008).
- Separately measuring evaporation and transpiration is difficult, so the processes are usually treated as a combined flux (ET).
- Daily ET varies greatly throughout the growing season due to day-to-day variability in weather conditions (Figure 1).
- On average, daily ET increases through the vegetative growth stages, peaks around silking, and declines through grain fill. (Table 1).
- Total ET over the course of the growing season depends on local climatic conditions and the relative maturity of the hybrid. Longer relative maturity hybrids will require more water over the course of the growing season (Figure 2).

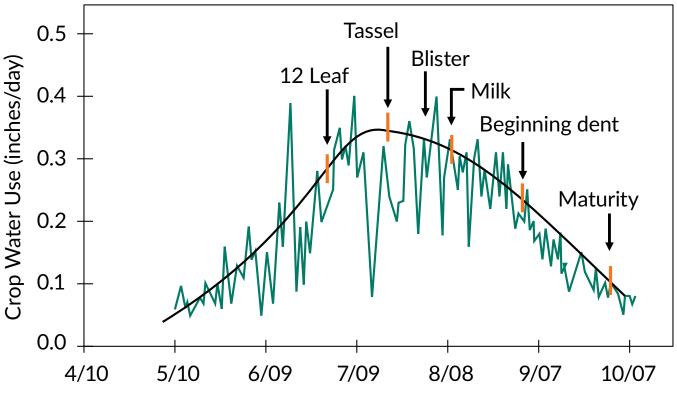


Figure 1. Long-term daily average (black line) and individual year (green line) corn water use by growth stage (Kranz et al., 2008).

- Peak water use, or ET, can often get as high as 0.35 inches per day during the early reproductive stages of growth and may even get as high as 0.50 inches per day on a hot, windy day on the southern High Plains.
- Seasonal corn water use can range from 21 to 28 inches during the growing season, depending on the local ET rates.
- Half of the total water use of a corn crop occurs during the reproductive stages of development.

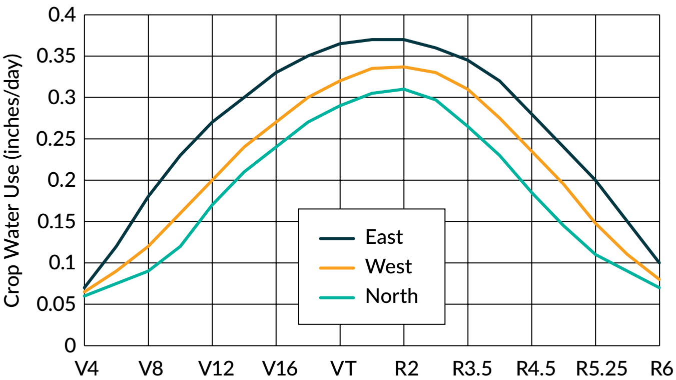


Figure 2. Average corn ET by growth stage in different regions of the Corn Belt.

CORN ROOTING DEPTH AND WATER UPTAKE

- Well-developed root systems are essential for corn water uptake and growth.
- Root systems that are unimpeded by soil factors will generally grow down through the soil profile at a rate of 2.75 inches per leaf stage to a maximum depth of around 60 inches.
- The effective rooting depth – the depth from which the majority of water uptake occurs – is less than the total rooting depth.
  - » Early in the growing season, the majority of water extraction occurs in the first foot of the soil profile.
  - » Water extraction from the second and third foot of the profile increases substantially around the R1 stage.
- Under drought stress conditions, water extraction can increase at deeper layers as water near the top of the profile is depleted (Irmak and Rudnick, 2014).

ROOT DEPTH DURING VEGETATIVE GROWTH

- Root development accelerates as the plant enters rapid growth, beginning around V5.
- Rooting depth increases by around 2.75 inches per leaf stage during vegetative growth.
- Maximum root depth is determined by the depth of the water table.

Growth Stage	Rooting Depth (in)
V4	14
V6	20
V8	25
V10	31
V12	36
V14	42
V16	47
V18	53
V20	58

IMPACT OF WATER STRESS

- The impact of water stress on corn grain yields varies with crop growth stage (Figure 3).
- Corn is relativity insensitive to water deficits during early vegetative growth because water demand is relatively low.
- Plants can adapt to water stress throughout most of the vegetative period to reduce its impact on grain yield; however, corn is much more sensitive to water stress from flowering through grain fill.
- Corn hybrids vary in their ability to withstand water stress. Pioneer® brand Optimum® AQUAmax® hybrids include key native traits designed to help withstand drought conditions and protect against yield loss.

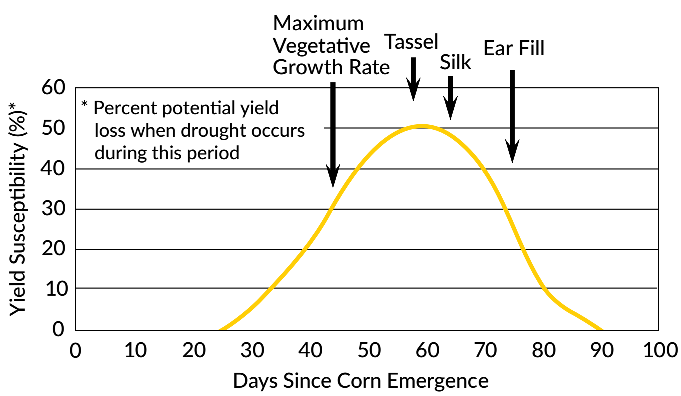


Figure 3. Yield susceptibility to water stress for corn (Sudar et al., 1981).

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GREEN CRIMP IN CORN

SUMMARY

- Green crimp is the bending or crimping of the corn stalk under high winds while the plant is still green and actively growing. This phenomenon is less commonly observed than other forms of wind damage, such as brittle snap and stalk lodging, following physiological maturity.
- Green crimp can be distinguished from brittle snap by the fact that stalk bending occurs at the internode and does not sever the vascular tissue, which allows the portion of the plant above the bend to continue some degree of growth.
- Effects on corn yield and harvestability depend on the severity and timing of wind damage to the plants.
- Green crimp during vegetative stages (V12 to VT) most commonly occurs immediately below, at, or above the primary ear node and is likely associated with weakness of the stalk during rapid growth.
- Green crimp during mid- to late-reproductive growth often occurs lower on the stalk and may be associated with weakening of the stalk due to remobilization of carbohydrates from the stalk to the developing ear.
- Fields that have experienced green crimp should be harvested as early as possible to maximize the harvestable yield.
- Management practices, such as timely planting, avoiding excessive planting densities, and selecting a diverse package of hybrids, can help reduce the risk of green crimp occurring.

INTRODUCTION

High winds can damage growing corn in a number of ways. One such way is the bending or crimping of the stalk, a phenomenon often referred to as green crimp. Green crimp can resemble stalk lodging but occurs while the plant is still green and actively growing, whereas stalk lodging typically refers to crimping or breaking of the stalk after physiological maturity and is often associated with stalk rots. Green crimp can be distinguished from brittle snap (also referred to as green snap) by the fact that stalk bending occurs at the internode and does not sever the vascular tissue, which allows the portion of the plant above the bend to continue some degree of growth. Brittle snap typically occurs at a node and involves the complete breakage of the stalk.

Figure 1. Plant at the R1 growth stage (silking) showing varying degrees of bending and recovery following a severe wind event in Illinois (July 14, 2016).

Green Crimp

- Bending/crimping of the stalk internode.
- Does not sever vascular tissue.
- Can occur from around V12 through physiological maturity.
- If green crimp occurs during vegetative growth, the plant can recover to some extent.
- Can negatively affect both yield and harvestability, depending on timing and severity of damage.

Brittle/Green Snap

- Breakage of the stalk, severing vascular tissue.
- Occurs immediately below, at, or above the primary ear node.
- Occurs most often during rapid vegetative growth (V5-V8 and V12-R1).
- Most productive fields are commonly the most susceptible due to rapid growth rate.
- Can result in complete loss of harvestable yield.

Stalk Lodging

- Crimping or breakage of the stalk following physiological maturity after grain fill is complete.
- Often associated with stalk rots.
- Reduces harvestability.

Figure 2. Plant at the R1 growth stage (silking) showing varying degrees of bending and recovery following a severe wind event in Illinois (July 14, 2016).

DAMAGE TO PLANTS

Green crimp effects on corn yield and harvestability depend on the severity and timing of damage to the plants. Occurrence of green crimp has been observed from late vegetative growth stages through mid-reproductive growth, approximately V12 to R4. Plants that are still undergoing vegetative growth at the time of green crimp are capable of some degree of recovery. As with root lodging during vegetative growth, affected plants will bend back toward vertical, which can result in crooked and odd-looking stalks (Figures 1 and 2). Damage at this stage can range from slight bending or leaning to a complete folding over of the stalk. Yield effects tend to correlate to the severity of the damage – a slight bending of the stalk may have little or no effect, whereas a complete folding over of the stalk is likely to be more detrimental.

Green crimp has the greatest potential to affect yield when it occurs around tasseling and silking. At this point, the plant has completed vegetative growth, is no longer capable of righting itself following a wind event, and is just beginning reproductive growth, so effects on kernel set and grain fill will be maximized.

Injury to the plant at this time can also potentially disrupt ear development, making it particularly detrimental to yield. In 2016, instances of abnormal ear development were observed at multiple locations across the Corn Belt following high winds and severe storms. High winds caused some fields to lodge or lean over. In many fields, these storms occurred close to tassel and pollination stages. In some cases, wind damage to plants resulted in abortion of the primary ear, which triggered development of an ear at the secondary node, a phenomenon likely due to hormonal disruption in plants following injury (Elmore et al., 2016). Ears growing at the secondary node often exhibited some degree of abnormality and the delay in silking resulted in poor pollination. Yield losses associated with green crimp occurrence around tasseling and silking can vary widely based on severity of damage and other environmental stresses that may be affecting the plants.

Green crimp during grain fill is much more analogous to stalk lodging – it often occurs lower on the stalk and is likely associated with weakening of the stalk due to remobilization of carbohydrates from the stalk to the developing ear. While the term stalk lodging typically refers to crimping of the stalk below the ear after physiological maturity, green crimp during grain fill manifests in much the same way. A key distinction is that stalk lodging affects only the harvestability of the ear, not its actual yield since grain fill is already complete at this point. Green crimp affects harvestability and yield since the damage takes place prior to physiological maturity and before grain fill is complete.

The later that green crimp occurs during grain fill, the less potential there is for yield to be affected. Yield losses of 5-15% have been observed with green crimp that occurred when corn was past ½ milk line. Yield losses due to green crimp that occurs later during reproductive growth are often less than expected relative to the appearance of the crop.

HYBRID DIFFERENCES

As with most adverse weather effects on corn, the nature and severity of green crimp symptoms will often differ among hybrids. These differences may be attributable to specific genetic characteristics of a hybrid or may be due to the growth stage and plant stature of a given hybrid at the time of a severe weather event. Plants that are taller and have larger leaves are generally more susceptible to all types of wind damage. Similar to brittle snap, green crimp is most commonly observed in fields with high yield potential where the plants are undergoing rapid growth.

CONTRIBUTING ENVIRONMENTAL FACTORS

Late Vegetative Through Early Reproductive Stages

Green crimp occurring between the V12 and VT growth stages appears to be influenced by many of same factors related to brittle snap. From V12 through tasseling, the corn plant is undergoing its most rapid stage of growth. It will increase in size to its mature height of 7 to 10 feet in approximately 21 to 28 days, or about 2 to 4 inches of growth per day. A key factor increasing susceptibility to wind damage at this stage is in leaf surface area enlargement and plant height, which increases wind resistance during potentially severe thunderstorms and wind events (late June, July, or early August depending on the planting date and growing season.) The most common sites for both green crimp and brittle snap at this stage are immediately below, at, or above the primary ear node. Upon reaching mature height, the plant becomes more resistant to wind damage as cell walls are strengthened by the deposition of lignin and other structural materials.

Field observations in 2016 and 2017 suggest some degree of correlation between hybrid susceptibility to green crimp and brittle snap. Pioneer® brand corn products are rated for genetic resistance to brittle snap. Hybrids in which green crimp was observed often had relatively low ratings for resistance to brittle snap. Whether damage from severe wind manifests as green crimp or as brittle snap may be related to moisture conditions at the time of the wind event. Cells of plants with ample moisture are more turgid and less able to bend without breaking, which can lead to brittle snap under high winds. Conversely, moisture deficit conditions resulting in less turgidity may favor bending of the stalk under high winds rather than breakage. Cell turgidity can be influenced by soil moisture conditions ahead of the wind event, as well as the time of day when the wind occurs. Brittle snap is often associated with thunderstorms that occur in the early morning hours, when temperatures are cooler and plant cells are more turgid.

Figure 3. Green crimp and brittle snap resulting from high winds between the V12 and VT growth stages commonly occur on the stalk near the primary ear node. **Top:** Green crimp following a wind storm in Illinois in 2016. **Bottom:** Brittle snap following storms in Texas in 2011.

Mid- to Late-Reproductive Growth Stages

Green crimp during mid- to late-reproductive growth may be associated with weakening of the stalk due to remobilization of carbohydrates from the stalk to the developing ear. As the plant goes through vegetative growth, photosynthate is directed to the stalk for temporary storage. Upon successful pollination, ear development places a great demand on the plant for carbohydrates. When the carbohydrate demands of the developing kernels exceed the supply produced by the leaves, stalk and root storage reserves are tapped. University studies indicate that during grain fill, about 60 to 70% of the non-fiber carbohydrates in the stalk are moved to other parts of the plant, but primarily the ear (Daynard et al., 1969; Jones and Simmons, 1983). This stalk depletion begins approximately two to three weeks following silking. Environmental stresses that decrease the amount of photosynthate produced by the plant can force plants to extract even greater percentages of stalk carbohydrates, which preserves grain fill rates at the expense of the stalk.

Figure 3. Green crimp in corn in Hall County, Nebraska (August 27, 2017).

Stress factors that reduce photosynthesis during grain fill will lead to greater remobilization of carbohydrates, which may increase the risk of green crimp. Foliar diseases are one such factor that can reduce plant photosynthesis by reducing effective leaf area. Low solar radiation during grain fill has also been associated with incidence of green crimp. Photosynthesis is most efficient in full sunlight. Studies show that the rate of photosynthesis increases directly with intensity of sunlight. One experiment indicated that photosynthesis rates are reduced by more than 50% on an overcast day compared to a day with bright sunshine (Moss et. al., 1960). Prolonged cloudy conditions during ear fill often result in severely depleted stalk reserves. In 2017, corn growers in the California Central Valley experienced the effects of prolonged heat and lower than normal solar radiation creating the perfect conditions for weakened stalks (Figure 4).

Figure 4. Green crimp in corn in the California Central Valley in 2017.

MANAGEMENT CONSIDERATIONS

For a field that has experienced green crimp, the best management option available is to harvest it as early as possible to maximize the harvestable yield. The longer the crop stays in the field the more stalk quality will degrade, which can result in greater harvest losses.

A number of management practices can help reduce the risk of green crimp occurring. Planting a package of hybrids with a range of maturities is always advisable to spread risk associated with stress events during the growing season. Hybrids that differ in maturity go through their windows of susceptibility to stress factors at different times. Planting a package of diverse hybrids spreads the risk of injury, as it is unlikely that all hybrids will be at the same stage of development at the time of any one storm.

Timely planting may also help reduce risk of green crimp. Occurrence of green crimp in Illinois in 2016 and California in 2017 tended to be associated with later-planted corn. Later planting tends to result in taller plants, which will be more susceptible to wind damage. Early planting may also help plants advance through the rapid growth phase during vegetative growth—when they are more susceptible to green crimp and brittle snap—before the latter part of the summer when stress conditions and severe weather are more likely.

Carefully managing seeding rate for hybrids in which green crimp has previously been observed can reduce the risk of it occurring again. Avoiding higher than optimum seeding rates can reduce the stress load on plants from intraspecific competition, allowing them to be more resilient against stressful weather events.

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HAS CORN RESPONSE TO ROOT LODGING CHANGED OVER TIME?

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KEY FINDINGS:

- The earlier that root lodging occurs, the greater the ability of corn plants to recover from it.
- Root lodging has the most impact on yield when it occurs right at flowering.
- Corn yield losses due to root lodging were greater in this study than in a similar study in the 1980s, which may be due to higher seeding rates with modern hybrids.

BACKGROUND AND OBJECTIVES

- When assessing the effects of root lodging in corn following severe wind and rain events, the results from a research study conducted in the 1980s have long served as the main reference for estimating impact on yield (Carter and Hudelson, 1988).
- A new, three-year field study was conducted to evaluate effects of root lodging on corn development and grain yield using contemporary hybrids and seeding rates.
- This study also explored underlying physiological factors causing yield decreases due to root lodging.

STUDY DESCRIPTION

- Simulated wind lodging experiments were conducted from 2018-2020 at the Western Agricultural Research Station in South Charleston, Ohio.
- A split plot randomized complete block design with three replications was utilized each year. Corn hybrids were the whole plot factor and lodging treatment was the subplot factor.
- **Hybrid/Brand[1]:**
  - P1283AM™ (AM, LL, RR2), 112 CRM, root strength* = 4
  - P1298AM™ (AM, LL, RR2), 112 CRM, root strength = 8
  - P1311AM™ (AM, LL, RR2), 112 CRM, root strength = 6
- **Root Lodging Timings (corn growth stage):**
  - Control (no lodging)
  - V10
  - V13-V14
  - VT-R1
  - R3
- Each plot was 25 ft long x 8 rows wide with a 30-inch row spacing and planted at 36,000 seeds/acre.
- All plants in the simulated wind lodging treatments were pushed over by hand perpendicular to row direction immediately after irrigation or heavy precipitation events.

** Root strength ratings on a 1-9 scale: 9 = Outstanding; 1 = Poor*

The ability of corn plants to recover from root lodging caused by severe wind depends on the growth stage of the corn when the lodging occurred.

Table 1. Planting, lodging, and harvest dates for each year of the study.

Field Activity	2018	2019	2020
Planting	May 9	June 4	May 14
V10 lodging	June 20	July 16	July 2
V13-14 lodging	June 28	July 23	July 15
VT-R1 lodging	July 10	Aug 6	July 21
R3 lodging	Aug 1	Aug 28	Aug 5
Harvest	Oct 4	Oct 29	Oct 15, 22**

**Two replications harvested first date; third replication harvested second date.

Table 2. Growth stage and canopy height and stage at the time of lodging treatments.

Treatment	Actual Stage at Lodging	Canopy Height at Lodging (in)
Untreated	---	---
V10	V10.0	58.8
V13	V13.3	84.6
VT-R1	R0.7	99.5
R3	R3.0	104.4

Table 3. Silk date, percent recovery, and plant characteristics rated at R4 for each hybrid and lodging treatment.

	Silk Date	Visual Recovery	Total Leaf Number	Ear Leaf Number	Final Stalk Length	Final Plant Height
Hybrid/Brand[1]	*day*	*% upright*			*in*	*in*
P1283AM™	201.9 b	69.5 b	19.4	12.9 b	104.9 a	71.1 b
P1298AM™	204.2 a	71.7 b	19.4	13.2 a	96.8 b	68.2 b
P1311AM™	204.5 a	75.3 a	19.4	13.4 a	101.7 a	77.2 a
P Value	<0.001	0.001	0.884	<0.001	<0.001	<0.001
Lodging						
Untreated	203.2 b	99.3 a	19.4 ab	13.2	104.0 a	103.9 a
V10	203.7 b	98.8 a	19.5 a	13.2	97.3 b	94.0 b
V13	204.6 a	94.1 a	19.4 ab	13.2	93.6 b	77.8 c
VT-R1	203.6 b	42.7 b	19.2 b	13.1	103.6 a	45.0 d
R3	203.2 b	25.9 c	19.5 a	13.2	107.2 a	40.2 d
P Value	<0.001	<0.001	0.042	0.785	<0.001	<0.001

RESULTS

Growth and Development

- Recovery from lodging, expressed as the percentage of stalks in the upper third of the crop canopy exhibiting upright growth, was highly dependent on crop growth stage (Table 3).
- Plants that lodged during vegetative growth (V10 and V13) recovered much more than plants that lodged after tasseling (VT-R1 and R3).
- Although both the V10- and V13-lodged plants had a high rate of recovery to vertical in the upper canopy, they differed greatly in the degree of displacement resulting from lodging.
  - » Plants lodged at V10 were displaced an average of 6 inches off the row, while plants lodged a V13 were displaced an average of 24 inches (data not shown), which could have a large effect on harvestability.
- Pioneer® P1311AM™ brand corn exhibited a greater rate of recovery than the other two hybrids (Table 3).
- Silk date was largely unaffected by lodging except for the V13 lodging treatment, which had slightly delayed silking.

Table 4. Grain yield, moisture, and percent vivipary.

	Yield	Moisture	Vivipary
Hybrid/Brand[1]	*bu/acre*	——— % ———	
P1283AM™	189	20.9	5.9
P1298AM™	191	21.7	4.8
P1311AM™	189	21.3	5.2
P Value	0.915	0.059	0.819
Lodging			
Untreated	239 a	20.3 cd	0.1 c
V10	227 a (-5%)	20.2 d	1.0 c
V13	186 b (-22%)	21.0 c	3.4 bc
VT-R1	135 d (-43%)	23.2 a	6.9 b
R3	159 c (-33%)	21.8 b	15.0 a
P Value	<0.001	<0.001	<0.001

- Lodging had little to no effect on total leaf number and ear position.
- Final stalk length was shorter for V10- and V13-lodged plants, suggesting internode elongation was reduced in response to the lodging treatments during vegetative growth.
- Final plant height from the soil surface to the uppermost leaf collar decreased with each successive lodging timing, with the VT-R1 and R3 timings reduced by more than half.

Applying simulated wind lodging treatment at the V10 growth stage.

Corn Yield

- Yield losses were similar for each lodging treatment regardless of hybrid (Table 4) and were greatest with lodging at VT-R1 (43% reduction) and R3 (33% loss). A 22% reduction in yield was seen with lodging at V13 and only 5% at V10.
- Yield did not significantly differ among hybrids.
- Grain moisture at harvest in the VT-R1 and R3 treatments (23.2% and 21.8%, respectively) was greater than the other treatments (Table 5).
- The percentage of ears exhibiting vivipary (sprouting of kernels on the ear) was greatest in the R3 and VT-R1 treatments (Table 4). Ears in these treatments were often in close proximity to the ground, which could have contributed to the elevated moisture levels.

Table 5. Ear yield components for hybrids and lodging treatments.

	Barrenness	Kernels/plant	Zippering	Jumbling	Basal Emptiness	100 Kernel Wt
Hybrid/Brand[1]	*%*	*count*	*1 to 5 rating*			*g*
P1283AM™	4.6 a	546	1.3 a	1.5 a	1.3 b	32.1
P1298AM™	1.5 b	530	1.1 b	1.1 b	1.2 b	27.0
P1311AM™	4.8 a	557	1.2 ab	1.3 ab	1.6 a	29.8
P Value	0.025	0.090	0.042	0.021	0.005	0.064
Lodging						
Untreated	1.1 b	595 a	1.0 b	1.2 a	1.3	33.1 a
V10	2.1 b	582 a	1.1 b	1.3 ab	1.2	32.6 a
V13	5.5 a	550 ab	1.1 b	1.2 b	1.3	31.1 a
VT-R1	8.5 a	463 c	1.9 a	1.5 a	1.4	30.5 a
R3	0.9 b	533 b	1.2 b	1.3 b	1.5	20.9 b
P Value	<0.001	<0.001	<0.001	0.033	0.203	<0.001

Contributors to Yield Loss

- Yield losses at each lodging timing likely stem from multiple factors.
- The percentage of barren plants increased with lodging at V13 and VT-R1, but barren plants were few when lodged at R3 due to the plants being at the milk stage at lodging (Table 5).
- The total number of kernels produced per plant decreased with later-stage lodging, although the magnitude of change from the untreated was two- to three-fold less than for total yield.
- Ear abnormalities of zippering and jumbled kernels were greatest with VT-R1 lodging, suggesting issues with pollination and kernel set contributed to the yield reduction.
- Substantial reductions in kernel weight were observed in the R3 lodged plants, suggesting this was a major contributor to reduced yield.

Comparisons to Previous Research

- Compared to the results from the Carter and Hudelson (1988) study, yield loss at V10 was similar in this study (5%) compared to the past work (3-4% loss) (Figure 1).
- Losses at V13-14 were greater in this study (22%) compared to the past study (10%), and losses at VT-R1 were much greater in the current study (43%) compared to the past work (14-24%).
- Some of these differences may be due to different hybrids and higher seeding rates used in the current study.

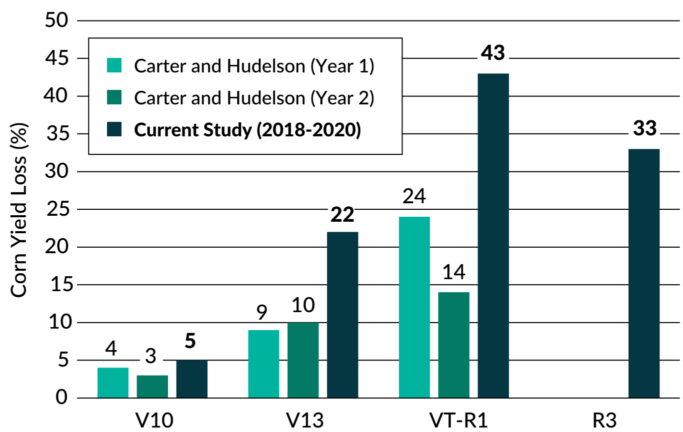

Figure 1. Yield loss associated with different lodging timings in the current study and as reported by Carter and Hudelson (1988).

CONCLUSIONS

- Yield loss resulting from lodging was greatest at VT-R1, stemming from reduced kernel number, poor pollination, and increased barren plants.
- High yield loss at R3 was mostly attributed to reduced kernel weight, and partially to reduced kernel number.
- Ears close to the ground at VT-R1 and R3 increased incidence of vivipary, which could also impact grain marketability.
- Potential yield losses during machine harvest of the plants with limited recovery after root lodging at VT-R1 and R3 could also be greater than the hand-harvested yields in this experiment.

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CORN VIGOR AND SEED QUALITY TESTING

KEY POINTS

- The Pioneer Stress Test (PST) is a proprietary vigor test used on all Pioneer® brand corn products.
- Pioneer Stress Test and field trial results are used to assign stress emergence ratings that characterize a hybrid's genetic potential to tolerate cold, wet conditions and germinate normally.
- The Pioneer Stress Test allows for optimal characterization of seed quality, which helps to ensure growers get the highest quality seed for planting.

COLD STRESS IS COMMON DURING GERMINATION

- Successful germination and emergence of corn is determined by three primary factors: environmental conditions, hybrid genetics, and seed quality (Figure 1).
- In North America, corn is nearly always subjected to some degree of environmental stress during germination and emergence.
  - » Corn is a warm season crop, with an optimal soil temperature range for germination and emergence of 85-90°F (29-32°C).
  - » Soil temperatures at planting are usually below, and often well-below, this range.
- The need for corn to tolerate stressful environments during germination and emergence means genetic vigor and seed quality are both critical for the establishment of a successful crop.
- Corn vigor tests have been used for decades to simulate stressful soil environments and assess the ability of hybrids and specific seed batches to germinate under those conditions.

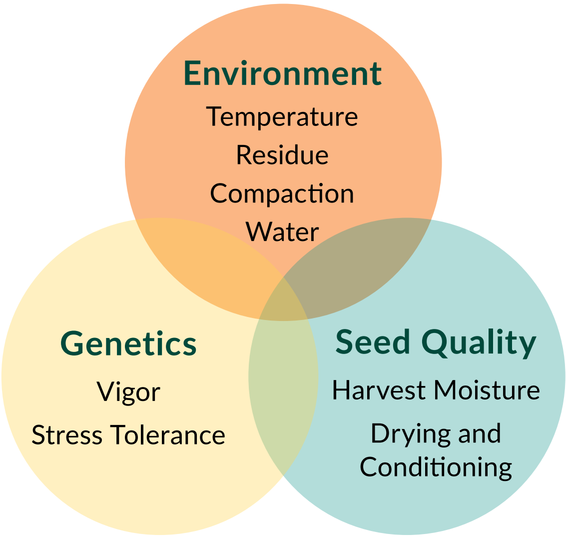
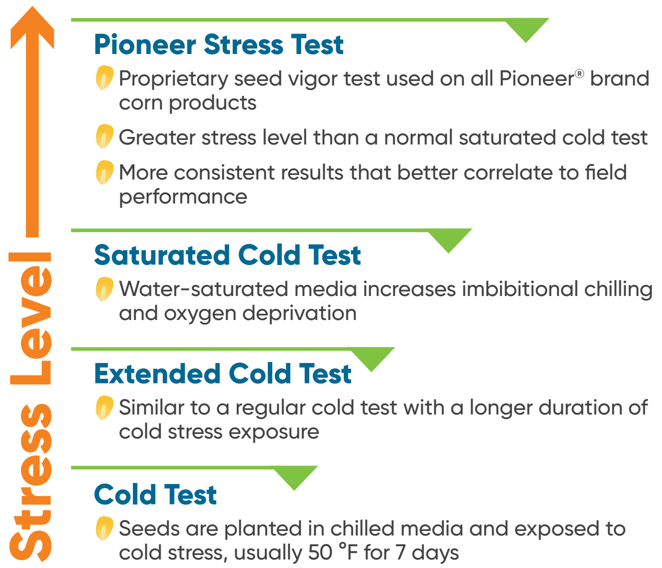


Figure 1. Critical environmental, genetic, and seed quality factors that affect corn stand establishment.

COLD GERMINATION TESTS

- The Association of Official Seed Analysts (AOSA) defines vigor as those seed properties that determine the potential for rapid, uniform emergence, and development of normal seedlings under a wide range of field conditions.
- Lab assays to test vigor are commonly referred to as cold tests. Different variations of cold tests have been in use in the seed corn industry since the 1950s.
- In North America, the most commonly used vigor tests are the cold test and saturated cold test.
  - A **cold test** typically consists of planting seeds in chilled media and maintaining them at a low temperature, usually 50°F for 7 days, followed by a grow out period at a higher temperature to assess germination.
  - An **extended cold test** is a variation offered by some labs with a longer duration of cold stress.
  - A **saturated cold test** increases the stress level by using water-saturated media, which increases imbibitional chilling and oxygen deprivation. Seeds are often placed embryo side down in order to increase overall stress levels.



- Unlike warm germination scores, which are derived using an industry-wide standard protocol and required by law to be reported on bag labels, cold test methodologies are not standardized and may vary among labs.
- Consequently, a cold test or saturated cold test score does not constitute an objective performance rating that is comparable across labs, but rather must be interpreted relative to the specific protocol that was used.

PIONEER STRESS TEST

- The Pioneer Stress Test (PST) is a proprietary vigor test used on all Pioneer® brand corn products.
- It was developed in the early 2000s as an improvement on the saturated cold test.
- The Pioneer Stress Test imposes extreme imbibitional chilling and anaerobic stresses, beyond that of the saturated cold test.
- The Pioneer Stress Test has proven to be more predictive of hybrid performance under extreme cold stress and to provide better differentiation among genetics and seed lots (Figure 2).

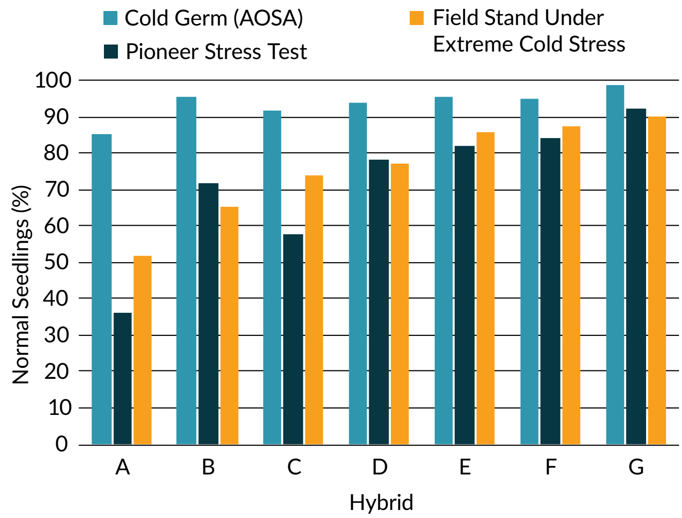
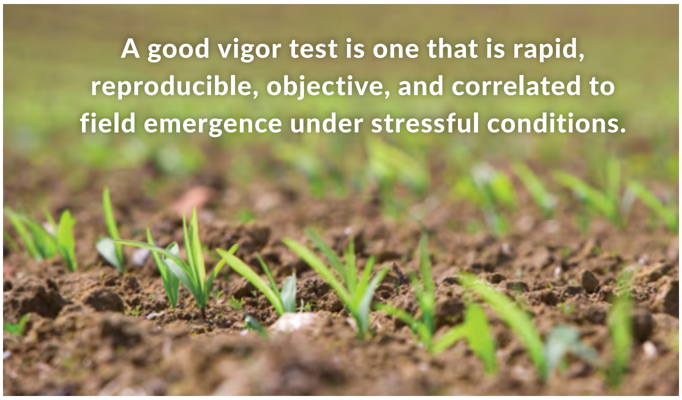


Figure 2. Cold germination test (AOSA protocol) and Pioneer Stress Test results of several hybrids compared to actual field stand establishment under extreme cold stress conditions.



FIELD VALIDATION

- The Pioneer Stress Test is continually validated in field research trials.
- Early planted stress emergence trials are conducted every year across multiple locations.
- Research sites are chosen to reflect the various seedbed and environmental conditions likely to be experienced by farmers.
  - Some eastern locations often have extended cold and wet conditions that persist into late spring and early summer.
  - Northern and Midwestern sites are more likely to provide extreme day/night temperature fluctuations.
- Field validation has shown that the PST produces consistent, reproducible results that strongly correlate to field emergence under stress (Figure 2).

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STRESS EMERGENCE SCORES

- The Pioneer Stress Test (PST) is used to support hybrid advancement decisions and support breeding efforts to improve early season stress tolerance through marker-assisted selection.
- For hybrids that are advanced to commercial status, PST and field trial results are used to assign stress emergence ratings that characterize a hybrid's genetic potential to tolerate cold, wet conditions and germinate normally.
- Figure 3 shows differences in emergence between two hybrids with differing stress emergence ratings in several field trials that experienced cold stress after planting.

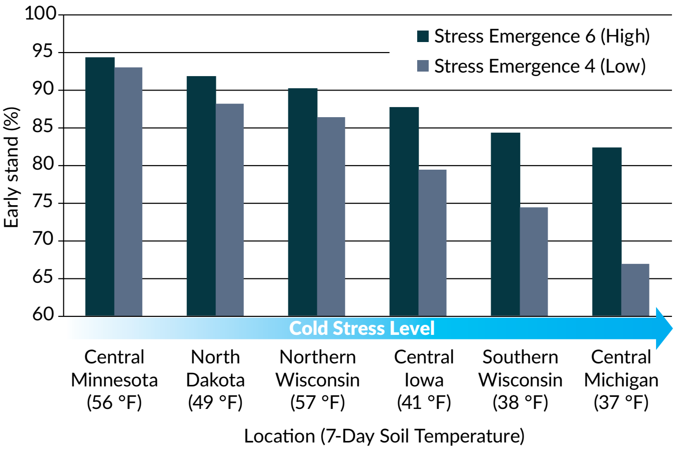

Figure 3. Average stand establishment for high and low stress emergence score hybrids in six stress emergence locations in 2018. Locations are sorted from least stressful (left) to most stressful (right) based on average early stand.

ENSURING SEED QUALITY

- Pioneer has the seed industry's highest production and quality control standards, assuring growers they get the highest quality seed for planting.
- The PST allows for optimal separation between high and low quality. It can detect small differences in vigor that may indicate a seed lot needs to be discarded.
- The PST has the ability to detect imminent standard (warm) germination failures in seed lots.

Testing Points

- New crop seed is tested in the fall at harvest to determine the initial quality.
- After conditioning, all seed sizes of each sizing run are tested again. All seed sizes must meet the same high-quality criteria.
- Carryover seed must meet the same quality criteria as new crop seed. Pioneer does not differentiate between new crop and carryover when evaluating test results.
- Pioneer customers can be confident that every batch they plant has been thoroughly tested in this extensive screening program and meets Pioneer's industry-leading standards.

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PLANTING ACCURACY GUIDELINES FOR CORN

Ron Sabatka,
Seed Applied Technologies Marketing Manager

PREPARING FOR A SUCCESSFUL CORN PLANTING SEASON

Best practices to improve seed flow and singulation

Several factors, such as air and seed temperature, relative humidity, seed treatment recipe, as well as seed size and shape, affect seed flow and plantability.

Excellent planting accuracy and plant stand establishment can be achieved with all seed sizes and shapes, regardless of seed treatment recipe and environmental conditions, through careful planter aid usage and planter adjustments.

This guide highlights environmental conditions that result in challenging planting conditions, as well as best practices to optimize planting accuracy.

The challenge: Spring weather is unpredictable

Warming spring temperatures signal the beginning of the crop planting season. However, spring weather is unpredictable with cold, dry conditions often followed closely by warm, humid conditions. Rapid fluctuations in weather can create condensation on the seed, causing poor seed flow, increased seed bridging and reduced planter accuracy.

While all LumiGEN® treated seeds leave the production plant dry, when the dew point outside is above the temperature of the seed (i.e., when it is removed from cold storage into warmer, humid conditions), condensation will start to occur.

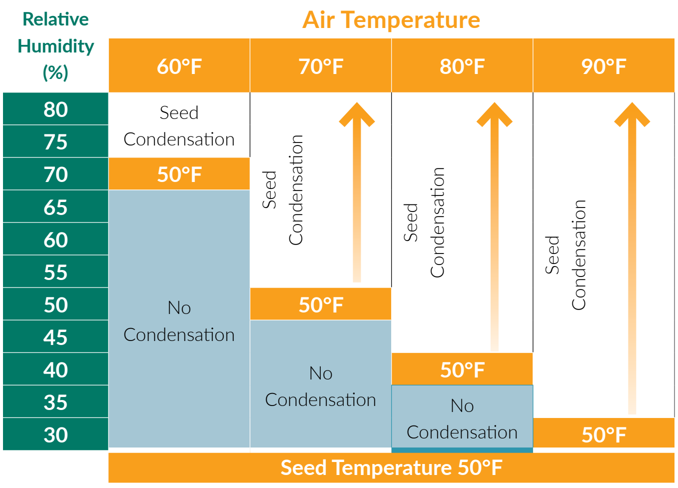

Figure 1. Relative humidity, along with seed and air temperature, determine the level of condensation present on the seed.

An example from Figure 1, when seed is stored at 50°F, condensation can start to occur as soon as the seed is moved into warmer, more humid conditions common during the spring planting season. When condensation accumulates on seed flow, planting accuracy can be impacted unless managed properly.

The opportunity: Be prepared for spring weather

1. **Planter aids:** Diligently and thoroughly apply planter aids as recommended by your planter manufacturer. Data has shown that priming the planter unit with graphite or a talc/graphite blend, as well as mixing the planter aid properly with the seed, can greatly improve seed flow and singulation (see details below).
   - Talc: A naturally occurring mineral that ***acts as a drying agent,*** while reducing static electricity.
   - Graphite: A crystalline carbon lubricant that helps reduce equipment wear, improves seed flow and reduces static electricity. ***Not a drying agent.***
   - Fluency Agent: A polyethylene wax-based lubricant used to aid seed flow. ***Not a drying agent.***
2. **Planter settings:** For precise recommendations on planter settings, access batch-specific information for individual planters on Pioneer.com or in the Granular Insights app. Adjust settings to planting conditions following manufacturer instructions.
3. **Environment:** Slowly increase seed storage temperature and provide increased air flow to minimize seed condensation. When using ProBoxes or large pallets of seed bags, warming the seed should be done over numerous days (ideally, 1-2 weeks) if feasible.

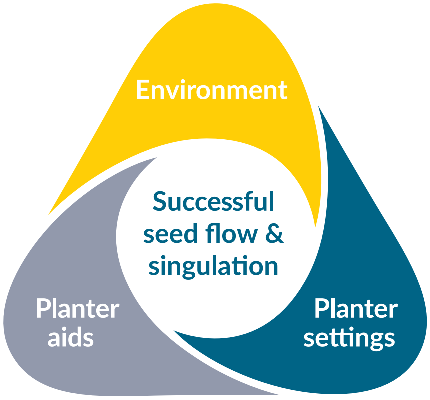

Figure 2. Three key management strategies for successful seed flow and singulation.

Planter aid research from Corteva Agriscience's Center for Seed Applied Technology, Johnston, Iowa

The benefits of planter aids are most evident under challenging environmental conditions, when flow and planting precision of large seeds are treated with a high-application rate recipe.

Large, flat corn seeds (F12) were treated with LumiGEN® seed treatments' enhanced corn rootworm package, dried and stored at 50°F (10°C) to mimic standard seed corn storage conditions. Seeds were moved directly from cold storage to our environmental chamber set at 80°F (27°C) with 80% relative humidity to evaluate both seed flow through bulk-fill planting equipment and planting precision. These seed and air temperatures are uncommon spring conditions, however can happen and may lead to challenging planting situations due to seed condensation. A talc/graphite (80:20) blend was applied at 0.25 cups per 80,000 seeds. Two levels of application quality were evaluated. In the poorly applied, planter aid was added to the middle and top of the seed pool with limited mixing. In the well-applied, it was added throughout the seed pool and mixed for uniform coverage.

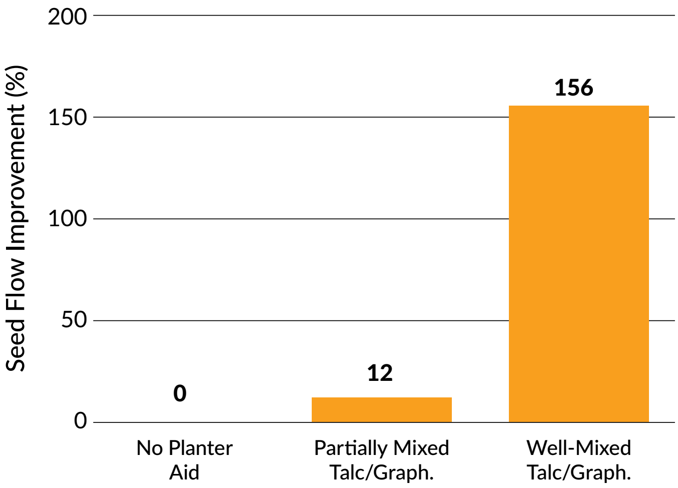

Figure 3. Planting precision was measured by using a Precision Planting Meter Max test stand to quantify singulation, skips and doubles.

Our relative seed flow assay predicts movement of treated seed through bulk-fill planting equipment. Larger values indicate better seed flow, whereas lower values indicate poor seed flow and bridging within the system.

A quality, well-applied application of planter aid resulted in free-flowing seed from the bulk fill and through the meter, whereas a poor application was only a marginal improvement over no planter aid. The poor application was also prone to seed bridging as humidity from the warm air condensed on the cold seed to re-wet the high-application rate seed treatment recipe.

Planting precision of cold seed with no planter aid applied was poor; however, application of talc/graphite greatly improved singulation. Interestingly, acclimating the cold seed so that it was the same temperature as the environmental chamber resulted in the best planting precision.

Figure 4. Planter singulation unit used in environmental growth chamber trials.

Under these difficult planting conditions, quality application of a planter aid resulted in excellent seed flow through planting equipment and planting precision. To maximize plantability under challenging environmental conditions, our research suggests:

- Use a planter aid as recommended by the planter manufacturer. Take the time to apply it uniformly as you fill hoppers or bulk fill systems. Consider utilizing more talc as risk of seed condensation increases.
- If possible, acclimate seed to match the outdoor planting environment in which it will be planted.

Figure 5. This bulk fill test stand was developed by Kinze Manufacturing to replicate their air seed delivery system. The system includes a small bulk fill chamber, entrainer, seed delivery tubing (length equivalent to a 24-row planter), and two individual vacuum meters.

Seed Singulation Trial from Corteva Agriscience and John Deere

Planter and meter maintenance is critical to seed singulation, spacing accuracy and planting the targeted population. Even spacing reduces competition between plants and maximizes ear count. It is recommended that meters be inspected and maintained prior to the planting season to allow for optimal performance.

Delivery of seed from the center-fill hopper to individual seed meters may be impacted by several factors, including planting time, environment, use of planter lubricant, ground speed, amount of seed treatment, and seed size. The use of talc, graphite, or a talc/graphite blend, specific to planter type, is critical. Thorough mixing of these lubricants in seed generally produces the best results.

The objectives of this trial were to evaluate the difference in seed singulation between:

- Poorly and well-mixed talc/graphite (80:20) planter aid.
- Small seed, 41 lbs/unit, and large seed, 64 lbs/unit (PDF & F12, respectively).
- Two LumiGEN® seed treatment options (mid- and high-rate seed treatment load).
- High planting speed (10 mph) and population (70k seeds/acre) were used as additional challenges.

Figure 6. Well-mixed treatment on the left, contrasted with poorly mixed treatment shown on the right.

On-farm testing was conducted with a 36-row John Deere DB60 planter to observe singulation of the treated seed with poorly and well-applied talc/graphite.

For each test, seed treatment and seed size were the same with well-mixed planter aid in one center-fill bulk tank and partially mixed planter aid in the other bulk tank. The partially mixed planter aid treatment followed the label without mixing. The well-applied planter aid followed the label by adding a scoop to the bottom of the hopper, then planter aid was added to seed flowing into the hopper and thoroughly mixed with a John Deere AA99640 Scoop throughout the fill.

Figure 7. Well-mixed treatment, adding planter aid to the hopper while seed is flowing.

Figure 8. Well-mixed treatment, mixing seed with scoop

When talc/graphite was poorly mixed, percent singulation (skips and doubles) decreased, indicating a less accurate planting experience. However, when talc/graphite was well-mixed, percent singulation increased and no difference was observed between seed size or seed treatment. Large seed treated with the higher seed treatment load, when talc/graphite was well-mixed, delivered >98% singulation at 10 mph and planting rate of 70,000 seeds per acre.

In conclusion, both the environmental chamber data and on-farm experience with John Deere's DB60 planter demonstrated excellent planting accuracy with all seed sizes and shapes, regardless of seed treatment recipe and environmental conditions, through careful planter aid usage and optimized planter adjustments.

Excellent planting accuracy and stand can be achieved with LumiGEN® seed treatments on all seed sizes through appropriate planter aid mixing and planter setting adjustments. Managing condensation on the seed, mixing planter aids well, and maintaining and adjusting planter settings will ensure seed flow and singulation are optimized for a successful planting season.

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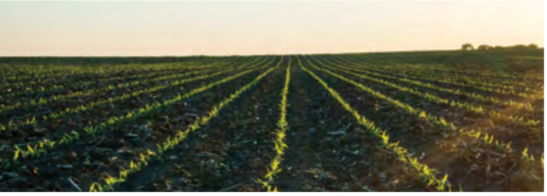

CORN PLANTING DEPTH

Mark Jeschke, Ph.D.,
Agronomy Manager

KEY POINTS:

- Planting corn around two inches deep is likely to provide the best odds of success in most environments in the Corn Belt.
- Research has shown that planting corn at least two inches deep can improve uniformity of emergence by placing seeds into a more consistent seedbed and improving seed-to-soil contact.
- Corn planted less than 1.5 inches deep is susceptible to less-uniform emergence and poor nodal root development.

COMMON PLANTING DEPTH RECOMMENDATIONS

- University Extension guidelines in the U.S. Corn Belt commonly recommend planting corn 1.5 to 2.5 inches deep.
- Specific seeding depth recommendations within the 1.5- to 2.5-inch zone are often based on soil texture and moisture conditions, with shallower planting recommended for poorly drained, finer-textured soils and deeper planting recommended for well-drained, coarser-textured soils.

Figure 1. Corn plant at V1 that was seeded two inches deep, with growing point ¾ of an inch below the soil surface. Correct planting depth is important for normal root development.

RISKS WITH PLANTING TOO SHALLOW

- Planting corn too shallow can hamper nodal root development by placing the crown too close to the soil surface.
  - » Plants with poor root development are less able to take up water and nutrients and can suffer dramatically during periods of summer drought.
  - » In severe cases, corn can develop a condition called “rootless corn syndrome” in which plants will fall over due to the lack of nodal root development in dry soil near the surface.
- Shallow planting can expose corn seedlings to herbicide residues, increasing the potential for herbicide injury.
- Emergence may be less uniform due to a greater variability in moisture and temperature conditions in the seed bed and poorer seed-to-soil contact.

Figure 2. Rootless corn syndrome caused by shallow planting followed by dry soil conditions.

RISKS WITH PLANTING TOO DEEP

- Planting too deep can be problematic when soils are cool and wet following planting. This can potentially result in uneven emergence and reduced stand establishment.

- Planting deeper can also place corn at a greater risk of emergence problems resulting from surface crusting if the field experiences a heavy rainfall event after planting.
  - » Crusting can affect corn planted at any depth, but deeper-planted corn can be at a slightly greater risk due to the longer time it takes for seedlings to reach the surface and emerge.
  - » Crusting risk is greatest in finely textured soils, low organic matter soils, and fields with poor soil structure and minimal residue.

KEY FINDINGS FROM RECENT RESEARCH

Ohio State Study (Lindsey and Thomison, 2020)

- Shallow planting (~1 inch) shortened the time to the start of corn emergence, but lengthened the duration of emergence, resulting in a less uniform stand.
- Soil moisture was lower and more variable closer to the soil surface, which likely contributed to the less-uniform emergence with shallower planting.
- Planting depth affected yield in a higher organic matter field, but had no effect in a lower organic matter field.

Univ. of Missouri Study (Kitchen et al., 2021a,b)

- Planting corn at the deeper end of the recommended range (2.5 to 3.0 inches) was advantageous for corn emergence in both coarse- and fine-textured soils.
- Planting deeper usually resulted in greater emergence uniformity and similar or improved corn emergence rates.
- Deeper planting (2.5–3.0 inches) was favorable for emergence rate and uniformity when temperatures after planting were high, but was unfavorable in one year of the study when temperatures were lower.

CORN PLANTING DEPTH RECOMMENDATIONS

- Research has generally shown that, within the standard recommended planting depth range (1.5 to 2.5 inches), there is more risk associated with planting too shallow than too deep.
- Corn should never be planted less than 1.5 inches deep.
- A target planting depth of around 2 inches is likely to provide the best odds of success in most situations in the Corn Belt.
- Deeper planting (2.5–3.0 inches) may be necessary in lighter, sandier soils in order to place seeds into consistent soil moisture.

HOW TO MEASURE CORN PLANTING DEPTH

- Planting depth can easily be determined after seedling emergence.
- The nodal root area (crown or growing point) typically develops about ¾ of an inch beneath the soil surface regardless of the seeding depth.
- Measure the mesocotyl length (the area between the seed and crown or growing point, then add ¾ inch to determine the planting depth.

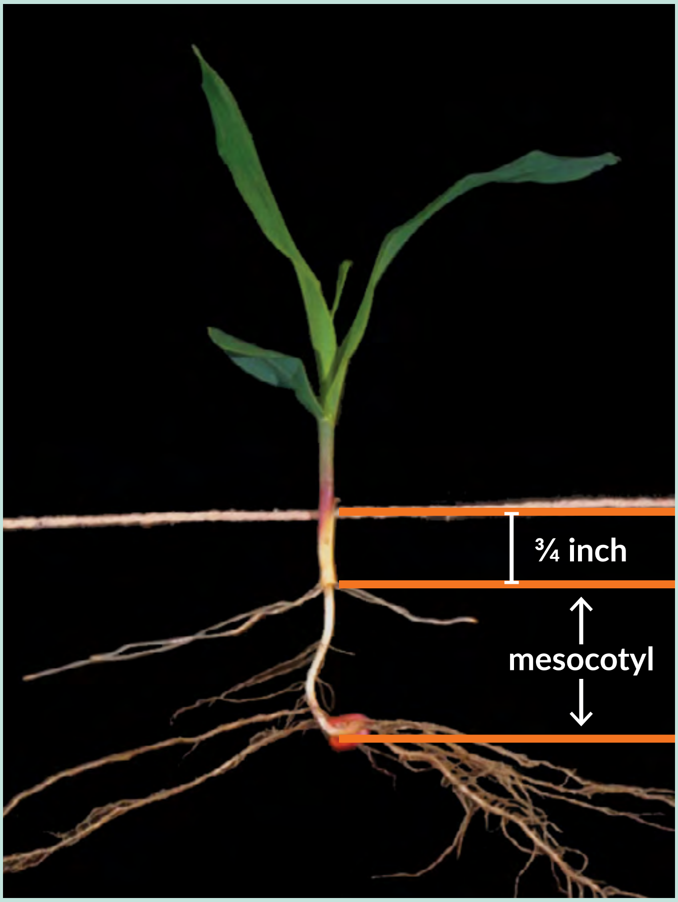

Figure 3. Corn seedling showing how to assess depth of seed placement after planting by measuring from the seed to the nodal roots.

BEST PRACTICES FOR UNIFORM PLANTING DEPTH

- Set the planting depth in the field, with the planter being pulled at full operating speed.
- Check for good seed-soil contact. Strive for firm seedbeds that promote uniform emergence and stronger root systems.
- Maintain slower planting speeds, between 4 to 5 mph, to achieve more uniform planting depths.
- Utilize in-row residue managers where needed, especially in corn-following-corn rotations.
- Utilize a planter down force control system.

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HOW PLANTING DEPTH AND SOIL TEXTURE AFFECT CORN EMERGENCE

KEY FINDINGS:

- Planting corn at the deeper end of the recommended range (2.5 to 3.0 inches) was advantageous for corn emergence in both coarse- and fine-textured soils.
- Planting deeper consistently resulted in greater emergence uniformity and similar or improved corn emergence rates.
- Corn planted shallow in fine-textured soil was vulnerable to poor emergence and yield loss.

TYPICAL CORN PLANTING DEPTH GUIDANCE

- Studies throughout the U.S. have found optimum corn seeding depths to vary from one to more than three inches depending on soil texture, moisture, temperature, seeding date, and other factors.
- University Extension guidelines in the U.S. Corn Belt commonly recommend seeding depths of 1.5 to 2.5 inches.
- Specific seeding depth recommendations within the 1.5- to 2.5-inch zone are often based on soil texture and moisture conditions.
- Shallower planting is recommended for poorly drained, finer-textured soils, while deeper planting is recommended for well-drained, coarser-textured soils.
- A field study was conducted by Dr. Newell Kitchen, USDA-ARS, and Stirling Stewart, Lance Conway, and Dr. Matt Yost of the University of Missouri as a part of the Pioneer Crop Management Research Awards (CMRA) Program to determine the influence of seeding depth and soil texture on corn emergence and grain yield.

STUDY DESCRIPTION

- Field studies were conducted in 2017 and 2018 near Claysville, Missouri. Within the same field, two contrasting soil textures in alluvial soils along the Missouri River were selected to provide separate experiment areas each year.
- In 2019, extensive and prolonged Missouri River flooding prevented this same farm being used for the study, so an alternative field with variable soil texture near Salisbury, Missouri, was used.
- In 2018 and 2019, planters used in the study were equipped with DeltaForce aftermarket hydraulic downforce systems to help ensure the target planting depth was consistently achieved.
- **Seeding Depths:**
  - » 1.5 inches
  - » 2.0 inches
  - » 2.5 inches
  - » 3.0 inches (not included in 2019)
- **Soil Textures:**
  - » Sand
  - » Silty clay loam
- **Plot Layout:**
  - » 2017-2018: 4 rows x 30 ft, 30-inch spacing
  - » 2019: 24 rows x 3,280 ft, 30-inch row spacing
- Seeding rate (25,000, 30,000, and 35,000 seeds/acre) and starter fertilizer were included as experimental factors in the initial year of the study, but were discontinued after no significant effects were found.
- All plant measurements were taken for both studies from two, 10-ft long sections from adjacent rows in each plot. Plant emergence was monitored and recorded daily for each plant.
- Three response measurements were generated from the collected emergence data.
  - » **Emergence rate:** Total time required from planting to 90% emergence.
  - » **Emergence window:** Time between first emergence and 90% emergence.
  - » **Emergence percent:** Fraction of emerged seedlings from total seed planted.
- Sensors capturing soil moisture, soil temperature, and electrical conductivity every 15 minutes were installed at the 4 seeding depths within each replicate of both soil texture sites.

RESULTS: PLANTING DEEPER IMPROVED EMERGENCE

- In 2017, the daily average air temperature within the first three days after planting was 70°F, substantially higher than the same for 2018 and 2019 (41 and 57°F respectively).
- Over the germination period, soil moisture was most variable in 2017. Soil moisture measurements indicated shallow planted corn had much less water available on fine-textured soil, as there was only 12% compared to 41% at the deepest planted depth.
- In 2018 and 2019, rainfall the weeks prior to planting was ample and therefore soil moisture was near field capacity at all planting depths.

Table 1. Analysis of variance for corn stand establishment characteristics from 2017 to 2019.

Model Terms	Emergence Rate	Emergence Window	Emergence Percent
Year	***	NS	***
Texture	NS	NS	NS
Depth	**	**	NS
Year x Texture	*	NS	NS
Year x Depth	*	NS	NS
Texture x Depth	NS	NS	NS
Year x Texture x Depth	NS	NS	NS

* Significant at α = 0.1
** Significant at α = 0.05
*** Significant at α = 0.01
NS = not significant

Corn Emergence Rate

- Emergence rate (days to 90% emergence) was affected by growing season conditions (i.e., year) and its impact on texture and planting depth (Table 1).
  - » Planting depth did not influence emergence rate in 2018 or 2019, but it did in 2017 (Figure 1).
  - » In 2017, seed planted at the 3 deeper depths had an emergence rate between 8 and 10 days, but at the shallow depth, an additional 5 to 6 days were needed to reach 90% emergence.
- In 2017, soil texture also affected emergence rate (Figure 2).
  - » Emergence rate was 3.3 days faster on the coarser soil.
  - » Field observations made at planting noted that the shallowest planting depth on fine-textured soil likely experienced reduced seed-to-soil contact due to larger soil clods and effects of residues from the previous crop.

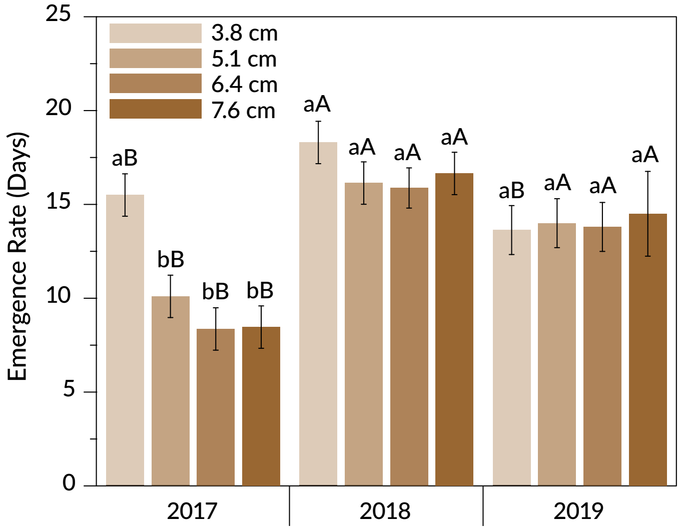

Figure 1. Planting depth effects on emergence rate by year. Lowercase letters indicate significant differences within years and uppercase letters indicate significant differences across years.

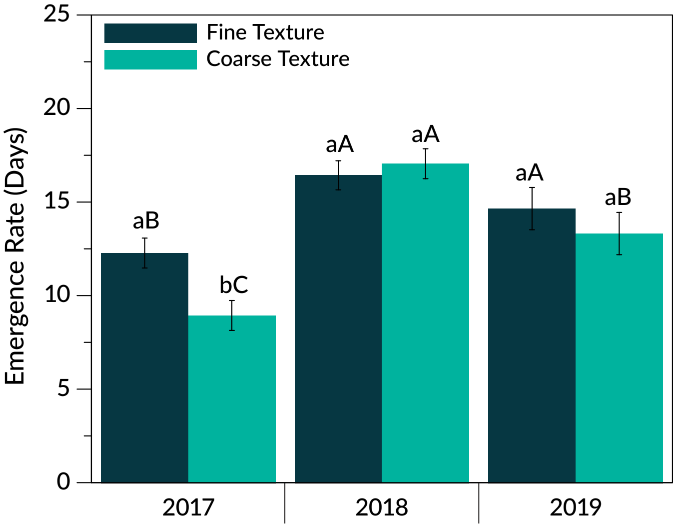

Figure 2. Soil texture effects on emergence rate by year. Lowercase letters indicate significant differences within years and uppercase letters indicate significant differences across years.

Corn Emergence Window

- Seed planted at the shallowest depth had an emergence window ~2.5 days longer than the deeper plantings (Figure 3).
- The shallowest-planted seed was more vulnerable as a result of a fluctuating seed-bed environment due to temperature and moisture.

Corn Emergence Percent

- Emergence percent relative to the targeted seed population was not affected by depth, but differed by year with averages of 102.1%, 97.7%, and 94.2% for 2017, 2018, and 2019, respectively.
    - » In 2017, a smaller round seed resulted in a relatively high number of doubles, which likely accounts for emergence being more than 100% of target.
    - » Cooler temperatures in 2018 and 2019 help explain some of the decrease in emergence percentage.

Yield

- Planting depth did not significantly impact yield in either the course or fine-texture soils (Table 2).
- Yield was significantly greater on the fine-texture soil than the course-texture soil at all planting depths (Table 2).

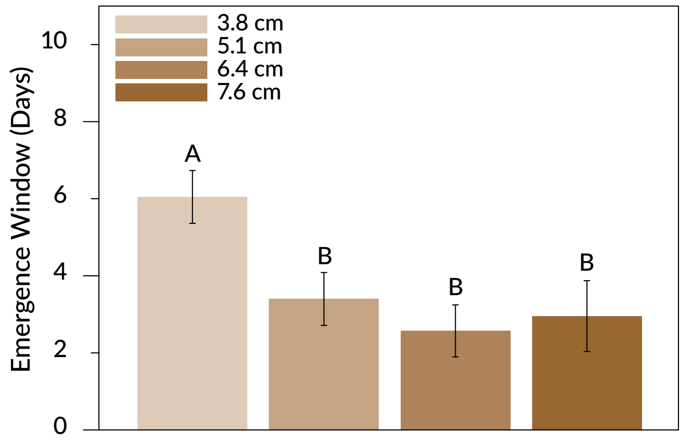

Figure 3. Planting depth effect on emergence window. Letters indicate significant differences.

Table 2. Plot yield for all planting depths and soil textures averaged across years. Letters indicate differences between textures.

Soil Texture	Target Depth	Grain Yield
	inches	*bu/acre*
Fine Texture	1.5	186 A
	2.0	193 A
	2.5	179 A
	3.0	192 A
Coarse Texture	1.5	135 B
	2.0	139 B
	2.5	127 B
	3.0	104 B
P-values	Depth	0.7069
	Texture	<0.0001
	Texture x Depth	0.6345

CONCLUSIONS

- University Extension guidelines in the U.S. Corn Belt commonly recommend seeding depths of 1.5 to 2.5 inches.
- Results of this study suggest that planting corn at the deeper end of the recommended range can be advantageous for emergence in both courser- and finer-textured soils.
- Planting deeper consistently achieved greater emergence uniformity. Additionally, planting deep on these soils achieved similar or improved emergence rates.
- Uniformity at target planting depth, which includes soil temperature, moisture, and structure, greatly impacts emergence window.
- Resilience of soil texture to maintain similar microenvironments when encountering temperature fluctuations impacts emergence percent.

PLANTING DEPTH AND LANDSCAPE POSITION EFFECTS ON CORN EMERGENCE

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KEY FINDINGS:

- The effects of landscape position and corn planting depth on corn emergence differed between the two years of the study due to differing weather conditions after planting.
- Deeper planting was generally favorable for emergence in 2018, when temperatures after planting were warm, but unfavorable in 2019, when temperatures were colder.
- The summit position had slower emergence in 2018 compared to other landscape positions, while corn on the backslope was slowest to emerge in 2019.
- Despite significant effects of planting depth on emergence characteristics, yield was not ultimately affected by planting depth in this study.

STUDYING CORN PLANTING DEPTH IN CLAYPAN SOILS

- Studies throughout the U.S. have found optimum corn seeding depths to vary from one inch to more than three inches depending on soil texture, moisture, temperature, seeding date, and other factors.
- University Extension guidelines in the U.S. Corn Belt commonly recommend seeding depths of 1.5 to 2.5 inches.
- Specific seeding depth recommendations within the 1.5- to 2.5-inch zone are often based on soil texture and moisture conditions.
- Claypan soils in Missouri possess landscape position and topsoil depth variations that result in complex hydrologic features.
- Site-specific management of corn seeding depth has the potential to homogenize stands and increase corn yield on variable soils within Missouri fields.
- A field study was conducted by Dr. Newell Kitchen, USDA-ARS, and Stirling Stewart, Lance Conway, and Dr. Matt Yost of the University of Missouri as a part of the Pioneer Crop Management Research Awards (CMRA) Program to determine the influence of seeding depth and landscape position on corn emergence and grain yield.

STUDY DESCRIPTION

- Plot studies were conducted in 2018 and 2019 near Columbia, Missouri, at the University of Missouri Bay Farm Research Facility on an upland alfisol soil with a claypan horizon.
- Three landscape positions—summit, back slope, and foot slope—were identified within a single field and used for the study.
- Plots at each landscape position were planted to four targeted seeding depths, 1.5, 2.0, 2.5, and 3.0 inches.
- Plots were four rows by 30-ft long, planted at 30-inch row spacing.
- The study was planted on April 26 in 2018 and on April 9 in 2019, with good soil moisture in both years.
- All plant measurements were taken for both studies from two, 10-ft long sections from adjacent rows in each plot. Plant emergence was monitored and recorded daily for each plant.
- Three response measurements were generated from the collected emergence data.
    - » **Emergence rate:** Total time required from planting to 90% emergence.
    - » **Emergence window:** Time between first emergence and 90% emergence.
    - » **Emergence percent:** Fraction of emerged seedlings from total seed planted.

RESULTS: DEEPER PLANTING BETTER IN WARM TEMPERATURES

- Varied weather events created conditions ranging from conducive to problematic for germination uniformity.
    - » In both 2018 and 2019, average air temperatures at planting were within 50-59°F.
    - » In 2018, temperatures rose after planting, while in 2019 they decreased, preventing the soil from warming.
    - » Low soil temperatures in 2019 slowed seed germination processes and resulted in seedling damage.

Corn Emergence Rate

- Emergence rate was impacted differently each year for both landscape position and planting depth (Table 1).
    - » All landscape positions required an average of three additional days to reach 90% emergence in 2019 vs 2018 due to colder soil temperatures (Figure 4).
    - » In 2019, the back slope required an additional 1.1 days to reach 90% emergence. Poor drainage and an eroded A horizon contributed to a soil environment with excessive moisture and poor root development.
    - » In 2018, the two deepest planting depths emerged on average about one day ahead of the shallowest planting depth (Figure 2).
    - » The opposite trend was observed in 2019. Emergence was delayed with increased planting depth. Compared to the two shallowest depths, the emergence rate was delayed 3.5 days for the deepest planted seed.

Table 1. Analysis of variance for corn stand establishment characteristics from 2018 to 2019 on landscape position study.

	Emergence Rate	Emergence Window	Emergence Percent
Year	***	*	NS
Landscape Position	NS	NS	NS
Depth	***	NS	NS
Year x LP	***	**	**
Year x Depth	***	***	NS
LP x Depth	NS	NS	NS
Year x LP x Depth	NS	NS	NS

* Significant at α = 0.1
** Significant at α = 0.05
*** Significant at α = 0.01
NS = not significant

Corn Emergence Window

- Emergence window had a similar response to emergence rate, with landscape position and planting depth factors differing by year.
    - » Deep planting was beneficial for emergence uniformity in 2018. Emergence window in 2018 was approximately one day longer for shallow-planted corn (Figure 3).
    - » The opposite was the case in 2019, with a longer emergence window for deeper-planted corn of 1.7 days compared to shallower-planted corn.
- The contrast between years was most pronounced at deeper planting depths, and can be explained by soil temperatures.
- Of the three landscape positions, only the back slope differed in emergence window, and that was for 2019 only. For this year, the back slope had an emergence window 1.2 days greater than the other two positions.
- Under cool conditions, seed planted deeper on the back slope position would undoubtedly be impacted more by the claypan effect since the seed would be closer to the argillic horizon.

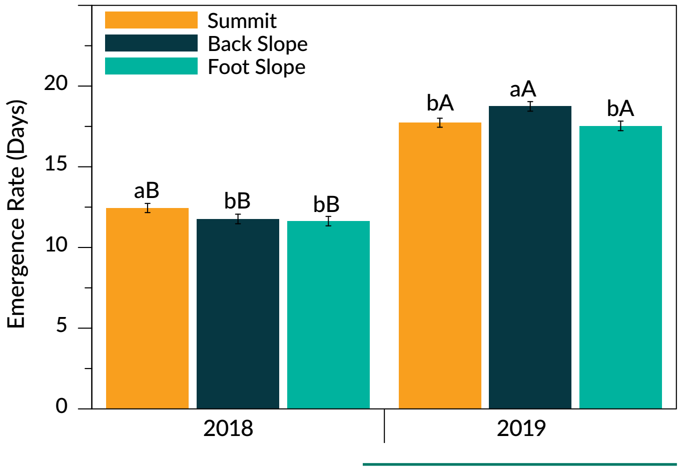

Figure 1. Landscape position effects on emergence rate by year. Lower case letters indicate significant differences within years and uppercase letters indicate significant differences across years.

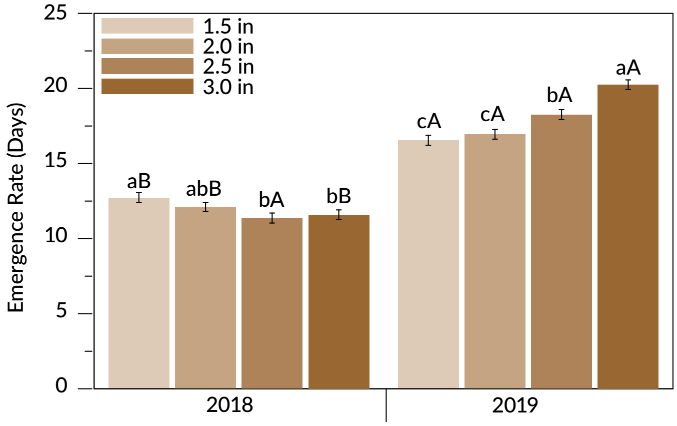

Figure 2. Planting depth effects on emergence rate by year. Lower case letters indicate significant differences within years and uppercase letters indicate significant differences across years.

Corn Emergence Percent

- In 2018, the foot slope experienced the lowest emergence percent of the three landscape positions. In this year, with warm conditions and adequate moisture, it is unclear what led to the greater emergence at the back slope compared to the foot slope position.
- In 2019, crop residue was slightly more abundant at the summit position compared to the eroded back slope and foot slope positions.
- The summit was the only landscape position to have reduced emergence compared to the warmer 2018 germination period, which suggests residue had a greater impact than cool temperatures on emergence percent.

Corn Yield

- Average corn yield was greater at the foot slope than the other two landscape positions; however, yield was not significantly affected by planting depth (Table 2).

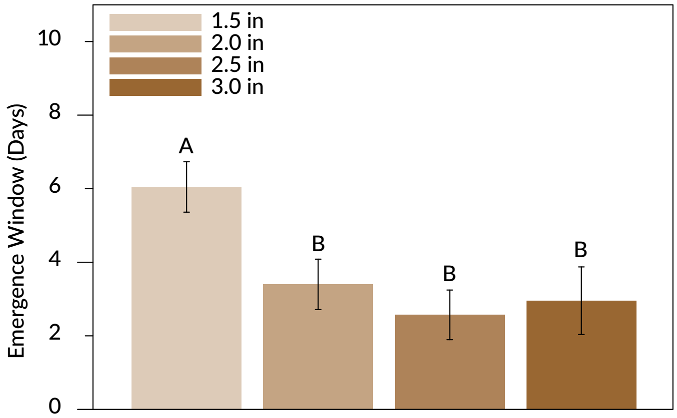

Figure 3. Planting depth effects on emergence window by year. Uppercase letters indicate significant differences across years.

Table 2. Plot yield from all depths and landscape positions averaged across years. Letters indicate differences between landscape positions.

Landscape Position	Target Depth	Grain Yield
	inches	*bu/acre*
Summit	1.5	130 B
	2.0	154 B
	2.5	162 B
	3.0	145 B
Back Slope	1.5	129 B
	2.0	159 B
	2.5	157 B
	3.0	148 B
Foot Slope	1.5	194 A
	2.0	206 A
	2.5	199 A
	3.0	198 A
P-values	Depth	0.1549
	Texture	<0.0001
	Texture x Depth	0.9769

CONCLUSIONS

- All three emergence performance metrics were uniquely affected each year by landscape position.
- Emergence timeliness and uniformity were also impacted differently each year by planting depth.
- Careful attention to conditions in uplands fields like the one used in this study is necessary, as emergence performance can vary substantially over changing landscape positions, planting depths, and growing seasons.

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PUTTING VARIABLE RATE SEEDING TO WORK ON YOUR FARM

SUMMARY

- Extensive field research has documented the value of increasing corn seeding rates in more productive field areas and decreasing rates where productivity is lower.
- To maximize variable rate seeding (VRS) value, appropriate crop management zones, or Decision Zones, must be defined. When available, Decision Zones can include soil types, topography, irrigation, and long-term yield history. In some cases, other information like soil electrical conductivity (EC) can also be used.
- Corteva Agriscience researchers conduct thousands of population trials at hundreds of locations across North America. Data from these trials provide the basis for seeding rate recommendations for each Decision Zone.
- Appropriate differences between seeding rates are field-specific and depend on the capabilities of the planting equipment, yield targets, field variability, soil productivity, and understanding of hybrid specific interaction of genotype by environment. Agronomically, seeding rates should differ by at least 4,000 seeds/acre.
- The Granular VRS tool helps farmers increase yields and maximize their seed input investment on every acre. Recommendations can be provided through Granular certified services agents (CSAs) and Pioneer sales professionals.

INTRODUCTION

Each year, an increasing number of farmers are utilizing planters with variable-rate seeding (VRS) capability, and are putting this feature to work to vary corn and soybean seeding rates. Those using the technology expect it to help increase yields as well as maximize the value of their seed investment.

The growing number of VRS-enabled planters and widespread on-farm use of GPS technology make it easier than ever to deploy a VRS strategy. However, growers still need to understand the variability within their fields and implement the appropriate hybrid-specific seeding rates. This Crop Insights will discuss guidelines for developing a VRS strategy, designating management zones, selecting seeding rates, and implementing a field prescription.

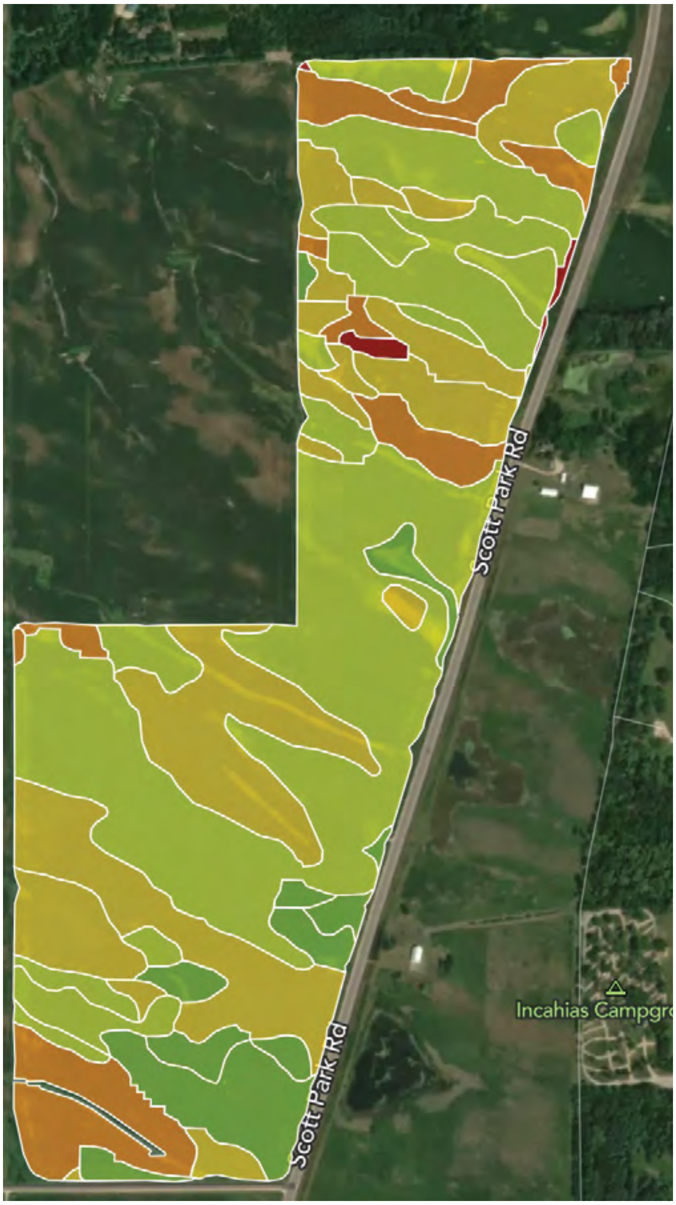

Figure 1. Decision Zones incorporate a field's historical yield data and management layers to segment and improve the precision of the soil productivity zones.

CREATING DECISION ZONES

Creating Decision Zones within a field is based on the following (Figure 1):

- Grower knowledge of yield history, cropping history, and general productivity of field areas.
- Environmental Response Units (ERUs) based on soil type, topography, landscape, slope, and drainage.
- Yield history based on multiple years of harvest data.
- Crop productivity ratings based on soil type, if yield history is not available.
- Irrigated and dryland areas of fields, if appropriate.

Decision Zones can also sometimes include:

- Soil electrical conductivity and/or soil color.
- Remote imagery to determine normalized difference vegetative index (NDVI), bare soil, and crop vigor

DEVELOPING A VARIABLE-RATE STRATEGY

Growers new to VRS may benefit by collaborating with someone knowledgeable in this area, such as a Granular certified services agent (CSA) or Pioneer sales professional. The first step in developing a VRS strategy is to identify candidate fields.

The grower is best qualified to identify management zones that will be predictive from year to year, based on trends that are historically consistent. For example, low-lying field areas may perform best in dry years and poorly in wet years, and the grower is most familiar with how to best manage such nuances.

SELECTING A HYBRID AND SEEDING RATES

Selecting a Hybrid

The next step is selecting the proper corn hybrid for the field, taking into account the range of possible growing conditions and resulting yield potential of field areas. Local Pioneer sales professionals are a valuable resource to help identify the right product for a particular growing environment.

Selecting Seeding Rates

Corteva Agriscience researchers conduct thousands of field research trials at hundreds of locations annually across North America to help understand grain yield response to planting rate for Pioneer® brand hybrids. In addition, many growers have their own data on variable planting rates gathered from as-planted and yield data. Decades of Corteva research has shown that corn yield response to seeding rate within a commercially relevant range can usually be well-described by a quadratic function. Grain yield will increase with seeding rate up to an optimum point and then decline as the seeding rate is increased above the optimum due to a higher rate of barrenness and extended anthesis-silking intervals (Jeschke et al., 2009). The optimum seeding rate can vary based on hybrid genetics. Figure 2 shows an example of quadratic response functions for two hybrid families with the same comparative relative maturity (CRM) that have been shown to differ in their response to plant population in Corteva research trials.

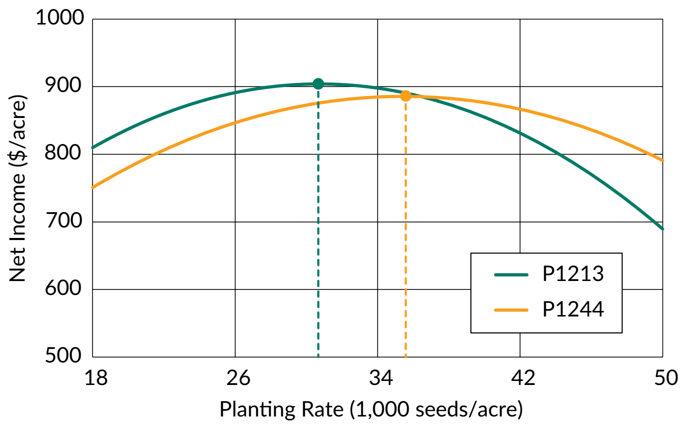

Figure 2. Economic optimum planting rates of two Pioneer brand hybrid families with similar comparative relative maturity at a 250 bu/acre yield level.

Seeding Rate Response to Productivity

Yield response to seeding rate by productivity level is the critical factor for creating variable-rate seeding (VRS) prescriptions. The population required to maximize yield increases as yield levels increase. When grouped by yield level, results from Corteva Agriscience plant population trials showed that the economic optimum seeding rate increased from approximately 31,000 seeds/acre at the 150 bu/acre yield level to more than 39,000 seeds/acre at the 240 bu/acre yield level (Figure 3). An Iowa State University study comparing corn yield response to plant population across soils with different corn suitability ratings found similar results. The most productive soils tended to have a higher optimum population for maximum yield (Woli et al., 2014).

The increase in optimum seeding rate by yield level has been shown to be roughly linear within the range represented by research data (Figure 3).

Economic and Agronomic Optimum Rates

It is important to note that suggested seeding rates produced via the Pioneer Planting Rate Estimator and Granular VRS Tools are based on economic optimum rates that consider both the revenue from yield and the cost of additional seed. This provides

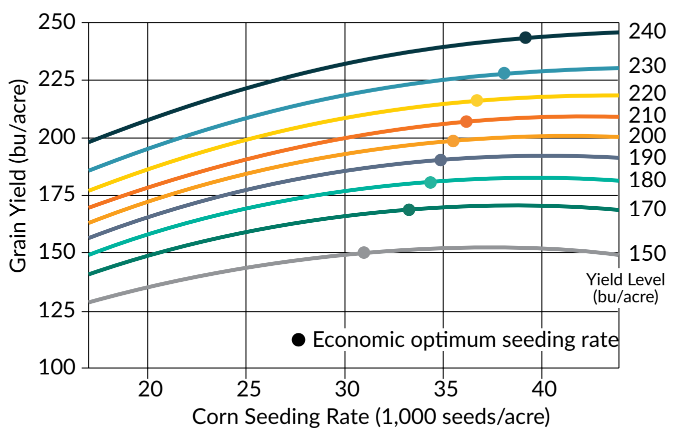

Figure 3. Corn grain yield response to seeding rate at nine yield levels, average of all hybrids tested over a six-year period. Dots indicate the economic optimum seeding rate within each yield level.

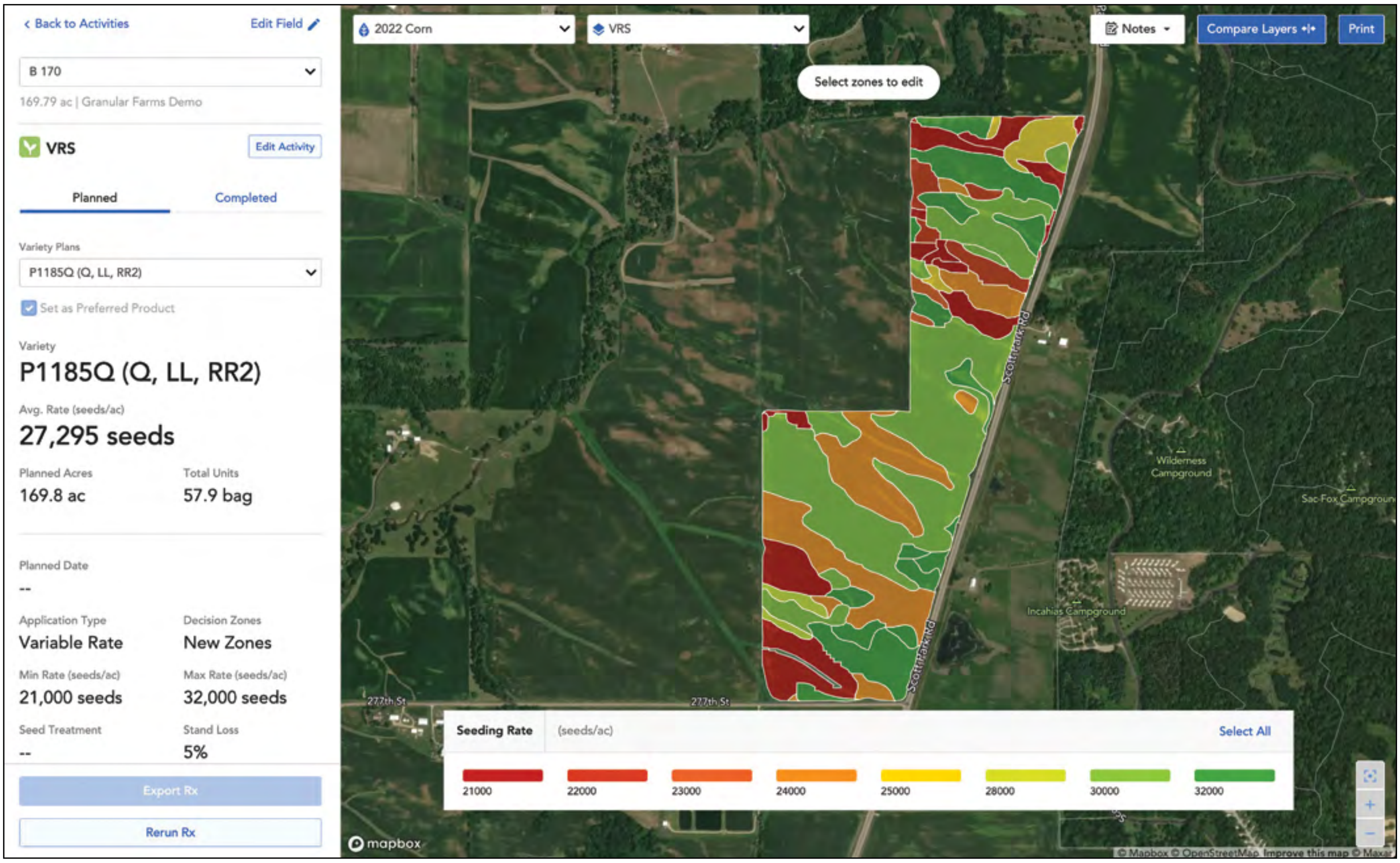

Figure 4. Example of a Granular Variable Rate Seeding prescription.

the most useful information for optimizing return on seed investment. When comparing recommendations from different companies, farmers need to understand the economic and genetic assumptions that affect each recommendation.

BUILDING A VRS PRESCRIPTION

- Working with a Granular certified services agent (CSA) or Pioneer sales professional, assign Decision Zone yield targets for each field. Decision Zones are typically defined by soil properties, topography, yield history, and irrigation management.
- Select each Pioneer® brand corn product and review the suggested seeding rates. Select any additional hybrids or varieties and seeding rates. Granular VRS prescriptions will be ready to review and edit (Figure 4).
- Review each prescription in Granular and make any Decision Zone specific edits to seeding rates. Granular conveniently generates prescriptions for every product, for every field to maximize flexibility when conditions or product changes occur during the planting season.
- Prescriptions can be received via email and copied to a storage device or uploaded wirelessly to capable monitors.
- Review planter monitor settings for user preferences and default settings (out of bounds rate, loss of signal rate, offset distance, etc.). Make sure the controller is set to record as-planted information. Upload the as-planted data to the Granular software platform for further analysis.

EVALUATING PRESCRIPTION EFFECTIVENESS

Setting Up Checks

The recommended best practice for evaluating the effectiveness of VRS prescriptions is planting check strips at rates higher and lower than the prescribed rates for the rest of the Decision Zone. These checks can help farmers understand those areas where yields may increase through higher seeding rates or decrease seeding rates where lower productivity doesn't typically support higher yields.

Strips are typically field-length strips of a single planting rate that pass through several management zones. A strip should be placed so that it crosses management zones of most or all other rates. There should be at least one strip for each designated seeding rate. Strips are typically one planter pass wide. Check strips can be created as part of the prescription or from the planter monitor in the field.

Blocks are an alternate approach where generally square blocks of higher and lower planting rates are located within different management zones. Block utility is decreasing as growers strive to differentially manage smaller and smaller areas of fields.

In-Season Monitoring

After stand establishment, take stand counts in the different planting rate zones and check areas (e.g. strips). It is important to verify that target populations were actually attained to assure the validity of the test. Pay special attention to high-stress areas, such as poorly drained spots or high crop residue areas.

INTERPRETING THE RESULTS

- Work with your Granular CSA or Pioneer sales professional to analyze yield results.
- Did higher seeding rates produce greater yields in higher productivity Decision Zones? What impact did weather play? What should be done differently next season?
- Evaluate profitability by comparing yields and accounting for seed costs for any two rates in question.

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Mark Jeschke, Ph.D.,
Agronomy Manager

MAXIMIZING THE VALUE OF FOLIAR FUNGICIDES IN CORN

SUMMARY

- Pioneer has conducted extensive research to better understand the value of foliar fungicide treatments in corn production.
- Corn yield increased an average of 7.4 bu/acre in response to a foliar fungicide application across more than 2,000 Pioneer on-farm trials conducted from 2007 to 2020.
- The most important factor determining the value of a foliar fungicide application is disease pressure. When weather conditions are conducive for foliar diseases, a fungicide application can be beneficial.
- Hybrids that have lower levels of genetic resistance to a given foliar disease are more likely to benefit from a fungicide application if that disease becomes prevalent.
- Continuous corn and minimum tillage fields can be at higher risk of foliar disease and more likely to benefit from a fungicide application due to greater amounts of surface residue harboring pathogens from the previous corn crop.
- Later-maturing fields can be at greater risk for yield loss due to foliar diseases and therefore are more likely to benefit from a fungicide application.

INTRODUCTION

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

This Crop Insights summarizes the key findings of several Pioneer research projects on foliar fungicide use in corn conducted between 2007 and 2020. These studies involved several different foliar fungicide products and included both aerial and ground applications, but all were focused on application timings between tasseling and brown silk (VT-R2) except where noted. Some of these studies provided the opportunity to assess the value of fungicide treatments against specific foliar diseases due to the presence of a single predominant disease at the trial locations.

ON-FARM FUNGICIDE TRIAL SURVEY

Between 2007 and 2020, Pioneer agronomists, sales professionals, and cooperators conducted more than 2,000 on-farm fungicide trials comparing yield of corn treated with a foliar fungicide between tasseling and brown silk to non-treated corn. These trials encompassed a wide range of different hybrids, management practices, environmental conditions, and disease pressure.

The results of these trials provide an estimate of the average yield response that corn producers might expect from a foliar fungicide application. This average can serve as a starting point for foliar fungicide treatments decisions. Whether yield response in a given field is likely to be above or below this average will depend on the combination of disease pressure, hybrid genetic resistance, agronomic practices, and environmental conditions unique to that field.

Across the more than 2,000 on-farm fungicide trials conducted from 2007 to 2020, the average yield response to fungicide application was an increase of 7.4 bu/acre (Figure 1). A positive yield response to fungicide application occurred in 78% of the trials. Yield response varied widely among the trials, as would be expected given differences in weather conditions, disease pressure, and trial locations.

The economic viability of a fungicide application can vary according to the price of corn and cost of the fungicide and application. Higher corn prices and lower treatment costs reduce the break-even yield response, while lower corn prices and higher costs increase it (Table 1). At a break-even yield response of 5 bu/acre, 56% of the Pioneer on-farm trials would have seen an economic benefit from a fungicide application (Figure 1). However, at a break-even point of 8 bu/acre, the success rate drops to 44%.

Table 1. Yield response necessary to cover the cost of fungicide and application over a range of costs and corn prices.

Fungicide + Application Cost /Acre	Corn Price/Bu			
	$4	$5	$6	$7
	bu/acre			
$22	5.5	4.4	3.7	3.1
$24	6.0	4.8	4.0	3.4
$26	6.5	5.2	4.3	3.7
$28	7.0	5.6	4.7	4.0
$30	7.5	6.0	5.0	4.3
$32	8.0	6.4	5.3	4.6

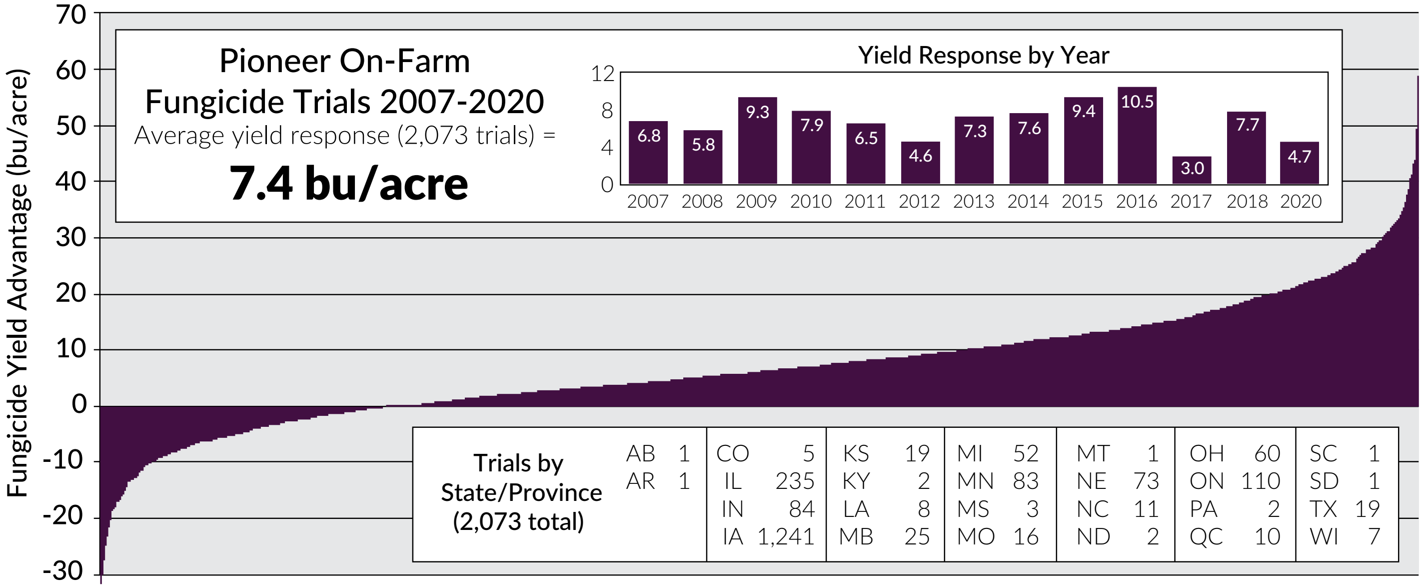

Figure 1. Corn yield response to foliar fungicide application in 2,073 Pioneer on-farm trials conducted from 2007 to 2020.

Yearly averages in fungicide yield response ranged from 3.0 to 10.5 bu/acre in the on-farm trial survey. The majority of trial locations were located in the central Corn Belt; consequently, variation in yearly averages is largely reflective of differences in weather conditions and disease pressure in those states.

FACTORS INFLUENCING FUNGICIDE RESPONSE

Disease Pressure

The most important factor determining the value of a foliar fungicide application is disease pressure. Foliar diseases can occur anywhere corn is grown in North America but are more common in the warmer, more humid growing areas of the South and East. Most widely-grown hybrids have at least moderate resistance to the major leaf diseases, which may be sufficient protection against low to moderate disease pressure. However, in years when weather conditions are very conducive for disease, a fungicide application may provide a substantial economic benefit.

There are two basic types of disease cycles among the fungal diseases that infect corn leaves. Many pathogens, such as northern corn leaf blight, overwinter in diseased corn leaves, husks, and other plant parts. Spores are produced on this crop residue when environmental conditions become favorable in the spring and early summer. These spores are spread by rain splash and air currents to the leaves of new crop plants, where primary infections are produced. Secondary spread then occurs from plant to plant and even from field to field as spores are carried long distances by the wind. As the plants die, the fungi remain in the dead plant tissue.

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

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

Hybrid Disease Susceptibility

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

Previous Crop and Tillage

Continuous corn and minimum tillage fields can be at higher risk of foliar disease and more likely to benefit from a fungicide application due to greater amounts of surface residue harboring pathogens from the previous corn crop.

Survival of diseases in corn residue can lead to earlier infection and higher disease incidence and severity in the subsequent corn crop. Many common diseases, including gray leaf spot, northern corn leaf blight, southern leaf blight, eyespot, tar spot, and northern leaf spot overwinter in corn residue, providing a source of inoculum to infect corn planted the following season.

Hybrid Maturity and Planting Date

Hybrid maturity and planting date have also been found to influence susceptibility to yield loss from foliar diseases. These factors are important relative to the timing of disease development. Later planted fields and/or later maturing hybrids can be more vulnerable to yield loss because they are still filling grain while disease development is peaking in late summer. Therefore, these later fields are often more likely to benefit from a fungicide application.

PIONEER FUNGICIDE RESEARCH

Pioneer scientists, agronomists, and university collaborators have conducted several corn fungicide studies in which a single foliar disease was predominant at the research location or locations. In some cases, research locations were chosen specifically due to their history of a specific disease; in others, environmental conditions happened to be favorable for a given disease when the study was conducted.

Corn leaf showing gray leaf spot lesions.

Gray Leaf Spot

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

Results of the study demonstrated the potential for gray leaf spot to cause substantial reductions in yield when disease pressure is very high. Hybrid resistance was effective in mitigating a large portion of yield loss due to gray leaf spot; however, even with the most resistant hybrid, the yield benefit of the foliar fungicide application was great enough to potentially cover the cost of product and application (Figure 2). Under more moderate disease pressure, a fungicide application would likely not provide an economic benefit on a resistant hybrid.

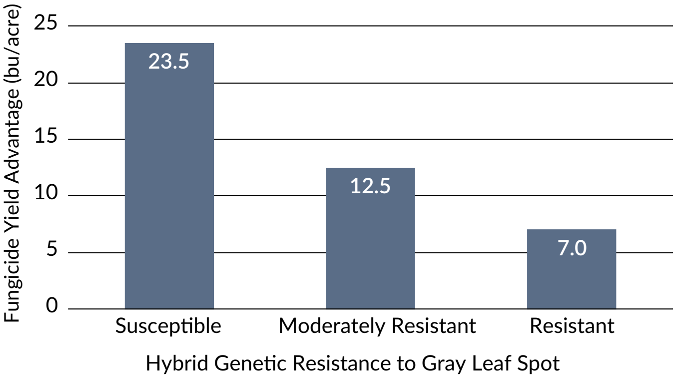

Figure 2. Average yield response of hybrids susceptible, moderately resistant, and resistant to gray leaf spot to a foliar fungicide application in a 3-year Univ. of Tennessee/ Pioneer research study.

Common Rust

Pioneer scientists conducted fungicide research trials at several Midwestern sites in 2009, a growing season that experienced unusually high common rust pressure in parts of the Midwest. Summer temperatures were cooler than normal in 2009, which favors development and spread of common rust. Studies were conducted at 10 different field locations across five states. Corn yield response to fungicide application varied widely among research locations, largely due to differences in common rust pressure. Common rust was prevalent at research locations in Iowa, Illinois, and Indiana.

Table 2. Average corn yield response to foliar fungicide treatment at Pioneer small-plot research locations.

Location	Previous Crop	Tillage	Yield Response
			bu/acre
Mankato, MN	Soybean	Conv.	6.4
Waltham, MN	Soybean	Conv.	4.6
Janesville, WI	Soybean	Conv.	0.6
Minburn, IA	Corn	Strip	10.6
Breda, IA	Corn	Conv.	11.5
Alleman, IA	Soybean	Strip	8.0
Seymour, IL	Soybean	Conv.	11.8
Macomb, IL	Soybean	Conv.	7.1
Windfall, IN	Corn	Conv.	5.8
Gwynneville, IN	Soybean	No-Till	22.6
Average			**8.9**

Average yield response across locations in Iowa, Illinois, and Indiana was 11.4 bu/acre (Table 2). Conversely, average yield response across Minnesota and Wisconsin locations where common rust was less prevalent was only 3.9 bu/acre. At sites with high common rust pressure, yield response to foliar fungicide application was greatest among hybrids with lower levels of genetic resistance to the disease (Figure 3).

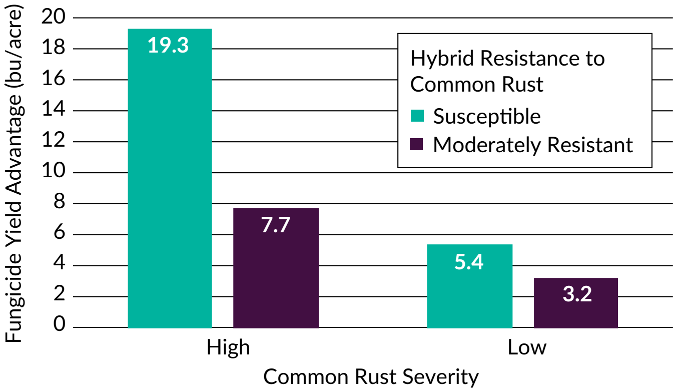

Figure 3. Average fungicide yield response of hybrids with low resistance (3 on a 1-9 scale) and moderate resistance (4-6) to common rust in Pioneer small-plot trials.

Common rust was prevalent at a trial at Macomb, IL, along with low to moderate levels of gray leaf spot and northern leaf blight. Notable differences in disease symptoms and yield response to fungicide were observed (Figure 4).

These research results from 2009 demonstrate the value of foliar fungicides in protecting yield when disease outbreaks occur; however, genetic resistance of hybrids may also provide adequate protection and should be considered in fungicide treatment decisions.

Figure 4. Two hybrids treated (left) and non-treated (right) with fungicide at Macomb, IL. The fungicide helped to protect yield of a susceptible hybrid (top) but provided little benefit on a moderately resistant hybrid (bottom).

Northern Corn Leaf Blight

Pioneer on-farm trials were conducted at 40 locations in Iowa in 2015 to evaluate corn yield response to foliar fungicides applied at different timings. Northern corn leaf blight pressure was high in much of Iowa in 2015 and it was the predominant foliar disease at the trial locations. Trials compared yield of corn treated with Aproach® Prima fungicide at the VT, R1, or R2 growth stage to non-treated corn.

Results showed that yield response to fungicide application varied by hybrid genetic resistance to northern corn leaf blight. A yield response of 13 bu/acre was observed with hybrids rated a 3 on a 1-9 scale for northern corn leaf blight (NCLB), while hybrids rated a 6 for northern corn leaf blight had an average yield response of 9 bu/acre (Figure 5). Fungicide yield response was greatest at the VT application timing (Figure 6).

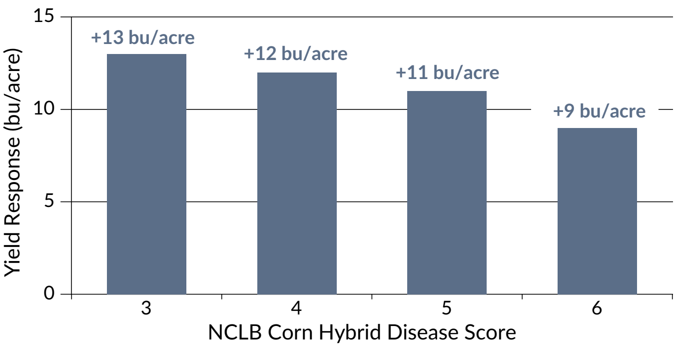

Figure 5. Average fungicide yield response of Pioneer® brand hybrids with different levels of genetic resistance to northern corn leaf blight in 40 Pioneer Agronomy trials in Iowa in 2015.

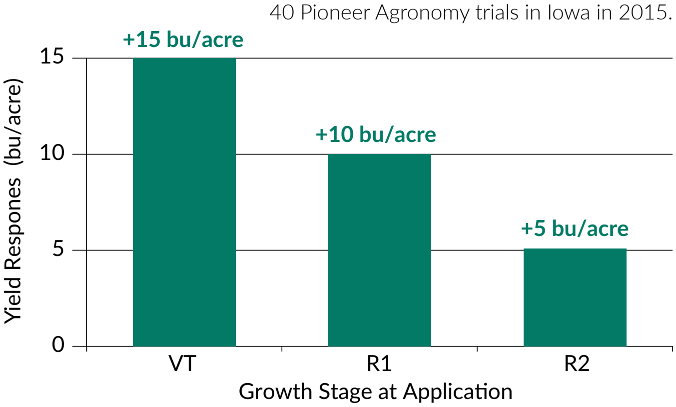

Figure 6. Average yield response to fungicide applications at the VT, R1, or R2 growth stages in 40 Pioneer Agronomy trials in Iowa in 2015.

Southern Rust

Pioneer conducted fungicide research trials over two years in the southeastern U.S. at locations where southern rust was the predominant foliar disease.

A replicated research study was conducted near Camilla, GA, in 2014 to assess southern rust infestation and corn yield response of six different Pioneer® brand hybrids with and without foliar fungicide treatment. This study included two different fungicide treatments: a single application at the V8-V10 growth stage, as well as a two-pass program with applications at both the V8-V10 stage and the VT-R1 stage. Averaged across hybrids, there was no yield increase with early fungicide application alone, but yields were increased by an average of 20 bu/acre when the VT-R1 application was included (Figure 7).

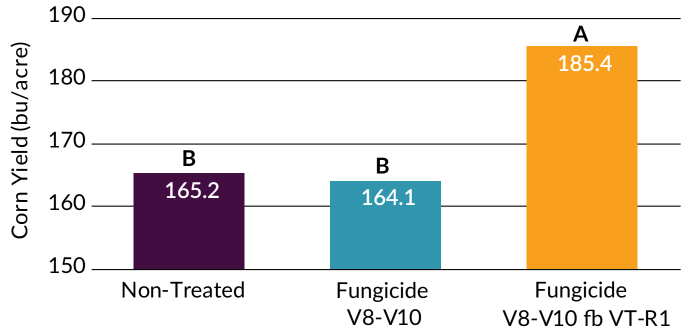

Figure 7. Corn yield as affected by fungicide treatments near Camilla, GA, in 2014.

Means followed by the same letter are not significantly different based on Tukey's HSD test conducted at the alpha=0.05 level. Means averaged over 2 planting dates and 6 hybrids.

A study was conducted the following year across seven locations in five southeastern states to evaluate corn yield response to a single-pass fungicide application at VT-R1 for control of southern rust. Averaged across four hybrids and seven locations, corn treated with fungicide at the VT-R1 stage yielded 11 bu/acre more than non-treated corn (Figure 9).

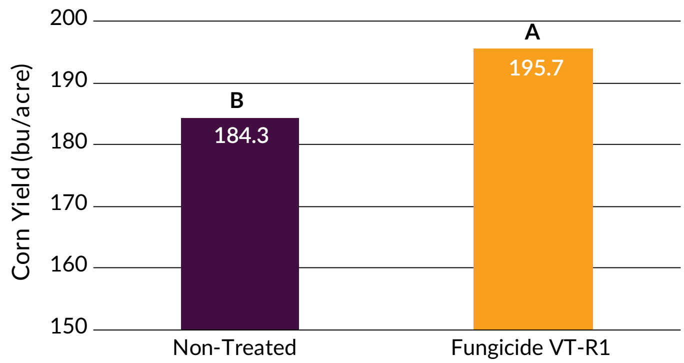

Figure 8. Average yield of corn treated with Aproach Prima fungicide at the VT-R1 corn growth stage and non-treated corn across seven southern research locations in 2015.

Figure 9. Corn treated with fungicide at VT-R1 compared to non-treated corn at a research location near Winchester, AR, in 2015. Southern rust pressure was low at the time of application but increased in severity and ultimately caused premature death in the non-treated check before the end of the season.

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

SUMMARY

- 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 favors cool temperatures (60-70°F, 16-20°C), high relative humidity (>75%), frequent cloudy days, and 7+ hours of dew at night.
- Tar spot can rapidly spread through the corn canopy under favorable conditions, causing premature leaf senescence.
- Commercial corn hybrids vary widely in their susceptibility to tar spot. Hybrid selection should be a primary consideration in managing for tar spot.
- Fungicide treatments have shown some effectiveness in reducing tar spot symptoms; however, application timing can be critical for achieving adequate control and two applications may be needed in some cases.

TAR SPOT: AN EMERGING DISEASE OF CORN

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

TAR SPOT ORIGINS

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

Historically, *P. maydis* was not typically associated with yield loss unless a second pathogen, *Monographella maydis*, was also present, the combination of which is referred to 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* (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 an Illinois field 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), and Nebraska (2021). 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.

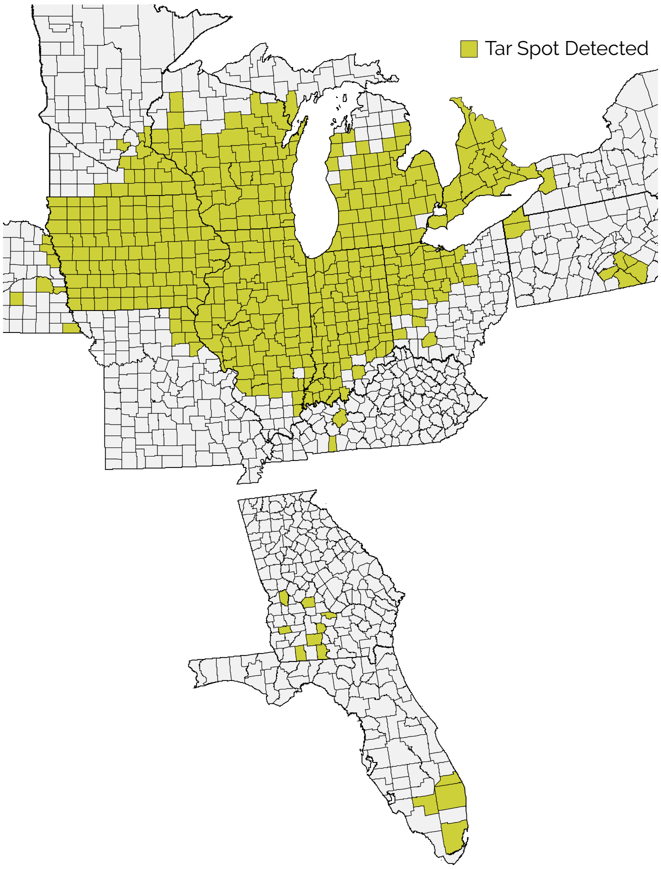

Figure 1. Counties with confirmed or suspected incidences of tar spot, as of October 2021. (Corn ipmPIPE, 2021).

2019 and 2020 Observations

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

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 there was 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.

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

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 (Figures 3 and 4). Tar spot spreads from the lowest leaves to the upper leaves, leaf sheathes, and eventually the husks of the developing ears (Bajet et al., 1994).

Figure 3. A corn leaf with tar spot symptoms.

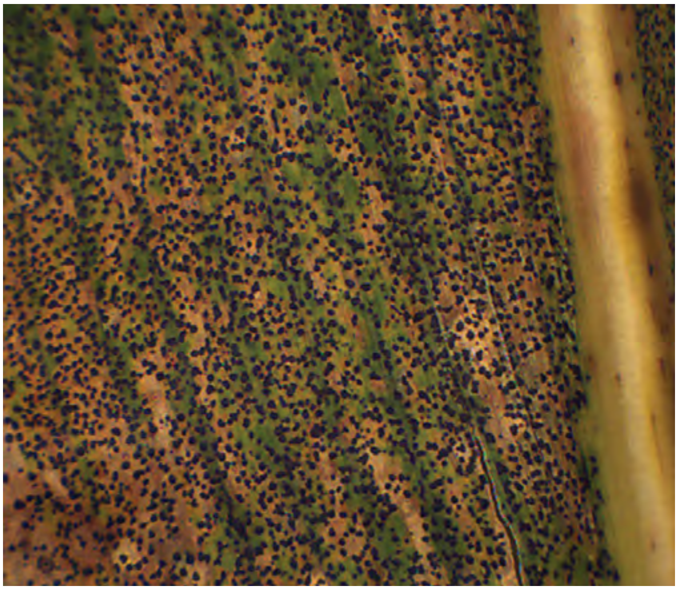

Figure 4. Corn leaf under magnification showing dense coverage with tar spot ascomata

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

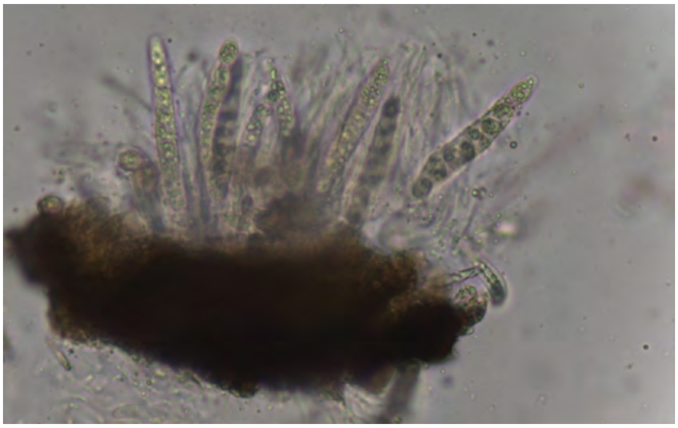

Figure 5. Microscopic view of fungal spores of *P. maydis*.

Tar Spot Look-Alikes

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

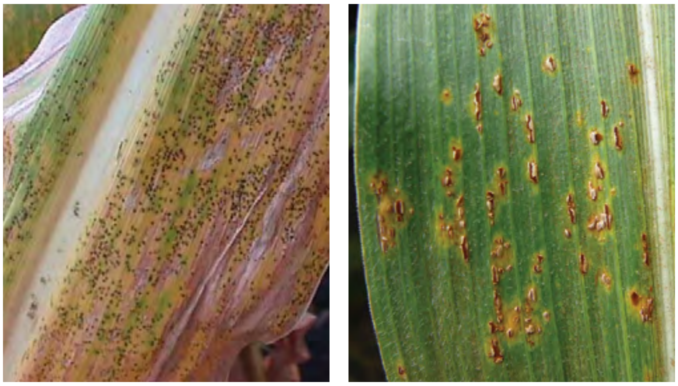

Figure 6a. Southern rust in the teliospore stage late in the season, which can resemble tar spot (left). **Figure 6b.** Corn leaf with common rust spores showing jagged edges around the pustules (right).

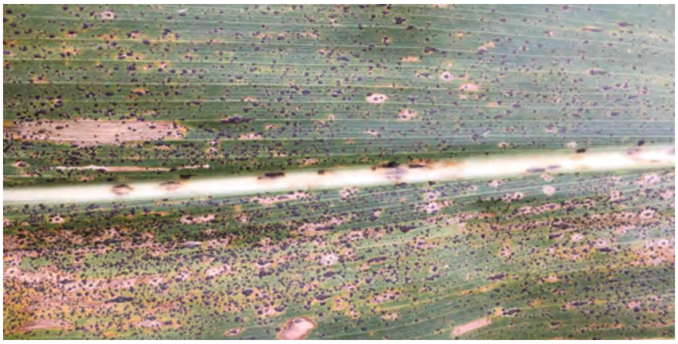

Figure 7. Corn leaf with tar spot symptoms.

TAR SPOT ARRIVAL IN THE U.S.

Numerous reports have speculated that *P. maydis* spores may have been carried to the U.S. via air currents associated with a hurricane in 2015, the same mechanism believed to have brought Asian soybean rust (*Phakopsora pachyrhizi*) to the U.S. several years earlier. However, Mottaleb et al. (2018) believe that this scenario is unlikely and that it is more plausible that spores were brought into the U.S. by movement of people and/or plant material. Ascospores of *P. maydis* are not especially aerodynamic and are not evolved to facilitate spread over extremely long distances by air.

Tar spot was observed in corn in Mexico for over a century prior to its arrival in the U.S., during which time numerous hurricanes occurred that could have carried spores into the U.S. Chalkley (2010) notes that *P. maydis* occurs in cooler areas at higher elevations in Mexico, which coupled with its lack of alternate hosts, would limit its ability to spread across climatic zones dissimilar to its native range. Chalkley also notes the possibility of transporting spores via fresh or dry plant material and that the disease is not known to be seedborne.

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; however, *P. maydis* is the only *Phyllachora* species known to infect corn, and it appears to only infect corn (Chalkley, 2010).

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

MANAGEMENT CONSIDERATIONS

Yield Impact

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

Differences in Hybrid Response

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

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.

1	P0688AM™ (AM,LL,RR2)	12	DKC 55-53 RIB
2	P0075AM™ (AM,LL,RR2)	13	P0720Q™(Q,LL,RR2)
3	DKC 51-40 RIB	14	DKC 55-85 RIB
4	DKC 52-35 RIB	15	P0825AM™ (AM,LL,RR2)
5	P0306Q™(Q,LL,RR2)	16	DKC 56-45 RIB
6	DKC 52-68 RIB	17	P0977AM™ (AM,LL,RR2)
7	P0506AM™ (AM,LL,RR2)	18	DKC 58-34 RIB
8	DKC 53-27 RIB	19	P0963AM™ (AM,LL,RR2)
9	P0574AM™ (AM,LL,RR2)	20	DKC 59-82 RIB
10	DKC 54-64 RIB	21	P1077AM™ (AM,LL,RR2)
11	P0688AM™ (AM,LL,RR2)		

Figure 8. Pioneer on-farm trial in Ottawa County, Michigan, with high tar spot pressure showing differences in canopy staygreen among hybrids (September 27, 2019).

Figure 9. Field with severe tar spot infection and extensive stalk lodging in Wisconsin in 2018. *Photo: Scott Rowntree, Pioneer Field Agronomist.*

Fungicide Treatments

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

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

A 2019 Purdue University study compared single-pass and two-pass treatments for tar spot control using Aproach® (picoxystrobin) and Aproach® Prima (picoxystrobin + cyproconazole) fungicides under moderate to high tar spot severity (Da Silva et al., 2019). Fungicide treatments were applied at the VT (August 8) and R2 stage (August 22), and disease symptoms were assessed on September 30. Results showed that all treatments significantly reduced tar spot symptoms relative to the non-treated 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).

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

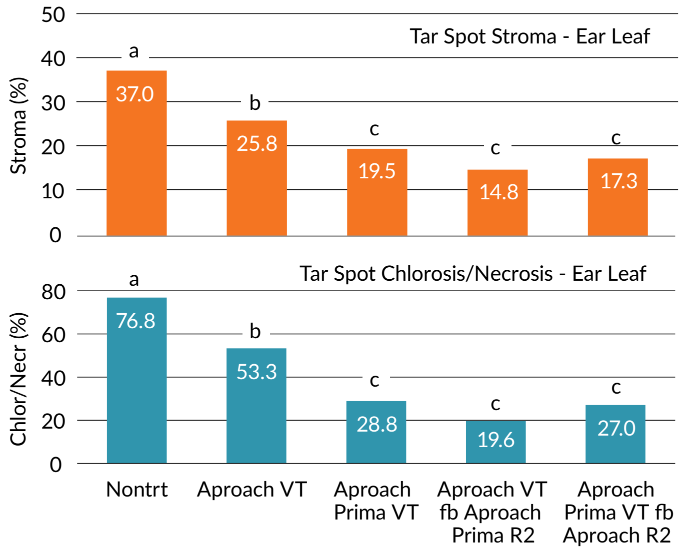

Figure 10. Fungicide treatment effects on tar spot symptoms in a 2019 Purdue University study. Visually assessed tar spot stroma and chlorosis/necrosis (0-100%) on the ear leaf.

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

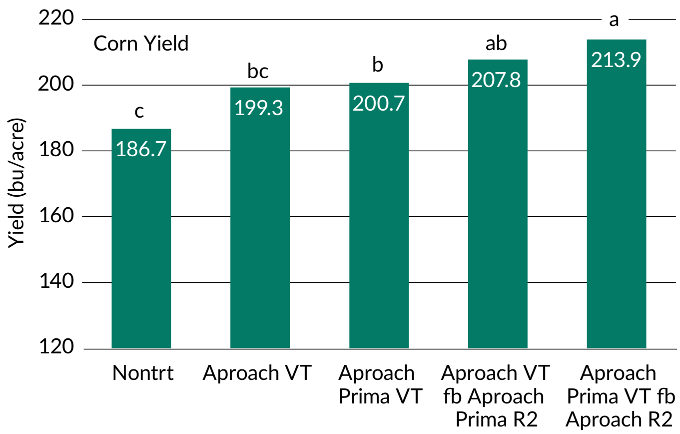

Figure 11. Fungicide treatment effects on corn yield in a 2019 Purdue University study.

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

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

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

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

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

G = good, VG = very good

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

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. Observations so far suggest that rotation and tillage probably have little effect on tar spot severity.

Duration of leaf surface wetness appears to be a key factor in the development and spread of tar spot. Farmers with irrigated corn in areas affected by tar spot have experimented with irrigating at night to reduce the duration of leaf wetness, 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 suggests a correlation between high nitrogen application rates and tar spot severity (Kleczewski et al., 2019).

Mycotoxins

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

HOW FAR WILL TAR SPOT SPREAD?

Mottaleb et al. (2018) used climate modeling based on long-term temperature and rainfall data to predict areas at risk of tar spot infection based on the similarity of climate to the current area of infestation. Model forecasts indicated the areas beyond the then-current range of infestation at highest risk for spread of tar spot were central Iowa and northwest Ohio. Observations in recent growing seasons have been consistent with model predictions, with further spread of tar spot to the east in Ohio, Ontario, and Pennsylvania and a dramatic expansion of tar spot across Iowa and into parts of Minnesota and Missouri. Results indicated the potential for further expansion to the north and south but primarily to the east and west, including corn production areas of New York, Pennsylvania, Ohio, Missouri, Nebraska, South Dakota, eastern Kansas, and southern Minnesota.

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CORN YIELD RESPONSE TO FUNGICIDES

IN EASTERN ONTARIO

Paul Hermans,
Pioneer Area Agronomist

Chris Olbach,
Pioneer Area Agronomist

KEY FINDINGS:

- Corn yield response to foliar fungicide treatment in Eastern Ontario was low in 2020, averaging only a 2.36 bu/acre increase.
- Yield response was affected by summer rainfall – locations that had greater amounts of rainfall in July had a higher yield response to fungicide, presumably due to more favorable conditions for disease development.

STUDY DESCRIPTION

- On-farm trials were conducted at 16 locations in eastern Ontario in 2020 comparing corn yields with and without a foliar fungicide treatment.
- Each location included between 4 and 8 Pioneer® brand corn products ranging in maturity from 84 to 100 comparative relative maturity (CRM).

RESULTS

- The average yield response to foliar fungicide treatment across all hybrids and locations was a 2.36 bu/acre increase (Figure 1).
- Precipitation in July appeared to be an important factor affecting yield response to fungicide treatment.
- Locations that had more than 60 mm of rainfall in July averaged a 5.9 bu/acre yield increase, while locations with less than 60 mm of rainfall averaged only 0.7 bu/acre (Figure 2).
- Similar results have been observed in other Pioneer on-farm studies, in which corn yield response to foliar fungicides is low when conditions are dry during and after pollination.
- Yield response to fungicide often varied widely among hybrids at a location, but no consistent differences across locations were observed. Among seven hybrids planted at eight or more of the locations, there were no significant differences in fungicide yield response.

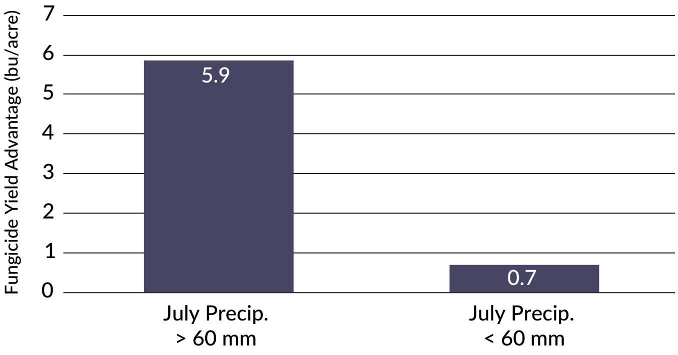

Figure 2. July precipitation effect on corn yield response to fungicide.

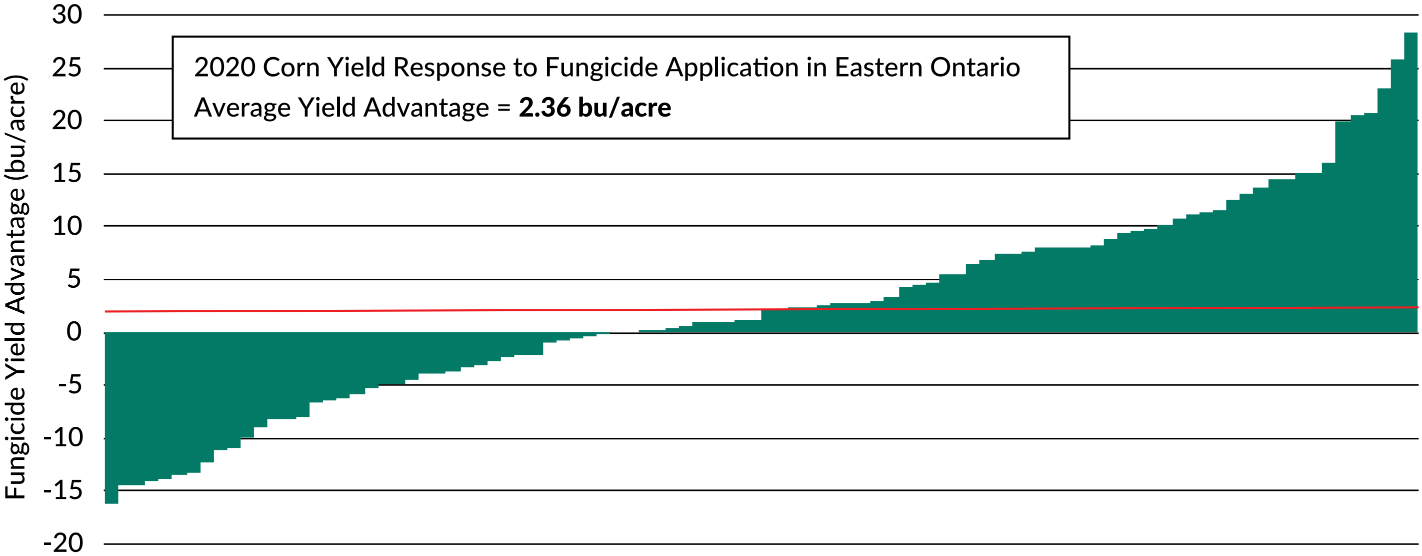

Figure 1. Corn yield response to foliar fungicide in eastern Ontario in 2020. All paired comparisons across 16 on-farm trial locations are shown.

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CORN NEMATODES:

SYMPTOMS, DAMAGE, AND CONTROL

Mark Jeschke, Ph.D.,
Agronomy Manager

KEY POINTS:

- Nematodes may be overlooked as a pest in corn due to their small size and non-distinctive damage symptoms, but they can cause yield loss by damaging corn roots.
- Many different nematode species can cause yield loss in corn. Damage in a field can be caused by a single species or by several species.
- Lumialza™ nematicide seed treatment is a biological treatment available with Pioneer® brand corn products with activity against all major corn nematode species.

NEMATODES: AN OVERLOOKED PEST OF CORN

- More than 50 species of nematodes are known to feed on corn in the U.S., several of which can cause economic damage.
- Corn nematodes are commonly thought of as a pest specific to sandy soils, such as in Kansas and Nebraska, and the coastal plains of North and South Carolina. While this is true of some species, other species can exist in a range of soil conditions.
- Nematodes normally do not kill plants but act as parasites on the host plant.

ARE NEMATODES BECOMING MORE COMMON?

- Recent trends in farming practices may be increasing nematode numbers as well as their economic impact in corn.
  - Reduced tillage is known to favor some nematode species, as is corn following corn.
  - Reduced use of carbamate and organophosphate insecticides for rootworm control has likely caused an increase in nematode populations. These insecticides have activity against nematodes, whereas newer alternatives, such as pyrethroid insecticides and CRW Bt corn, do not.
- Our ability to sample and diagnose nematode damage has also improved. Symptoms that may have once been attributed to other factors are now correctly being traced to nematodes.

CROP DAMAGE

- Plant parasitic nematodes are typically soil-borne and feed on plant roots. Nematodes use a stylet to pierce the corn root and extract nutrients.
- Tissue damage at the feeding site can provide easy entry into the root system for commonly associated root pathogens.
- Nematode damage can occur throughout the growing season; however, corn is most vulnerable during early-season crop establishment.

VISUAL SYMPTOMS IN CORN

- Visual symptoms usually show up as "hot spots" in the field.
- Plants may appear to be moisture-stressed, stunted and chlorotic, or exhibit less-extreme signs of poor plant growth.
- Symptoms are often mistaken for another problem, such as low fertility, soil compaction, weather stress, or insect damage.
- No specific patterns are usually identifiable with nematode damage, although as the problem grows, it often moves in the direction of field tillage.
- Root pruning is usually evident, as well as proliferation of fibrous roots, thickening or swelling of the smaller roots, and mild to severe discoloration.
- Soil may stick to the roots due to the oozing of damaged cells.

Figure 1. A lesion nematode, one of the more ubiquitous nematode pests of corn (left). Severe feeding damage from lance nematodes (right).

PRIMARY CORN NEMATODE SPECIES

- There are many species of nematodes with different biological characteristics that are capable of reducing corn yield. Different soil environments will favor different nematode species.
- It is difficult to establish widely applicable economic thresholds for nematode populations given their tendency for patchy distribution and other stress factors that can influence yield.

- Scientists at Corteva Agriscience have developed high population indicators for corn nematode species as a relative measure of low, medium, or high population levels (Table 1).
- The foundation of these indicators is university and nematologist thresholds plus yield results from Corteva research trials. The purpose of the high population indicator is to simplify characterization of nematode population levels while taking into account varying thresholds across states.

MANAGING CORN NEMATODES

- Sampling conducted by Pioneer agronomists across hundreds of locations has shown that potentially damaging levels of corn nematode populations are prevalent throughout corn production areas in the U.S. (Gumz, 2020).
- If damaging levels of corn nematodes are found, implementing control measures, such as rotation, sanitation, or use of nematicide seed treatments, should be considered.
- Nematode species vary in their host range, so rotation can be effective for reducing populations of some, but not all, corn nematode species.
- Pioneer® brand corn products are available with a seed treatment option for nematode control:
  - » Lumialza™ nematicide seed treatment is a biological product that contains the active ingredient *Bacillus amyloliquefaciens* – Strain PTA-4838 and has activity against all primary corn nematode species.
  - » National trials have shown yield improvements of 3.7 bu/acre under low pressure and up to 9 bu/acre in high pressure fields.[3]
  - » Research has shown that nematode protection lasts for more than 80 days in the upper, middle, and lower root zones.

Table 1. Corn nematodes of economic importance in North American corn production.

Common Name	Genus	Damage Rating	Prevalence	Soil Type	High Population Indicator	Notes
Sting	*Belonolaimus*	Very damaging	Occasional in Corn Belt, common in coastal and plains states	Sandy	1 per 100 cm^3 of soil	Ectoparasitic. Severe stunting and chlorosis. Small, coarse, devitalized root system. Wide host range.
Needle	*Longidorus*	Very damaging	Occasional	Sand and loamy sand. Occasionally in finer soils	1 per 100 cm^3 of soil	Ectoparasitic. Causes stubby roots and can kill corn plants. Rotation can help reduce populations.
Lance	*Hoplolaimus*	Moderate	Occasional	Many types; varies by species	50 per 100 cm^3 of soil	Endoparasitic. Reduces root system. Darkened and discolored roots. Moderate stunting and chlorosis.
Stubby-root	*Paratrichodorus*	Moderate	Common	Many types	50 per 100 cm^3 of soil	Ectoparasitic. Severe stunting and chlorosis. Stubby lateral roots. Wide host range.
Root-knot	*Meloidogyne*	Damaging with high populations	Common	Many types; worse with sandy soils	50 per 100 cm^3 of soil	Sedentary endoparasitic. Form galls on the roots. Affected plants appear stunted and water or nutrient deficient.
Dagger	*Xiphinema*	Moderate	Occasional	All types; worse with sandy soils	100 per 100 cm^3 of soil	Ectoparasitic. Kill root tips. Sensitive to tillage. Severe stunting and chlorosis.
Lesion	*Pratylenchus*	Moderate	Very common	All types	150 per 100 cm^3 of soil	Migratory endoparasitic. Most damaging in corn. Cause smaller root systems that are dark and discolored.
Ring	*Criconemoides*	Low	Common	Sandy	200 per 100 cm^3 of soil	Sedentary ectoparasitic.
Stunt	*Tylenchorhynchus*	Low	Common	More common in heavier soils	300 per 100 cm^3 of soil	Ectoparasitic. Moderate stunting and chlorosis. Reduced root system.
Spiral	*Helicotylenchus*	Low	Common	More common in heavier soils	500 per 100 cm^3 of soil	Ectoparasitic. Mild stunting. Smaller than normal root system. Root decay.
Pin	*Gracilacus, Paratylenchus*	Low	Occasional	Fine-textured soils		Sedentary ectoparasitic. May contribute to yield loss in conjunction with other nematode species.
Sheath	*Hemicycliophora*	Low	Rare			Sedentary ectoparasitic.

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Samantha Teten,
Pioneer Agronomy Intern

BACTERIAL LEAF STREAK OF CORN

DISEASE FACTS

- Caused by the bacterium *Xanthomonas vasicola* pv. *vasculorum*
- First detected in North America in 2014 in a Nebraska corn field.
- Currently confirmed in 11 states: Nebraska, Colorado, Illinois, Iowa, Kansas, Minnesota, Missouri, South Dakota, Oklahoma, Texas, and Wisconsin.
- Can be found in field corn, seed corn, popcorn, and sweet corn.
- Plant does not have to be injured for disease to enter the plant. Bacterium can enter through stomatal openings.
- Bacterial inoculum overwinters on plant residue and causes symptoms on several host plants.
- Many diseases look similar to bacterial leaf streak, so it is recommended to confirm disease through a diagnostic laboratory.
- A different but closely related pathogen affects sorghum; *Xanthomonas vasicola* pv. *holcicola*.

GLOBAL DISTRIBUTION AND SPREAD

- Bacterial leaf streak of corn was first detected in 1948 in South Africa.
- The first confirmed case in the United States was in Nebraska in 2014; although, there is evidence it may have been present as early as 2010.
- Bacterial leaf streak has also been confirmed in Argentina (2017) and Brazil (2018).
- It is not known how the pathogen was spread to North and South America.

DISEASE CYCLE

- *X. vasicola* pv. *vasculorum* appears to overwinter in infected crop residue from the previous growing season.
- Bacteria move from residue onto living plant tissue via rain splash. Bacteria can enter the plant through stomata or wounds.
- Symptoms often appear on the bottom leaves of a plant and spread upward.
- Spread of secondary infection upward through the canopy, from plant to plant, and into adjacent fields is facilitated by overhead irrigation or wind-driven rain.

SYMPTOMS AND IMPACT ON CROP

Symptoms

- Bacterial leaf streak produces narrow tan, yellow, brown, or orange lesions that have a bright-yellow halo when backlit.
- Lesions can extend to several inches long and stay in between leaf veins (interveinal).
- Edges of the lesions are wavy and have a jagged appearance, which is a key distinguishing feature.
- Lesions can also appear greasy or water-soaked.
- Symptoms have been observed as early as the V4 growth stage in the field.

Impact on Corn Yield

- Preliminary observations suggest that severe infestations can impact corn yield. The extent of yield reduction in these cases and the frequency with which severe infestations capable of reducing yield occur are not well-understood at this point.

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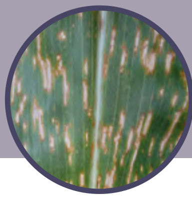
SYMPTOMS OF BACTERIAL LEAF STREAK COMPARED TO OTHER FOLIAR DISEASES

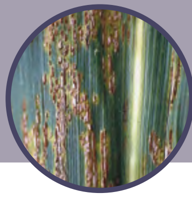
Bacterial Leaf Streak

- Bacterial.
- Long lesions with a wavy edge.
- When backlit, has a translucent appearance with a yellow halo.
- Will exhibit bacterial streaming under a microscope.



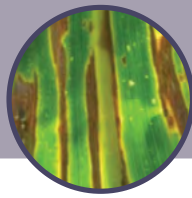
Gray Leaf Spot

- Fungal.
- Rectangular lesions that have very straight sides.
- Light does not shine through easily (more opaque).
- Can have dark, fungal structures, which produce clear spores characteristic of gray leaf spot.



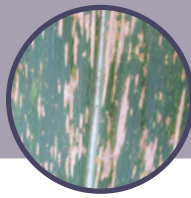
Common Rust

- Fungal.
- Lesions often more oval or circular in shape.
- Appear dark when leaf is backlit.
- Pustules are raised above the leaf surface and are orange to reddish-orange from rust spore production.



Diplodia Leaf Streak

- Fungal.
- Lesions are mostly oval to elongated.
- Lesions may have yellow edges, especially when backlit.
- Often contain black pycnidia (fungal fruiting structures) imbedded in leaf tissue.



Southern Corn Leaf Blight

- Fungal.
- Lesions are rectangular to oblong in shape.
- Appears tan in color.
- Lack of uniformity makes it difficult to identify. Laboratory testing can help differentiate.

Impact on Corn Yield (continued)

- Generally, yield losses appear to be minimal as long as extensive symptoms are not present before or during grain fill.
- The presence of other foliar diseases, such as gray leaf spot, in combination with bacterial leaf streak can result in more yield loss due to greater leaf area loss. Fungicides do not control bacterial leaf steak, but can help protect yield by managing accompanying fungal diseases.

FACTORS FAVORING BACTERIAL LEAF STREAK

Weather

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

Management Systems

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

DISEASE MANAGEMENT

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

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

- Crops: Corn, oats, rice
- Weeds: Johnsongrass, yellow nutsedge
- Prairie grasses: Orchard grass, Indiangrass, big bluestem, little bluestem, green foxtail, bristly foxtail

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Mark Jeschke, Ph.D.,
Agronomy Manager

CORN ROOTWORM BIOLOGY AND MANAGEMENT

SUMMARY

- The western and northern corn rootworm are the two most damaging rootworm species in corn in the Midwestern U.S. and in Canada.
- Both species have a history of adapting to and overcoming control practices, which has increased the complexity and difficulty of effective management.
- No single tactic can be relied upon to provide complete protection against corn rootworm, however crop rotation and Bt traits are still effective when used as part of an integrated management strategy.
- Environmental factors over the course of the corn rootworm life cycle can have a large effect on population levels. Like many other insect pests, it's not unusual for populations to be higher in some years compared to others.
- Understanding the different phases of the corn rootworm life cycle and environmental factors that can influence population density can be useful in developing management strategies.
- Scouting for larval activity early in the season and monitoring beetle densities later in the summer can be helpful in tracking corn rootworm population levels and allow management practices to be tailored accordingly.

Western Corn Rootworm

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

Northern Corn Rootworm

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

Southern Corn Rootworm

Also known as the spotted cucumber beetle. Has a black head, green pronotum, and 12 black spots on the yellowish-green wing covers.

Mexican Corn Rootworm

Legs are dark colored. Wing covers are often a mixture of yellow, green, and light blue, and lack distinctive stripes.

Figure 1. Rootworm species that can affect corn in North America.

INTRODUCTION

Corn rootworm has long been one of the most damaging insect pests of corn in North America. Both larvae and adults feed on corn plants and both are capable of causing economic levels of yield loss. Combined costs of corn rootworm control and lost yield from corn rootworm damage have historically been estimated to exceed $1 billion annually in the U.S.

Corn rootworms also have a history of adapting to and overcoming control tactics, which has increased the complexity and difficulty of successfully managing these pests, particularly in continuous corn production. Crop rotation, insecticides, and Bt traits have all been relied upon to manage corn rootworm at various points over the past several decades and have all proven susceptible to the evolution of resistant populations.

CORN ROOTWORM SPECIES

Corn rootworms belong to the insect order Coleoptera, a massive order comprised of around 400,000 species. The genus *Diabrotica* consists of more than 350 different species worldwide, including the four rootworm species that affect corn in North America (Figure 1). The western corn rootworm (*Diabrotica virgifera virgifera*) and northern corn rootworm (*D. barberi*) are the two most damaging species to corn in the Midwestern U.S. and in Canada (Figure 2). Both species can be found throughout much of the Corn Belt, often coexisting in the same fields (Figure 2). Mexican corn rootworm (*D. virgifera zeae*) is a pest of local importance in Oklahoma and Texas, and southern corn rootworm (*D. undecimpunctata howardi*) is found throughout the U.S., but rarely causes economic levels of damage.

Figure 2. Western (left) and northern (right) corn rootworm are the two most economically important *Diabrotica* species in North America and coexist throughout the Corn Belt. Northern and western corn rootworm adults will feed on the same corn ears but may attempt to bite each other when they are in close proximity.

ADAPTATION TO MANAGEMENT

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. Resistance to several classes of insecticides has been documented in populations of western corn rootworm, both to soil applications for larva control and foliar applications for adult control. Crop rotation was historically an effective and widely used management strategy; however, both species have developed adaptations that have challenged the effectiveness of soybean crop rotation in many areas.

Crop Rotation

A population of western corn rootworm, dubbed the "rotation-adapted variant," developed the ability to defeat two-year corn-soybean crop rotations by laying its eggs in soybean fields rather than corn fields. Larvae hatch the following spring into the corn year of the rotation, allowing their survival. First discovered in eastern Illinois in 1987, this population quickly spread to Indiana, and eventually moved across the entire state to Ohio and Michigan counties (Figure 3). It also moved north and west in Illinois (Cook, et al., 2005), and can now be found in southern Wisconsin and eastern Iowa as well (Dunbar and Gassmann 2013, Prasifka et al., 2006).

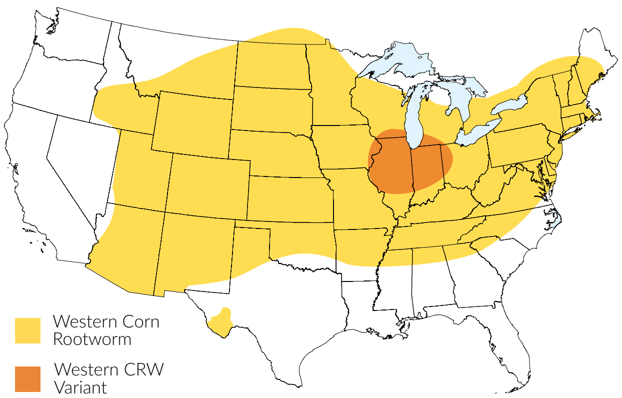

Figure 3. Approximate distribution of western corn rootworm and rotation adapted variant populations.

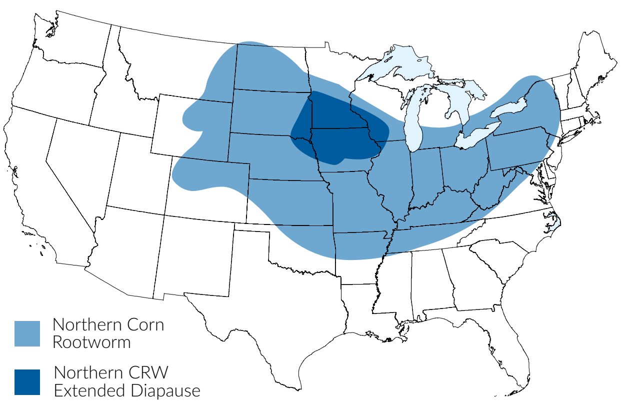

Figure 4. Approximate distribution of northern corn rootworm and extended diapause populations.

Northern corn rootworm populations defeated rotation by a different adaptive mechanism – extended diapause. Diapause is a winter dormancy stage of rootworm eggs. Eggs exhibiting extended diapause remain viable in the soil for two or more years before hatching, allowing the insect population to survive until corn returns to the rotation. Instances of northern corn rootworm damage to corn grown in rotation with other crops was noted as far back as the 1930s, and research in the 1980s determined that extended diapause was the mechanism by which populations were able to survive and cause damage in rotated corn (Krysan et al., 1984). Rotation-resistant northern corn rootworms can now be found throughout much of the northern Corn Belt (Figure 4). Extended diapause can last up to four years and has shown adaptability to rotation patterns over time; i.e., fields with corn every other year have a relatively high percentage of eggs that hatch in the second year, and fields with corn every third year tend to have more eggs that hatch the third year, etc. (Levine et al. 1992).

INSECTICIDES

Cyclodiene insecticides were commonly used as soil treatments for the control of western and northern corn rootworms during the mid-20th Century. Populations of western corn rootworm resistant to this class of insecticides began to show up in the late 1950s and early 1960s (Ball and Weekman, 1962). After the failure of cyclodienes, organophosphate and carbamate insecticides became the predominant rootworm insecticides throughout the Corn Belt during the 1970s. Resistance to carbaryl and methyl parathion was confirmed during the 1990s. Resistance to organophosphate and carbamate active ingredients has been documented in both adults and larvae, indicating that the metabolic mechanisms conferring resistance are present in all stages of life. In the 21st Century, pyrethroids became the primary insecticide class for corn rootworm control. Low-level resistance of a western corn rootworm population to pyrethroid insecticides was documented in 2019 (Souza et al., 2019).

Bt Traits

Bt corn hybrids have been engineered to express genes isolated from the common soil bacterium *Bacillus thuringiensis*. The insecticidal properties of Bt were first recognized in 1901, and the use of Bt formulations as insecticides, which began in 1920 has continued to the present. Bt corn hybrids for European corn borer control were first commercially grown in the U.S. in 1996 and Bt hybrids designed to protect against corn rootworm larval feeding were introduced in 2003.

The potential for insect pest populations to become resistant to Bt was recognized before Bt corn entered the market, with the first instance reported in 1985 (McGaughey 1985). To reduce the probability of insects developing resistance to Bt corn, the Environmental Protection Agency (EPA) mandated certain provisions on the use of Bt corn products. One of the most important EPA requirements was that growers implement an IRM (insect resistance management) program, which includes planting a non-Bt insect refuge. The goal of a refuge is to ensure that susceptible insects are available in sufficient numbers to mate with any rare resistant survivors from Bt fields. Susceptible × resistant matings dilute resistance in the population and reduce the probability of building up resistant insect populations. This approach is most effective when the Bt trait delivers a "high-dose" of the Bt protein against the target pest, and the resistance gene in the pest population is inherited recessively.

The first case of field-evolved resistance of a corn rootworm population to a Bt trait was reported in 2011, when several fields in Iowa planted to hybrids expressing the Cry3Bb1 Bt protein experienced severe root injury from western corn rootworm larvae in fields (Gassmann et al., 2011). Cross resistance of these populations to the mCry3A Bt protein was documented in 2014 (Gassmann et al., 2014) and eCry3.1Ab Bt protein in 2016 (Zukoff et al., 2016). Reduced efficacy of the Cry 34/35Ab1 Bt protein for control of western corn rootworm was documented in Minnesota and Iowa beginning in 2013 Ludwick et al., 2017; Gassmann et al., 2016).

LIFE CYCLE

Western and northern corn rootworms complete one generation per year. Populations overwinter as eggs in the soil. Larvae hatch in the spring and go through three instars in the soil before they pupate and emerge as adults in mid-summer. After mating, females deposit eggs in the soil near the base of cornstalks where they will remain through the winter and hatch the following season.

Overwintering

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 suspended state until diapause ends. The duration of diapause is genetically determined, hence the term *obligate* diapause, and not impacted by environmental conditions. Duration of diapause can vary widely across populations and among individuals within a population (Branson, 1976; Krysan, 1982).

Selection pressure imposed on corn rootworm populations will tend to select for individuals with a diapause duration that gives them the best chance for survival by timing hatch to correspond with food availability. This has been the case with extended diapause populations of northern corn rootworm, in which repeated use of crop rotation as a means of control selected for individuals with a longer diapause period that would allow eggs to hatch when the field was rotated back to corn.

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.

Egg Hatch

The length of time between the end of facultative quiescence and egg hatch can vary based on soil temperature. In general, higher 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. 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.

Figure 5. Corn rootworm larvae

Larvae

Newly hatched larvae are less than ⅛ 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. Corn rootworm larvae molt twice, with the molts separating the first and second instars, and second and third instars. Third instars are approximately ⅝ inch (16 mm) long and creamy white with a brown head and a brown plate on top of the last abdominal segment. At a constant temperature of 70°F (21°C), western corm 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 CO_2 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. 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. In cases where high feeding pressure creates intense competition among larvae for food, larvae may leave the plant on which they initially started feeding in search of another food source. 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. The pupa stage lasts around 10 to 12 days as the larva transforms into an adult. Pupation success can be significantly reduced if soil is heavily saturated. Additionally, pupation success is reduced in soil types high in sand content, as larvae cannot successfully create a pupal chamber. Corn rootworm pupa are creamy white and partially translucent (Figure 6).

Figure 6. The corn rootworm larva makes an oval chamber in the soil, then it transforms into a pupa before later emerging as an adult.

Adults

Adult rootworm emergence begins in late July and may extend over several weeks. Typically, western corn rootworms emerge slightly ahead of northern corn rootworms, and males emerge slightly before females. Peak emergence in much of the Corn Belt will occur from the last week of July through mid-August. However, adult occurrence, feeding, and egg-laying in corn fields typically persist into September.

Females are sexually mature when they emerge and typically mate within a couple days of emergence. After mating, females will continue to feed in the field where they initially emerged for up to a week. Females have a pre-ovipositional period of about 14 days where they must feed to develop their eggs. Females tend to lay most of their eggs in their field of emergence. After a few days of feeding, mated female beetles may disperse to other fields where they will resume feeding. The likelihood and distance of dispersal from the home field can be influenced by larval density. Females emerging from fields with high larval density are more likely to disperse and tend to travel farther than females in fields with low larval density (Yu et al., 2019). Northern corn rootworm adults are less likely to engage in long-range dispersal compared to western corn rootworms. Northern corn rootworm adults will frequently leave the cornfield to forage on flowering weeds and grasses but return to cornfields for oviposition.

Corn rootworm adults are strongly attracted to silking corn plants. Since corn plants in a field will not all silk at exactly the same time, the distribution of adults can shift around as they cluster on plants that are silking at a given time. This same phenomenon can be observed across fields as well, as adults migrate from earlier- to later-silking fields to continue feeding. Adults may also move into first-year corn fields where population levels and competition for food are likely to be lower. High densities of volunteer corn in soybean fields can attract corn rootworm adults, which can lead to rootworm pressure the following year if the field is rotated back into corn.

Figure 7. Northern corn rootworm adults feeding on silks *(left)*. Western corn rootworm adult feeding on leaf tissue (*right*).

Rootworm adults primarily feed on corn silk and pollen. Adults may aggregate on corn ears and chew the silks off below the tip of the husk, thereby inhibiting pollination (Figure 7). Western corn rootworm adults may also feed on the soft epidermal tissue of leaves, especially if the tassel and silks have not yet emerged. Leaf feeding is usually minor, appearing sporadically in a field, and is unlikely to impact yield. However, extensive leaf feeding can be indicative of a large adult population that may cause problems when pollination begins.

Adults may also feed on other crops and weed species if it's their best available option, particularly after corn pollination has ended. Corn rootworm adults are known to feed on soybean, sorghum, and alfalfa later in the growing season, as well as certain weed species (Figure 8).

The most commonly known and economically important case of corn rootworm adults feeding on an alternate host is that of the "eastern variant" of the western corn rootworm that feed and lay eggs in soybean fields. Eastern variant populations are able to survive on soybean foliage and lay eggs in soybean fields due to evolved changes in gut enzymes and microbiota (Curzi et al., 2012). This adaptation does not allow eastern variant adults to thrive in soybean fields – they are only able to survive on soybean foliage for a few days and will commonly disperse in search of a better food source (Spencer et al., 2021). However, this adaptation extends the window of survival in soybean fields long enough for gravid females to deposit some of their eggs in the field before either departing or dying, establishing a population of corn rootworms in the field to infest corn planted the following season.

Figure 8. Corn rootworm adults will sometimes feed on flowers of other crop and weed species, such as yellow squash *(left)* and thistles *(right)*.

Egg laying

Adult western and northern corn rootworms start laying eggs around two weeks after emergence, which is typically in August. Once egg laying begins, adult females will deposit most of their eggs over the next month in clutches of 50 to 80 eggs. During this time, females will alternate between depositing eggs in the soil and returning to the surface to feed, laying eggs approximately every five days (Hill, 1975). A single western corn rootworm female may deposit more than 1,000 eggs during its life (Branson and Johnson 1973; Hill 1975). Northern corn rootworm females do not produce as many eggs, laying approximately 300 in their lifetime (Naranjo and Sawyer 1987). Egg laying will continue until frost as long as temperatures are about 50°F (10°C).

Figure 9. A western corn rootworm adult female with eggs.

FACTORS INFLUENCING POPULATION LEVELS

Environmental factors over the course of the corn rootworm life cycle can have a large effect on population levels. Like many other insect pests, it's not unusual for populations to be higher in some years than others, and an increase in population compared to the prior year is not necessarily indicative of management failure but may just be a result of favorable conditions. Fluctuations in population density may go unnoticed unless they rise to the level of causing visible crop damage–typically when corn starts lodging during summer rainstorms. Scouting for larval activity early in the season and monitoring beetle densities later in the summer can be helpful in tracking corn rootworm population levels and allow management practices to be tailored accordingly (Figure 10).

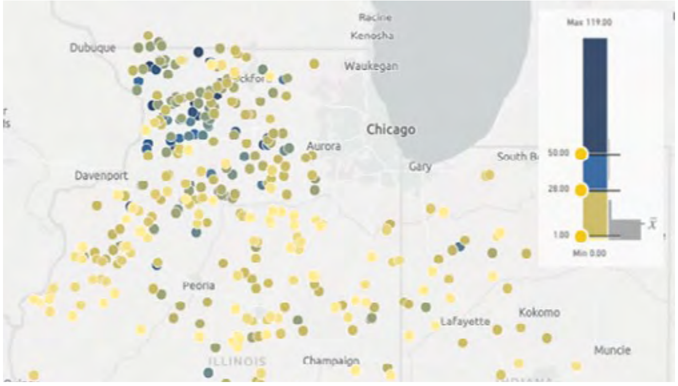

Figure 10. Moderate to high corn rootworm beetle trap counts across many locations in northwestern Illinois in 2020 indicated the potential for high larval feeding pressure in 2021, a forecast that turned out to be accurate.

Overwintering Egg Mortality

The potential corn rootworm population level in a field for a given year is set by the number of eggs that hatch in the spring. The number of eggs deposited in the soil will depend in large part on the density of the corn rootworm adult population the previous year, so high adult populations can be an important warning sign of the potential for high larval feeding pressure the following year. However, environmental conditions during the fall at the time of egg laying and over the winter can have a substantial effect on egg mortality and population levels.

The proportion of corn rootworm eggs that are able to survive over the winter and successfully hatch in the spring is influenced by a number of factors, beginning with the soil condition at the time of egg laying in the fall. Gravid females will seek oviposition sites with optimal moisture conditions, which can be influenced by soil texture and residue cover. Egg laying can be spatially variable due to variation in soil texture and moisture levels throughout a field. Gravid females are not able to burrow in the soil, so they rely on already-existing openings in the soil, such as drought cracks and earthworm burrows, to move down in the soil to find suitable moisture levels. Most egg laying occurs 4-6 inches (10-15 cm) deep in the soil profile but under dry conditions may extend as deep as 8 inches (20 cm) for northern corn rootworm and 12 inches (30 cm) for western corn rootworm.

The depth at which eggs are deposited in the soil profile can affect their ability to survive the winter. Extremely low temperatures and repeated freeze-thaw cycles can cause egg mortality. The deeper eggs are positioned in the soil, the more they will be buffered against fluctuations and extremes in air temperature. Soil texture and moisture can influence temperature buffering as well, as courser and drier soils have lower buffering ability than wetter and finer soils. Snow cover and crop residue can insulate the soil from extreme temperatures, which can result in higher overwinter survival.

All of these factors can produce spatial variation in overwintering survival across a field, as soil moisture, snow cover, and exposure to wind can vary based on soil texture and topography. Differences in overwinter survival mean that areas of a field with the greatest density of eggs during the fall will not necessarily be the areas with the most eggs that hatch in the spring. If larval feeding pressure during the summer appears to be relatively uniform across a field, it is likely indicative of a high level of winter survival that allowed larvae to establish throughout the field.

Figure 11. Snow cover insulates the soil from extreme temperatures, which can increase the survival of corn rootworm eggs overwintering in the soil.

Fall tillage does not appear to have a uniformly positive or negative impact on egg survival (Gray and Tollefson, 1988). Tillage redistributes eggs within the plow layer, which may move some eggs shallower in the soil, where they are less likely to survive, and some eggs deeper, where they are more likely to survive.

Eggs of northern corn rootworm are more cold-tolerant than those of western corn rootworm, which is not surprising given its historically more northerly distribution. However, the continued trend toward higher winter temperatures could allow western corn rootworm to become more dominant in the northern Corn Belt.

Larval Mortality

Just as environmental conditions can have a large impact on the survival of corn rootworm eggs over the winter, conditions during the spring can influence how many larvae are able to establish feeding and survive to adulthood. 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 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 abrasions 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.

Figure 12. Soil saturation after corn rootworm eggs have hatched can dramatically reduce larval survival.

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's 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.

Of all the weather conditions that can affect corn rootworm population levels, flooding after hatch likely has the greatest potential to reduce populations. 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.

Survival to Adult Stage

Somewhat counterintuitively, high corn rootworm larval density can be associated with lower adult populations. Multiple studies have shown that the proportion of the larval population that survives to adulthood can be density dependent, with percent adult emergence declining with higher larval densities (Hibbard et al., 2010). Greater larval density leads to more intense competition for food, reducing survival. Adults that do emerge in fields with high larval density are often smaller, shorter lived, and lay fewer eggs (Branson and Sutter, 1985). The survival rate of northern corn rootworm larvae to adulthood is generally lower than that of western corn rootworm (Onstad et al., 2006).

MANAGEMENT

High corn rootworm populations can make management very challenging. No single tactic can be relied upon to provide complete protection against corn rootworm, however crop rotation, Bt traits, soil insecticides, insecticide seed treatments, and insecticide treatments targeted to adults can all be effective tools for managing corn rootworm populations when used as part of an integrated management strategy.

The first step for effective corn rootworm management is scouting fields to determine beetle population levels. This allows growers to make more informed decisions on tactics necessary to successfully manage corn rootworm the following season. Start scouting when silks appear in the field and continue weekly through grain fill. The fields with the highest likelihood of heavy corn rootworm pressure are continuous corn fields. Be aware that beetles can migrate to late-planted fields, late CRM hybrids, and delayed maturity areas, creating very high localized populations. Rootworm beetles are very attracted to fresh silks and will move and concentrate in fields where fresh silks are present. Timely treating of gravid or pregnant females can be very effective in reducing egg-laying and subsequent problems.

Rotation to a crop other than corn is still the single most effective way to counter corn rootworm resistance. Rotating out of corn at least one in three years, or on 20% of total acreage annually, can significantly reduce selection pressure and have a positive impact on resistance management. Volunteer corn can serve as a host for corn rootworm beetles in soybeans. Controlling volunteer corn early will reduce this risk as well as competition with the soybean crop. Even in areas where rotation-resistant populations are present, crop rotation will still reduce selection pressure and may provide some benefit in reducing corn rootworm population levels.

CORN ROOTWORM BEST MANAGEMENT PRACTICES

1. **Proactively Lower Corn Rootworm Populations:**
   - Build in a crop rotation every three years
   - Use an adult control program (using appropriate thresholds and timing)
2. **Use of non-Bt corn with a soil-applied insecticide can be very effective (especially if CRW populations are at low to moderate levels).**
3. **In situations with high CRW pressure, consult with a local expert regarding these options in combination with Bt corn:**
   - Use a high-rate insecticidal seed treatment (1,250 rate)
   - Use of a soil-applied insecticide with Bt corn is not recommended for control except in limited circumstances. Consult with your Pioneer agronomist, extension service, crop consultant or other local experts for further guidance.

Dan Berning, Ph.D.,
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CORN ROOTWORM: SCOUTING AND MANAGEMENT STRATEGIES

KEY POINTS

- Corn rootworms can evolve and overcome management tactics. Controlling this pest is difficult.
- An integrated approach is key to an effective corn rootworm management program.
- Develop a scouting program that monitors larvae and adult numbers, which predicts potential egg laying and future problems.
- In areas with high numbers of adult corn rootworms, consider incorporating a beetle suppression program that utilizes foliar-applied insecticides.

CORN ROOTWORM: A CHALLENGING PEST OF CORN

Corn rootworm (CRW) larvae and adults cause economic loss every year. The impact of CRW larvae on yield varies greatly depending on:

1. The timing of rootworm feeding.
2. Available moisture.
3. The hybrid's ability to regenerate damaged roots.

Plants with damaged root systems are more susceptible to drought stress and lodging. Adult CRW feeding on corn silks during pollination can cause poor seed set and subsequent yield loss.

This pest's ability to evolve has made crop rotation ineffective in many areas. The soybean variant, western corn rootworm, has evolved to lay eggs in non-corn fields. The northern corn rootworm has shown extended diapause, in which eggs remain viable in the soil for several years before hatching. Additionally, resistant populations have now been documented for all four commercially-available Bt proteins for CRW control.

Figure 1. Corn rootworm larvae

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HOW TO SCOUT FOR CORN ROOTWORM LARVAE

- Begin in early to mid-June, or when the corn is in the V6 to V12 growth stage.
- Dig up two plants at each of five locations with the soil from six to eight inches around the plant. Sift soil over a sheet of black plastic looking for 1/32- to ½-inch long larvae.
- There is no economic threshold for larvae per plant. Some consultants determine emergency controls are needed when they find an average of two to three larvae per plant using a visual search, or eight or more larvae using soil washing.
- If average length of larvae is >½ inch or pupae are found, a rescue treatment may be too late.

Figure 2. Severe corn rootworm feeding damage.

HOW TO SCOUT FOR ADULT CORN ROOTWORM

- The western corn rootworm (WCRW) and northern corn rootworm (NCRW) are the most destructive species found throughout the Midwestern U.S. and Canada.
- Adults begin emerging in early to mid-July with male beetles emerging before females.
- Evaluate fields for silk clipping. If pollination is in progress and the beetles have chewed back the silks so that less than ½ inch of silks is exposed beyond the husks, beetles should be controlled.

Figure 3. Northern (left) and western (right) corn rootworm beetles.

- To control adults before egg laying, examine 2 plants in 25 locations in the field. Consider an insecticide treatment if the number of beetles averages 0.75 or more per plant and 10% of females are gravid with eggs (abdomen visibly distended with eggs).
  - » The first beetles to emerge are mostly male, and females require at least 10-14 days of feeding before they can lay eggs.
  - » Treatments applied too early may be ineffective if large numbers of females emerge after the residual effectiveness of the treatment has dissipated.
- If more than 10% of the adult females within a field are gravid, significant egg laying probably has already occurred, so suppression of adult rootworms will likely not be as effective in reducing larval damage the next year.
- Fields may become re-infested two to three weeks after an insecticide application, so some fields may require two applications of insecticide to significantly reduce egg laying.

Figure 4. Gravid female western corn rootworm beetle (left). Western corn rootworm eggs squeezed from the abdomen of a female beetle (right).

CORN ROOTWORM MANAGEMENT

- A yearly scouting program is the first step to effective management, because corn rootworms can rebuild their populations rapidly. Monitor larvae and adult beetle numbers to predict potential egg laying and future problems. The level of rootworm feeding and beetle activity will determine the best management options. Incorporate several of these options to effectively control CRW with an integrated approach.

Crop Rotation

- Can reduce corn rootworm pressure.
- Ineffective in areas with soybean variant WCRW that lay eggs in non-corn fields or variant NCRW whose eggs may remain in the soil for several years before hatching (extended diapause).

Suppress Larval Development

- Use a granular or seed-applied insecticide at planting.
- Plant a product with multiple modes of action of control against CRW, such as Optimum® AcreMax® Xtreme or Qrome® products.

- Use a corn product with a higher-rate insecticide seed treatment for additional protection. Pioneer® brand Optimum® AcreMax Xtreme and Qrome® products with the enhanced corn rootworm (CRW) package of seed treatments comes with a higher rate of insecticide active ingredient (Lumisure™ 1250) plus Lumialza™ bio-nematicide. the enhanced CRW Package improves yield potential and standability through improved root protection, demonstrating a three bu/acre yield advantage in CRW-prone areas compared to a seed treatment with a lower insecticide rate.
- Applying a soil-applied insecticide in addition to using a CRW Bt-traited product is not recommended except in limited circumstances. Consult with your Pioneer sales professional, university extension, or other local experts for further guidance.

Control CRW Beetles with Insecticides

- A well-timed foliar insecticide application can effectively reduce gravid egg-laying beetles.

Be sure to alternate modes of action when using insecticides. When using corn hybrids that contain Bt traits for corn rootworm control, it is essential that refuge acre requirements are followed. Failure to comply with refuge requirements and lack of control of adult beetles within the refuge acres will only accelerate the pest's ability to develop resistance.

Areas with high numbers of adult corn rootworms should consider incorporating a beetle suppression program that utilizes foliar-applied insecticides. This should help reduce the amount of egg laying and potential problems in the future.

Table 1. Insecticide treatments for adult corn rootworms. **Always read and follow product label directions.**

Mode of Action	Product Name	Common Name	Rate (Formulation per Acre)	Restrictions / Comments
3A R	Ambush® 2EC	permethrin	6.4-12.8 fl oz	REI 12 hrs. PHI 30 days for grain or fodder.
3A R	Asana® XL 0.66	esfenvalerate	5.8-9.6 fl oz	Field corn. May be chemigated.
3A R	Baythroid® XL	beta-cyfluthrin	1.6-2.8 fl oz	PHI 21 days for grain or fodder. REI 12 hrs.
3A R	Bifenture® 2E, Brigade® 2EC, Discipline® 2E, Sniper® 2E, Tundra® 2EC	bifenthrin*	2.1-6.4 fl oz	
3A	Delta Gold®	deltamethrin	1.5-1.9 fl oz	REI 12 hrs. PHI 21 days for grain or fodder, 12 days for cutting or grazing for forage.
1B	Dimethoate 4EC, Dimate 4E	dimethoate	1.0 pt	REI 48 hrs. PHI for harvest, feeding, or grazing 14 days. Do not apply to corn during pollen-shed if bees are present.
3A R	Hero®	zeta-cypermethrin + bifenthrin	4.0-10.3 fl oz	REI 12 hrs. PHI 30 days for grain and stover, 60 days for forage, 30 days for grazing. Use of ultra-low volume on corn is prohibited. Do not make aerial or ground applications to corn if heavy rainfall is imminent.
1A R	Lannate® LV	methomyl	1-1.5 pt/acre	REI 48 hrs. PHI 21 days for field corn, 0 days for sweet corn.
3A R	Mustang® Maxx EC, Respect®	zeta-cypermethrin	2.72-4.0 oz	Apply in a minimum of 2 gal/acre by air and 10 gal/acre by ground.
3A R	Proaxis™	gamma-cyhalothrin	2.56-3.84 fl oz	REI 24 hrs. PHI 21 days, grazing 1 day, feeding corn forage/fodder/silage 21 days.
1A	Sevin XLR	carbaryl	1-2 qts	Field corn and popcorn. See bee caution on label. May be chemigated.
22A	Steward® EC	indoxacarb	6.0-11.3 fl oz	REI 12 hrs. PHI 14 days for grain and stover.
3A, 4A	Swagger®	bifenthrin + imidacloprid	8.45-25.6 fl oz	PHI 30 days. Apply in a minimum of 2-5 gal/acre by air or 10 gal/acre by ground.
3A R	Warrior II w/Zeon Technology®	lambda-cyhalothrin	1.28-1.92 fl oz	

IRAC Mode of Action Classification:

Group 1 = Acetylcholine esterase inhibitors: 1A = Carbamates, 1B = Organophosphates

Group 3 = Sodium channel modulators: 3A = Pyrethroids, Pyrethrins

Group 4 = Nicotinic acetylcholine receptor (nAChR) competitive modulators: 4A = Neonicotinoids

Group 22 = Voltage-dependent sodium channel blockers: 22A = Oxadiazines

R = Restricted-use product

* Resistance to the pyrethroid insecticide bifenthrin has been documented in corn rootworm in southwest Nebraska.

ESTIMATING CORN ROOTWORM POPULATIONS WITH STICKY TRAPS
IN SOUTHWESTERN ONTARIO

Greg Stopps,
Pioneer Area Agronomist

Rachel MacDonald,
Pioneer Agronomy Intern

KEY FINDINGS:

- 17% of sampled locations had moderate to very high corn rootworm (CRW) levels, 60% had low or very low populations, and 23% had no CRW beetles found.
- Western corn rootworm (WCRW) was the dominant species present in southwestern Ontario, with only 20% of sites trapping any northern corn rootworm (NCRW) beetles.
- Crop rotation affected CRW pressure levels. All locations with moderate to very high CRW pressure were planted to corn following corn.

OBJECTIVES

- Quantify WCRW and NCRW populations across southwestern Ontario (Bruce, Huron, Perth, and parts of adjacent counties) using Pherocon® AM/NB sticky traps.
- Understand how modern management practices influence CRW population levels.
- Identify best management practices for growers to make informed decisions for the following growing seasons.

STUDY DESCRIPTION

Year: 2020

Locations: 30 field locations across Bruce, Huron, Middlesex, Oxford and Perth counties, including:

- 10 continuous corn.
- 10 first year corn in rotation.
- 10 soybean following corn.

Figure 1. A new Pherocon® AM/NB sticky trap set at ear height. Trapping extended for five consecutive weeks, with traps replaced and beetles counted every week.

Corn Rootworm Sampling Methods:

- Three sticky traps per field were placed starting at blister stage (R2).
- NCRW and WCRW beetles were counted every seven days and average counts per trap were recorded.
- Trapping continued for five consecutive weeks.

RESULTS

- CRW populations were characterized at six different levels for each sampling location based on peak average beetles per trap/week:
  - » Zero = no beetles collected.
  - » Very Low = traps averaged <1 beetles/week.
  - » Low = traps averaged 1-10 beetles/week.
  - » Moderate = traps averaged 10-20 beetles/week.
  - » High = traps averaged 20-50 beetles/week.
  - » Very High = traps averaged >50 beetles/week.
- Peak CRW beetle population levels observed at sampled fields across testing period (Figure 2):
  - » 23% of fields had zero beetles collected.
  - » 27% of fields had very low populations.
  - » 33% of fields had low populations.
  - » 7% of fields had moderate populations.
  - » 7% of fields had high populations.
  - » 3% (just one field) had very high populations.

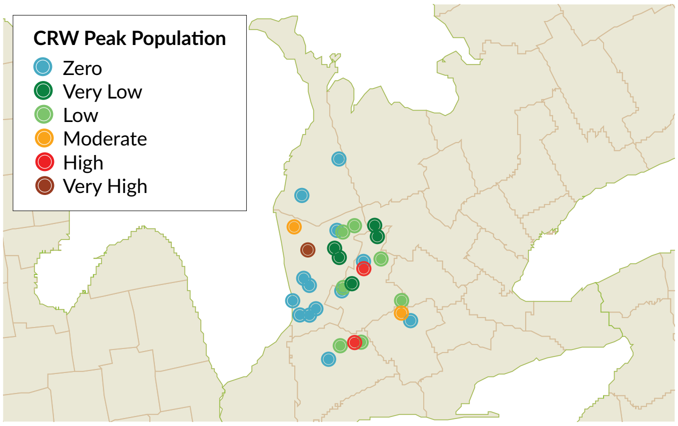

Figure 2. Peak population levels observed at corn rootworm beetle trapping locations in 2020.

RESULTS (CONTINUED)

- Western corn rootworm (WCRW) was the dominant species present in southwestern Ontario with only 20% of sites trapping any northern corn rootworm (NCRW) beetles. Species composition varied at sites where NCRW were found (Figure 3), but still heavily favored the WCRW species.
    - » The single location deemed to have very high pressure trapped zero NCRW over the course of five weeks.
    - » High population locations consisted of 88-98% WCRW beetles captured over the five-week period.
    - » One moderate population location in Oxford county showed a mix of 69% WCRW to 31% NCRW, while the other moderate location trapped zero NCRW beetles.

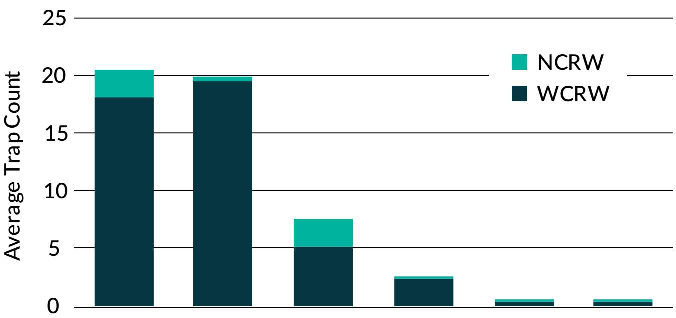

Figure 3. Peak population levels observed at corn rootworm beetle trapping locations in 2020.

- Crop rotation affected CRW pressure levels (Table 1).
    - » 100% of the moderate to very high pressure locations were planted to corn following corn.
    - » All first year corn locations had low, very low, or zero corn rootworm populations.

Table 1. Distribution of pressure levels based on crop rotation.

CRW Pressure	Crop Rotation		
	Continuous Corn	First Year Corn In Rotation	Soybeans Following Corn
Very High	1	0	0
High	2	0	0
Moderate	2	0	0
Low	2	5	3
Very Low	2	2	4
Zero	1	3	3

- CRW populations in all soybean locations were classified as low, very low, or zero.
    - » Of the three soybean locations classified as "low," the location showing the highest trap counts recorded a weekly peak of 1.67 beetles/trap, trapping a total of 13 WCRW (0 NCRW) beetles across 15 traps in 5 weeks.
    - » Only one NCRW beetle was captured across all 10 soybean locations over the 5 week trapping period and all 150 individual traps.

DISCUSSION

- Sampling of CRW populations in 2020 revealed the variable geographic nature of CRW pressure and effects of crop rotation. All locations with moderate to very high pressure were continuous corn locations, lending support for the use of rotation out of corn as a critical management tool to keep CRW populations low. The location with very high pressure was located in the center of a geography that has now been confirmed by the Canadian Corn Pest Coalition to be showing CRW resistance to Bt traits associated with a long-term history of continuous corn.
- Similar investigations into possible CRW Bt resistance observed under continuous corn are underway in other fields across the geography tested here. Continuous corn practices have been shown by university and Pioneer research to increase CRW pressure and can result in the development of resistance to Bt traits. Improved rotational practices are the best way to keep these valuable Bt traits effective going forward.
- Results indicate that WCRW is the predominant species present in southwestern Ontario. NCRW populations were present at some locations but at low rates relative to the WCRW. Discovery of only a single NCRW beetle in soybean fields is likely incidental but worth further investigation given the extended diapause shown by some NCRW populations.

CONSIDERATIONS / ACTION THRESHOLDS

If traps average <20 beetles per week:

- **Low/Moderate** CRW populations are anticipated next year.
- Select a control option for each field:
    - » Rotate acres to another crop.
    - » Plant a corn rootworm Bt corn product. (If a Bt-rootworm product has already been planted three years in a row or you are in a geography where CRW Bt resistance is already confirmed/suspected, rotate out of corn.)
    - » Plant a non-Bt rootworm product with Poncho® 1250/ VOTiVO® insecticide treatment.

If traps average >20 beetles per week:

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

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

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

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

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JAPANESE BEETLE

Chuck Bremer, Ph.D.,
Former Agronomy Manager

PEST FACTS

- Latin name is *Popillia japonica*.
- Native to Japan; found in United States in 1916.
- Most damage is from adult feeding; however, the larval grub also can feed on roots.
- Late-planted fields are at greater risk.
- Japanese beetles are often found in field edges or areas of delayed growth.
- Over 300 hosts: corn, soybean, ornamentals, fruit trees, grapes, weeds.
- One generation per year.

KEY CHARACTERISTICS

- Half inch adults are shiny, metallic green with bronze wing covers, and have six white hair tufts on each side of their abdomen.

Figure 1. Japanese beetle

RELATED/ CONFUSED SPECIES

1. Masked Chafer
   » The Masked Chafer is lighter in color than the Japanese beetle.
2. Green June Beetle
   » The Green June Beetle is twice as large as the Japanese Beetle and does not have the distinctive white hair tufts on the side of the abdomen.
3. False Japanese Beetle/ Sand Chafer
   » The False Japanese Beetle/Sand Chafer is dull in appearance and lacks white hair tufts.

DISTRIBUTION

- Well established east of the Mississippi River, the Japanese beetle is also present in most other corn and soybean growing states.

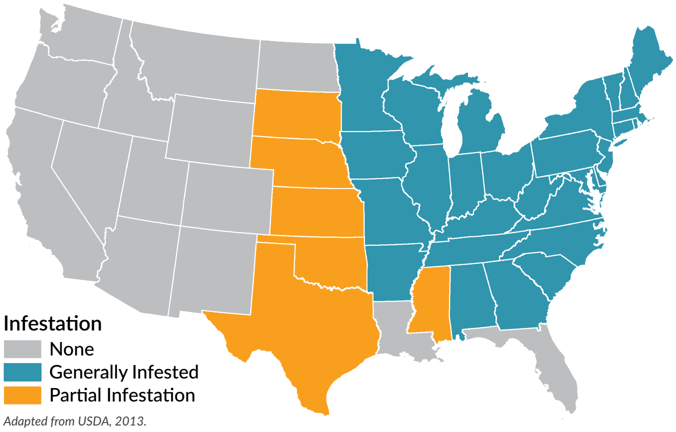


Figure 2. Japanese beetle infestation according to USDA data in 2013.

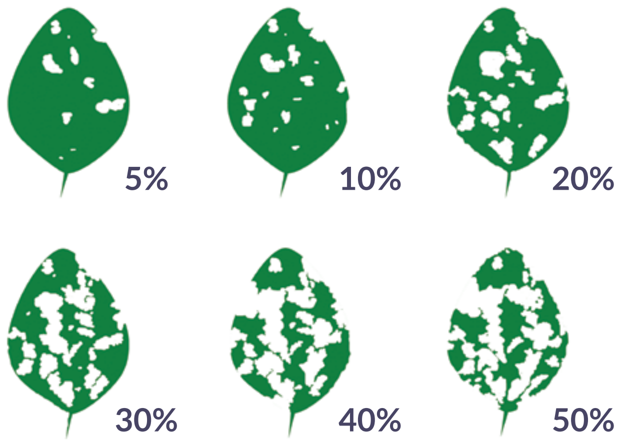
PEST INJURY SYMPTOMS/IMPACT ON CROP

- Clipped corn silks may reduce pollination and yield.
- Skeletonized or lacy leaf patterns between veins are symptoms of either corn or soybean feeding.
- Leaf feeding is typically insignificant in corn.
- Leaf feeding may be more significant in soybeans, causing defoliation prior to pod fill.

ECONOMIC THRESHOLDS

Treatment thresholds for corn insecticides:

- Silks clipped to within ½-inch of the ear tip.
- Less than 50% of plants pollinated.
- Beetles are present and feeding.

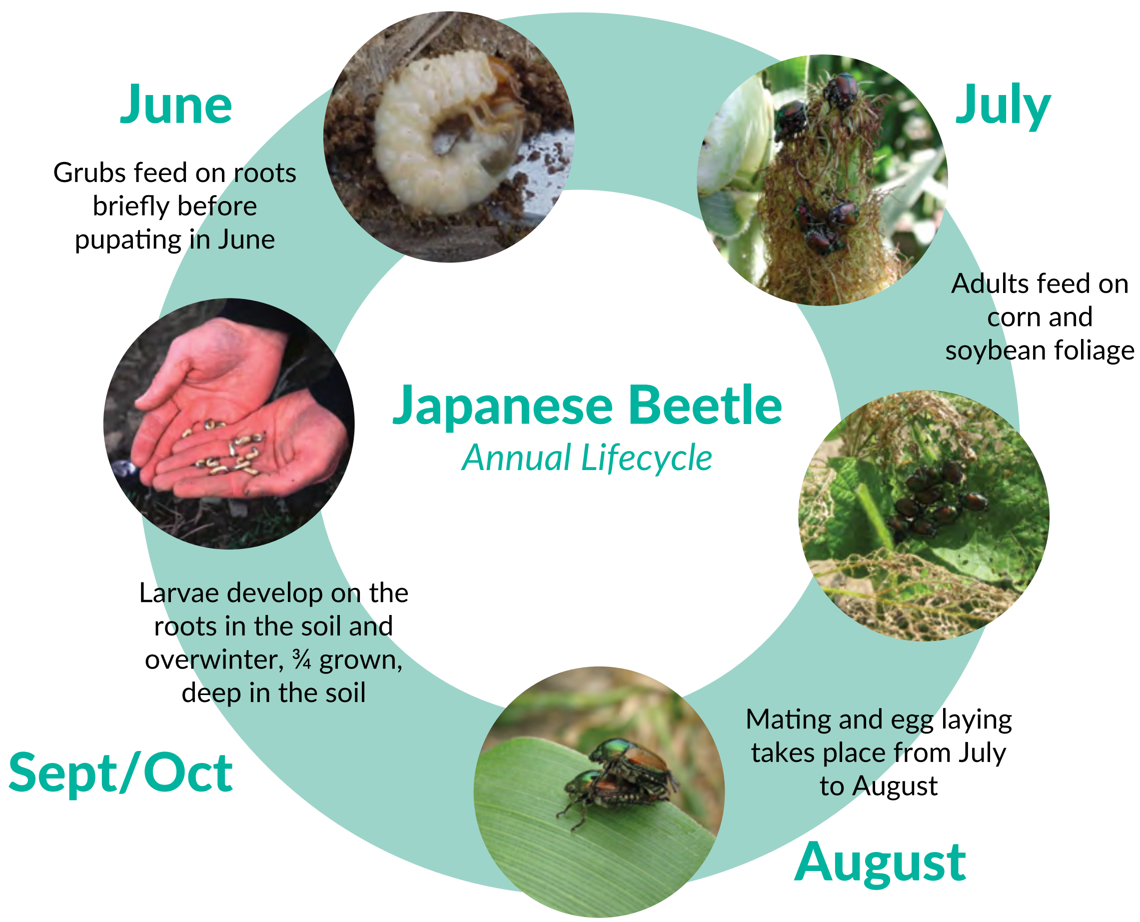


Economic thresholds for soybeans:

- Up to V7 = 40 to 50% defoliation.
- Flowering, pod development, pod fill = 15 to 20% defoliation.
- Pod fill to harvest = greater than 25% defoliation.

MANAGEMENT CONSIDERATIONS

- Favorable conditions
  - Adults prefer lighter soil for egg laying.
  - First entry into an area is usually near transportation, such as railroads or major highways.
- There are no significant natural enemies in the United States.
- IPM Practices
  - No transgenic or native gene resistance is currently available for either soybeans or corn.
  - Trapping is NOT recommended as it has a tendency to attract the beetles.
  - Scouting should begin in corn in July and August and switch to soybeans during August.
  - Use percent pollination and presence of uncut silks as a guide when deciding treatment of corn. Leaf feeding is rarely significant in corn.
  - Use percent defoliation and amount of pod fill remaining to help decide economics of insecticide treatment for soybeans.



Dan Berning, M.S.,
Agronomy Manager

10 TIPS FOR MAKING THE SWITCH TO NO-TILL

- Adoption of conservation cropping practices, such as no-till, continues to increase.
- The development of carbon markets may incentivize farmers to expand the implementation of this farming practice.
- Here are 10 tips to keep in mind for a successful no-till cropping system.

1. PREPARE FOR THE LONG HAUL

- It is difficult to quickly correct the condition of the soil to alleviate drainage issues, compaction, or very low soil fertility once a no-till cropping system is established.
- Consider addressing these issues before implementing no-till.

2. MANAGE CROP RESIDUE AT HARVEST

- The crop residue in a no-till cropping system will protect the soil from erosion, heat, and excessive evaporation of moisture in the seed zone in areas with limited rainfall.
- Spread crop residue behind the combine evenly across the entire harvest width of the combine header.
- This will help ensure uniform seed zone moisture and soil temperature for the succeeding crop.
- It also makes it easier to adjust the planter row units to achieve a uniform stand if all planter units are encountering the same amount of residue.

3. ADJUST SOIL FERTILITY MANAGEMENT

- Consider nutrient and soil fertility options, such as starter fertilizer containing nitrogen and phosphorous, in corn to give seedlings a boost when soil temperatures remain cooler under the crop residue.
- Banding of fertilizer has frequently shown a benefit compared to broadcast applications in no-till.

4. SELECT THE RIGHT HYBRIDS OR VARIETIES

- Consider yield potential and adaptability for the local expected environment.
- Pioneer® brand corn products with higher stress emergence scores establish more consistent, uniform stands, on average, than ones with lower scores. Pioneer brand corn products with highly suitable (HS) and suitable (S) high-residue suitability ratings produced higher and more uniform stands in high-residue locations than hybrids with a poorly suited (X) rating.

- Select for adequate levels of disease tolerance. Previous crop residue can harbor inoculum of diseases, such as gray leaf spot, northern corn leaf blight, Goss's wilt, tar spot, etc.
- Treatment with an insecticide or fungicide during the growing season may be warranted with moderate to high insect or disease pressure.

5. USE A PREMIUM SEED TREATMENT

- Use a premium seed treatment, such as LumiGEN® seed treatments, to control the broad spectrum of seedling-attacking pathogens and insects that may be present during germination and stand establishment of the crop.

6. STEP UP YOUR WEED MANAGEMENT PLAN

- Use a layered weed control plan with multiple modes of action and application timings to reliably control weeds before they begin to compete with the crop.
- Proactively controlling weeds before they emerge or when they are small often achieves better results than attempting to control bigger weeds.

7. PLANT WHEN FIELD CONDITIONS ARE FIT

- A primary objective during field operations should be to minimize compaction.
- Do not perform field operations, including planting, if the field is too wet. Under wet conditions, sidewall smear of the seed slot may occur, preventing good root development.

8. SET THE PLANTER TO MANAGE RESIDUE

- Seed to soil contact is critical for proper germination and uniform seedling emergence.
- Ensure openers are sharp enough to cut the residue. Dull openers will 'hairpin' residue, resulting in poor seed to soil contact.
- If row cleaners are used, set them to brush heavy residue aside. They should not move soil.

9. MAINTAIN UNIFORM PLANTING DEPTH

- Ensure seeds are placed at a uniform depth of two inches.
- This may require a reduction of planter speed if field conditions are rough enough to cause the planter row units to bounce.
- Make sure the planter is running level at planting speeds in the field.
- Down pressure of the row units may need to be increased to cut through the residue, especially when soil conditions are hard or dry. Make sure down pressure is not excessive on wetter soils, which can create compaction under the planter or sidewall compaction of the seed slot. Check this frequently as field conditions may change over the course of the day.

10. ENSURE PROPER SEED SLOT CLOSURE

- Closing attachments on the planter should close and firm the seed trench around the seed, providing good moisture in the seed zone and good seed to soil contact.
- Be sure the top of the seed slot is not the only part of the trench being pinched shut, leaving an air pocket around the seed.
- Be sure dry, loose soil is not falling into the seed slot before closing.

Matt Essick, M.S.,
Agronomy Manager

10 TIPS FOR MAKING THE SWITCH TO STRIP-TILL

- Advances in technology and increased interest in nutrient and conservation management have led to higher interest in strip-till.
- Strip-till disturbs less soil than traditional tillage and allows you to place fertilizer in a band for crop use.
- This article addresses some key considerations to keep in mind if you are thinking of switching to strip-till.

1. SELECT THE RIGHT STRIP-TILL UNIT

- Will you be strip-tilling in the fall or spring? Will you be applying fertilizer with your strips? Do you want to apply anhydrous ammonia in your strips? The best strip-till unit for your farm will depend on your field conditions and goals.
- If you are planning to strip-till in the spring, consider using a coulter type system versus a shank.
- If you want to put on anhydrous ammonia, use a shank type of row unit. A shank row unit may also better break up compaction versus a coulter type of unit.
- Some tool bars allow you to change out the row unit to have the flexibility to run either coulters or shanks.

2. TAKE REPRESENTATIVE SOIL SAMPLES

- If you are banding fertilizer with your strip-till pass, make sure you are soil sampling with some cores pulled from the band and some not from the fertilizer band to avoid skewing results.

3. MAKE SURE YOU HAVE ENOUGH HORSEPOWER

- Make sure you have a tractor with adequate horsepower to pull the strip-till bar through the field.

- Power requirements vary widely based on equipment configuration and soil conditions, but can be as much as 30 horse power per row for a shank type unit in finer textured soils.
- Running a strip-till bar with an underpowered tractor can lead to excessive wheel slip and fuel consumption, poor quality strips, and damage to the tractor.

4. USE REAL-TIME KINEMATIC (RTK) GPS

- Real-time kinematic (RTK) GPS allows you to save your guidance lines from year to year so you can reliably plant right over the strips that you create.
- If you get off the strip, you will essentially be no-tilling, which can reduce early season stand establishment and yield if your planter is not able to handle the higher amount of residue.

5. HAVE A SKILLED OPERATOR

- Strip-tilling requires more attention to detail than conventional tilling, so the operator needs to be up to the task.
- The layout of the strip-till operation sets how the field must be planted, and the quality of the strips is critical for optimizing seed placement, germination, and emergence.
- Ideally, the operator who does the strip-till operation will be the same operator who plants the field.

6. BE CAREFUL ON CONTOURS AND HILLS

- It can be challenging to keep the planter on strips when running on the contour on rolling ground, even when using RTK.
- Fields with hills may be subject to erosion if the strips run downhill, particularly when strip-tilled in the fall.

7. CHECK THE QUALITY OF THE STRIP-TILL PASS

- Just like with planting, it is important to check the quality of the strip-till pass.
- The strip should be slightly higher in elevation than the soil around it. If the strip is lower than the soil around it, that can create issues with getting the correct planting depth.
- An ideal strip-till pass will remove residue from the strips and not mix it into the seed zone.
- Fertilizer applied using the strip-till unit should be placed at an adequate depth to avoid crop injury.

8. IF THE SOIL IS WET, WAIT

- As with any other type of tillage, running a strip-till bar in wet soil can cause compaction.
- Coulter units have the potential to create a compacted layer, while shanks can cause smearing in the soil.

9. CHOOSE HYBRIDS THAT HAVE STRONG STRESS EMERGENCE AND DISEASE TOLERANCE

- Pioneer® brand corn products with higher stress emergence scores establish more consistent, uniform stands, on average, than ones with lower scores. Pioneer brand corn products with highly suitable (HS) and suitable (S) high-residue suitability ratings produced higher and more uniform stands in high-residue locations than hybrids with a poorly suited (X) rating.
- Strong stress emergence can be important in scenarios where it is challenging to stay on the strips when planting.
- Select for adequate levels of disease tolerance. Previous crop residue can harbor inoculum of diseases, such as gray leaf spot, northern corn leaf blight, Goss's wilt, tar spot, etc.

10. WATCH OUT FOR WEED SPECIES SHIFTS

- Reduced tillage can lead to more winter annual and perennial weed species than you are used to.
- Winter annuals include shepherd's purse, field pennycress and marestail.

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Mary Gumz, Ph.D.,
Agronomy Manager

10 TIPS FOR GETTING STARTED WITH COVER CROPS

- **Cover crops, such as cereal rye, annual ryegrass, oats, brassicas, and legumes are planted to cover the soil between cash crop rotations.**
- **Well-managed cover crops can provide erosion control and improved water quality, as well as scavenge for nutrients and help manage weed populations.**
- **High-yield crop production can occur with cover crops, but successful cover cropping often requires the same time and attention as cash crops.**

1. KNOW YOUR GOAL WITH COVER CROPS

- Cover crops can be used for a variety of purposes: Decreased erosion, improved water quality, improved soil health, decreased compaction, weed control, or nitrogen scavenging or fixation.
- Decide which benefits are most important to you and determine your goal in adding cover crops to your cropping system before selecting your cover crop species or mixture.

2. SELECT THE RIGHT SPECIES OR MIXTURE

- Winter hardy grasses – including cereal rye, wheat, barley and triticale – can be seeded in the fall and will produce above- and below-ground growth before going dormant for the winter. Grasses are good for producing a lot of biomass, carbon sequestration, and soil stabilization due to root mass accumulation. Hardy grasses need to be terminated in a timely manner in order not to compete with the subsequent crop.
- Oats and other non-winter hardy grasses can establish quickly in the fall and accumulate biomass but will winter kill. While oats don't generally accumulate as much biomass as winter hardy grasses, there is no chance of termination failure and competition with the cash crop.
- Brassicas, such as tillage radish or turnip, can produce a large taproot to aid in addressing compaction issues but have the advantage of winterkilling with below freezing temperatures and breaking down quickly in the spring.
- Legumes that help fix nitrogen (N) include winter pea, hairy vetch, and crimson clover, among others. These species can provide N to the field but must be allowed to grow later into the spring, which can interfere with cash crop seeding.
- Mixtures of species can also be seeded to obtain multiple benefits.

Previous corn field with emerged cereal rye cover crop.

3. PLANT YOUR COVER CROP IN A TIMELY MANNER

- Cover crops need to be planted in a timely manner to establish fall growth and overwinter or provide enough biomass to stabilize the soil before being killed by frost.
- An early maturing cash crop can allow for more timely cover crop harvest in the fall.
- In the central Corn Belt, plant cereal rye or rye grass as soon as possible after corn harvest or interseed with the crop via aerial seeding.
- Interseeding of cover crops should be done late enough to prevent the germinating cover crop from competing with the cash crop during grain fill.
- Legumes need to be able to get six weeks of growth in order to fix nitrogen.

4. TERMINATE YOUR COVER CROP IN A TIMELY MANNER

- The goal is to terminate your cover crop before it interferes with your cash crop. The most common termination methods are rolling/crimping or herbicide application.
- Rolling and crimping grasses involves flattening the cover crop with a roller and crimping the stem to inhibit further root growth. Plants fall in the same direction, creating a mat of vegetation for weed control while reducing build up on planter units during cash crop planting.
- Herbicide termination (commonly with glyphosate or a glyphosate tank mix) has more timing flexibility than rolling/crimping. However, spray applications made in weather cooler than 55°F (13°C) may be less effective. Tall grass species may fall in multiple directions, hampering equipment movement and planting efficacy of your cash crop.
- If not "planting green," terminate your cover crop at least two weeks prior to planting.

5. PLANTING GREEN

- "Planting green" refers to planting your cash crop into a living cover crop.
- Planting green into a standing cover crop (6-12 inches, 15-30 cm tall) may make for easier planter movement through the field and better planting of the cash crop. The cover crop must be terminated, though, before it competes with the cash crop.
- Increased top growth of the cover crop from planting green may bring you more benefits, such as increased nitrogen (N) fixation from legume cover crops.

Corn planted no-till into rye cover crop, then rye was sprayed with herbicide to terminate it.

6. PLANTING BROWN

- "Planting brown" refers to planting into a terminated cover crop.
- Planting brown terminates the cover crop before the cash crop is planted, eliminating competition for water and nutrients.

7. ADJUST YOUR PLANTING PRACTICES

- Plant into a fit, warm seedbed. Planting can get delayed with cover crops, so make sure you are optimizing emergence.
- Maintain a seeding depth of at least 2.5 inches (6.4 cm) for corn and 1.5 inches (3.8 cm) for soybeans.
- Adjust coulters and other planter equipment as needed in order to properly slice cover crop residue and make a clean seed slot.
- In a dry spring where the cover crop growth has used available soil moisture, irrigate after planting, if possible, to ensure timely and even germination.

8. OPTIMIZE YOUR FERTILITY

- Nitrogen management is key.
- Front load N applications to your cash crop. Up to 50-75 lbs/acre of actual N is needed for a no-till corn crop with a cover crop at planting.
- Use starter with 2 x 2 placement or in-furrow to overcome N tie up and place N closer to the root zone. Apply no more than 20 lbs/acre of N on the seed to prevent salt burn.

9. BE AWARE OF NEW PESTS

- Cover crops can exacerbate pest problems, such as slugs, seed corn maggot, black cutworm, or white grubs.
- Use a fungicide + insecticide seed treatment to protect seedlings from diseases and insect pests.
- Choose a corn hybrid with strong stand establishment and early growth.
- Matted vegetation after cover crop termination can prevent residual herbicide applications from making complete soil contact.

10. EVALUATE COSTS AND RETURN

- Cover crops require management and are another input cost that will have to be covered by "benefits." Plan for the benefits you want to see and measure so that you can best evaluate ROI.
- Calculate savings, such as decreased erosion, income from carbon credits, reduction of tillage passes, improved weed control, etc.
- Consider costs, such as cover crop seed, planting, and termination.
- Realize that some costs and benefits may take more than a year to see.

Forage radish or 'tillage radish,' a cover crop species that can help remediate soil compaction by producing a large taproot.

Matt Essick M.S.,
Agronomy Manager

COVER CROP CONSIDERATIONS IN NORTHERN LATITUDES

- **Implementing cover crops can be challenging in the northern Corn Belt due to shorter growing seasons and colder spring temperatures.**
- **A cover crop may need to be seeded before the cash crop is harvested to give it time to get established in the fall.**
- **Low temperatures during the spring can make it difficult to effectively terminate a winter hardy cover crop using herbicides.**
- **When starting with cover crops, it's best to begin with a simple program to gain experience.**

COVER CROP CHALLENGES IN NORTHERN LATITUDES

- Cover crops have increased in popularity in recent years and offer potential benefits, such as:
  - » Reducing erosion.
  - » Improving soil structure.
  - » Improving biological activity of the soil.
  - » Sequestering nutrients.
  - » Suppressing weeds.
- While there are many benefits to incorporating cover crops into farming operations, there can also be challenges.
- Getting a cover crop established and then terminated in northern latitudes can be challenging due to shorter growing seasons and lower spring temperatures.

Forage radish or 'tillage radish', a cover crop species that can help remediate soil compaction by producing a large taproot.

Soybean emergence through terminated cover crop.

TIPS FOR GETTING STARTED WITH COVER CROPS

1. Cost of Cover Crop System

- Seeding cover crops is an added expense and it is important to consider species of cover crop to be seeded, herbicides utilized, timing of seeding, equipment used to seed and weather conditions following seeding, along with terminating cover crops in the spring.

2. Establishment Timing

- The growing season in northern latitudes is shorter and to get the most out of a cover crop, it often needs to be seeded prior to harvest of the cash crop. Cover crops require six weeks of growth before a hard freeze to be most beneficial.

3. Establishment Method

- Seeding equipment continues to evolve but one of the predominant methods of seeding cover crops has been with aerial application. This requires the use of a cover crop species that does not need good seed to soil contact to grow.
- Aerial seeding or broadcast seeding in late August can be an effective way to establish a cover crop. In dry summers and falls this may not work.
- Ideally, cover crops would be seeded with a drill after harvest of the cash crop. The length of the fall growing season often prevents this from occurring in northern latitudes.

Corn growing in killed rye stubble.

4. Cover Crop Species

- Consider using cover crops, such as oats, that winter kill if the subsequent cash crop is corn to prevent stand establishment issues in corn.
- Cover crops like cereal rye will overwinter through most winters and will provide cover in the spring. This may create challenging planting conditions for corn, but it may be a good choice for use ahead of soybeans.

5. Cover Crop Termination

- One challenge with terminating cereal rye can be low air temperatures, which can be common during spring in northern latitudes. Try to time herbicide applications when nighttime temperatures are above 40°F (4°C) and daytime highs reach 60°F (16°C).
- Planting corn after cereal rye can be done but it is usually best to gain experience with a species that winter kills first, then begin to incorporate winter hardy species.
- There is some evidence that cereal rye can have an allelopathic effect on corn if termination is too close to corn planting.
- Planting soybeans after cereal rye can be done when the rye is still green or after it has been terminated.

6. Herbicide Selection

- Pre-emergence herbicides may reduce stand establishment or reduce grazing opportunities of cover crops. Always read and follow herbicide label guidelines.

Oat cover crop seedlings that have emerged beneath the corn canopy in the fall

CONCLUSIONS

- Start with a simple program to gain experience.
- Understanding how to terminate cereal rye ahead of soybeans will lead to better management of winter hardy cover crops ahead of corn.
- Other species, such as brassicas and legumes, can begin to be added to the cover crop mix as experience is gained.

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Mark Jeschke, Ph.D.,
Agronomy Manager

ACHIEVING 100 BU/ACRE YIELDS IN SOYBEANS

INCREASING YIELDS IN SOYBEANS

- Improvements in genetics and management have driven substantial gains in soybean yields in the U.S. over the past 50 years, at a rate of 0.48 bu/acre/year (Figure 1).
- U.S. average soybean yields topped 50 bu/acre for the first time in 2016 and again in 2018 and 2020.

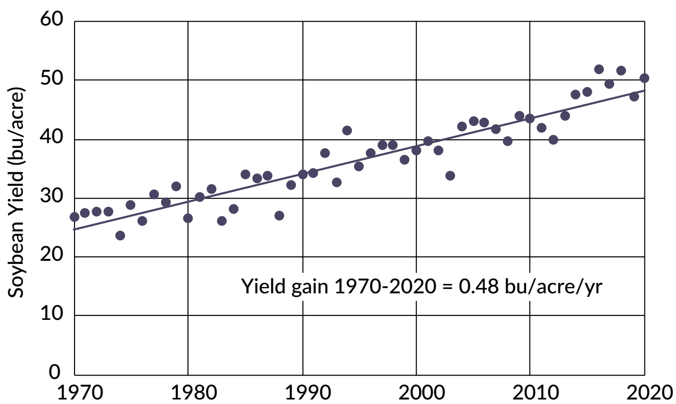

Figure 1. U.S. average soybean yields 1970-2020 (USDA-NASS).

- 100 bu/acre has often served as a target yield level for farmers wanting to see how high they can push yields with optimized management and the newest genetics.
- Across all the on-farm genetic and agronomic trials Pioneer conducts each year in the U.S. and Canada, it has not been unusual for a few entries each year to top 100 bu/acre.
- Beginning in 2018 however, the number of plots exceeding 100 bu/acre increased dramatically. This number declined in 2019 due to weather challenges but hit a new high in 2020 (Figure 2).

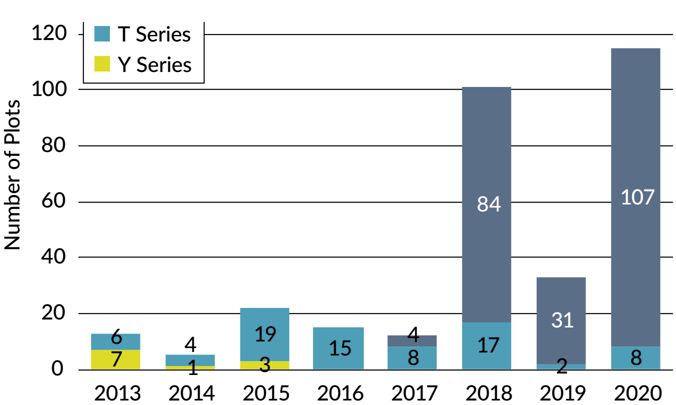

Figure 2. Series of Pioneer® brand soybean varieties used in Pioneer on-farm trial entries exceeding 100 bu/acre, 2013-2020.

PIONEER ON-FARM TRIAL RESULTS

- A total of 115 on-farm soybean trial entries exceeded 100 bu/acre in 2020, 107 of which were planted to A-Series soybean varieties (Figure 2).
- 100 bu/acre was achieved with 40 different Pioneer® brand varieties from maturity group 1.8 to 4.8 (Table 1). Yields greater than 100 bu/acre were achieved over a relatively wide geography from 2013 to 2018, including 19 U.S. states and 2 Canadian provinces.

Table 1. Pioneer brand soybean varieties used in 2020 Pioneer on-farm trials entries exceeding 100 bu/acre.

Variety/Brand[2]	Plots	Variety/Brand[2]	Plots
P18A33x (RR2X)	2	P35A70x (RR2X)	1
P23A15x (RR2X)	2	P35A91BX (BOLT, RR2X)	6
P24A80x (RR2X)	3	P35T01SE (STS, E3)	1
P25A04x (RR2X)	6	P35T15E (E3)	1
P25A54x (RR2X)	2	P36A83x (RR2X)	4
P26T23E (E3)	1	P37A27x (RR2X)	1
P27A17x (RR2X)	6	P37A69x (RR2X)	1
P27A30x (RR2X)	5	P38A92x (RR2X)	1
P28A42x (RR2X)	11	P38T20x (RR2X)	1
P29A25x (RR2X)	1	P39A45x (RR2X)	3
P31A22x (RR2X)	1	P39A58x (RR2X)	4
P31A29L (LL)	1	P42A96x (RR2X)	2
P31A95BX (BOLT, RR2X)	12	P44A72BX (BOLT, RR2X)	1
P31T77R (R)	1	P45A02x (RR2X)	3
P32T26E (E3)	2	P46A16R (R)	1
P33A24x (RR2X)	2	P46A86x (RR2X)	5
P33A53x (RR2X)	4	P47A12L (LL)	2
P34A79x (RR2X)	2	P47A64x (RR2X)	5
P34T21SE (STS, E3)	1	P48A32x (RR2X)	3
P35A55x (RR2X)	1	P48A60x (RR2X)	3

Pioneer® brand soybean varieties topping 100 bu/acre in on-farm trials in 2020 included:

- 4 varieties with Peking SCN resistance source (P18A33x, P25A04x, P27A17x, P27A30x).
- 5 Enlist E3® soybean varieties.
- 2 varieties with the LibertyLink® gene.

AGRONOMIC PRACTICES FOR SOYBEANS

- 100 bu/acre yields were achieved in several different environments and with a range of different agronomic practices.
- Analyses of management practices used in yield contest winners in other crops have produced similar findings (Jeschke, 2019), indicating that there is no single one-size-fits-all formula for achieving high yield potential.

Previous Crop

- The vast majority of 100 bu/acre plots (92%) were planted to corn the prior season, while 4% were planted to soybeans and 4% to another crop (data not shown).

Tillage

- The most common tillage system used at locations with 100 bu/acre plots was conventional tillage, followed by no-till (Figure 3).

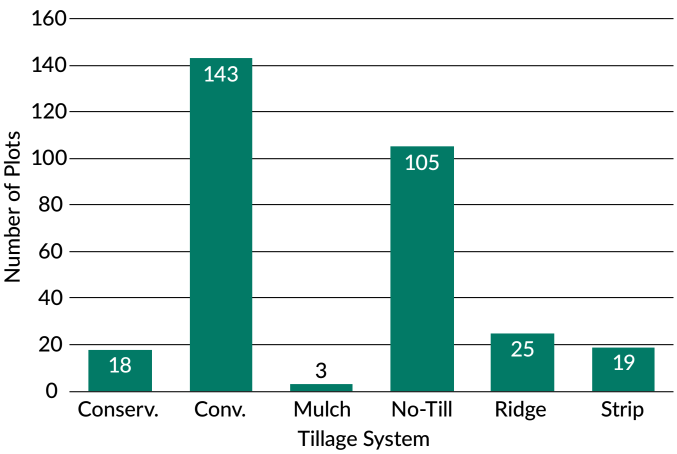

Figure 3. Tillage practices used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2013-2020.

SEEDING RATE

- Seeding rates used in plots yielding above 100 bu/acre ranged from 110,000 seeds/acre to 225,000 seeds/acre (Figure 4).
- Average seeding rate was slightly higher among no-till locations (156,000 seeds/acre) than conventional till locations (149,000 seeds/acre).

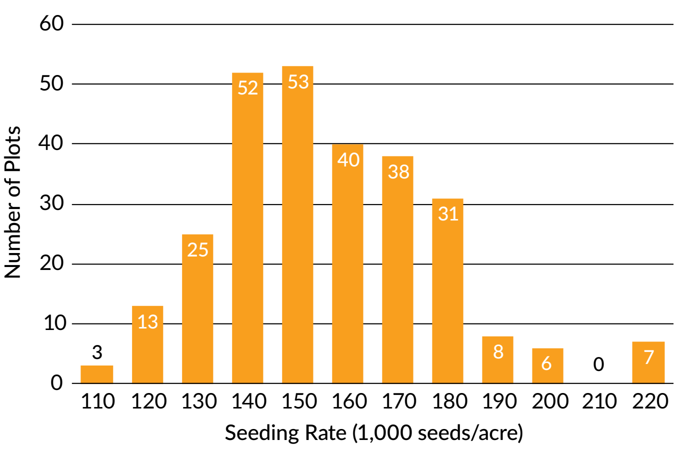

Figure 4. Seeding rate used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2013-2020.

- Seeding rates differed among the four states with the most 100 bu/acre plots:
  - » The average seeding rate across Illinois and Indiana locations was 153,000 seeds/acre.
  - » The average seeding rate across Kansas and Nebraska locations was 166,000 seeds/acre.

ROW SPACING

- The most common row spacing of 100 bu/acre plots was 30-inch rows, followed closely by 15-inch rows (Figure 5).

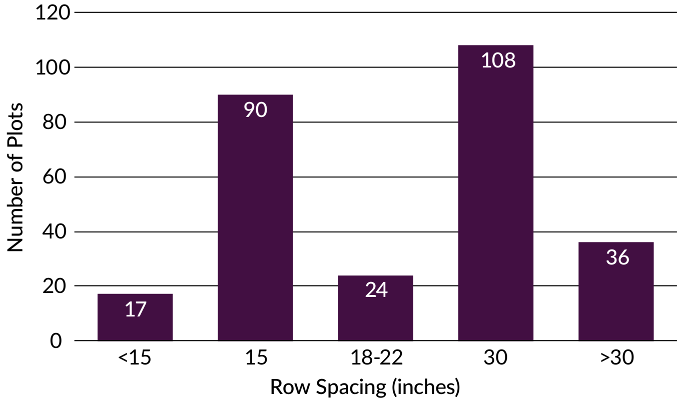

Figure 5. Row spacing used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2013-2020.

- Geographic distribution of row spacing practices roughly corresponded with findings of recent USDA surveys, with 30-inch rows most common from Illinois west and narrower rows more common from Indiana east (Jeschke and Lutt, 2016) (data not shown).

Planting Date

- Recent research has shown the importance of early planting for maximizing soybean yields (Van Roekel, 2019). Most trial locations with 100 bu/acre plots were planted in the latter half of April through the first half of May (Figure 6).

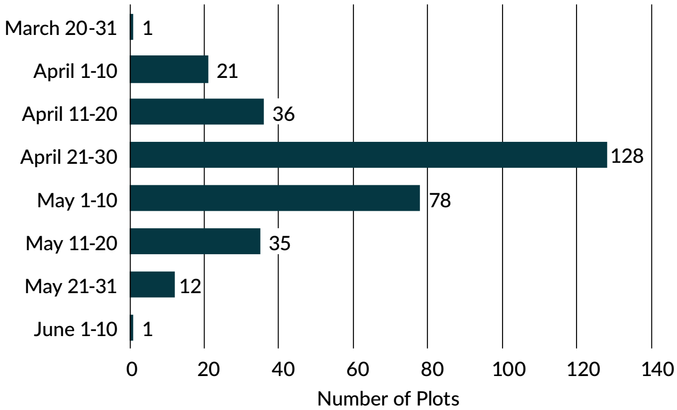

Figure 6. Planting date used in Pioneer on-farm trials with entries exceeding 100 bu/acre, 2013-2020.

Other Practices

- Other management practices employed at locations with 100 bu/acre plots included foliar fungicides, foliar insecticides, and supplemental nitrogen applications.

Mark Jeschke, Ph.D.,
Agronomy Manager

Greg Stopps,
Pioneer Area Agronomist

HIGH YIELD SOYBEAN MANAGEMENT
IN EASTERN CANADA

INCREASING YIELDS IN SOYBEANS

- Improvements in genetics and management have driven substantial gains in soybean yields in eastern Canada (Ontario and Quebec) over the past 50 years, at a rate of 0.33 bu/acre/year (Figure 1).
- Ontario's average soybean yields topped 50 bu/acre for the first time in 2018 and again in 2020. In 2020, Quebec's average soybean yields reached an all-time high of 48.4 bu/acre.

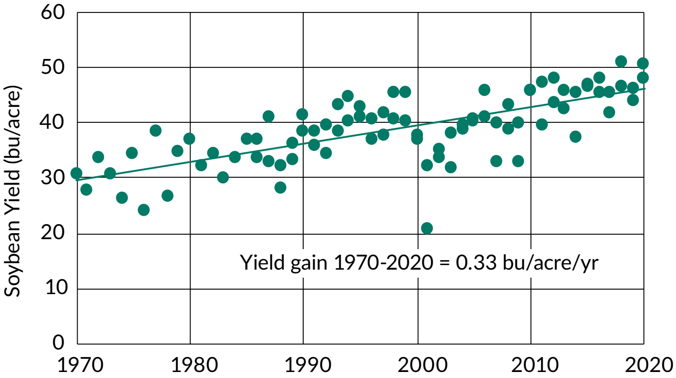

Figure 1. Ontario and Quebec average soybean yields 1970-2020. *(Statistics Canada. Table 32-10-0359-01, Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units).*

- 75 bu/acre has often served as a target yield level for farmers seeking high yields with optimized management and the newest genetics.
- Across all of the on-farm genetic and agronomic trials Pioneer conducts each year in eastern Canada, it has not been unusual for a few entries each year to top 75 bu/acre.
- Beginning in 2018, the number of plots exceeding 75 bu/acre increased dramatically. This number declined in 2019 due to weather challenges but increased again in 2020 (Figure 2).

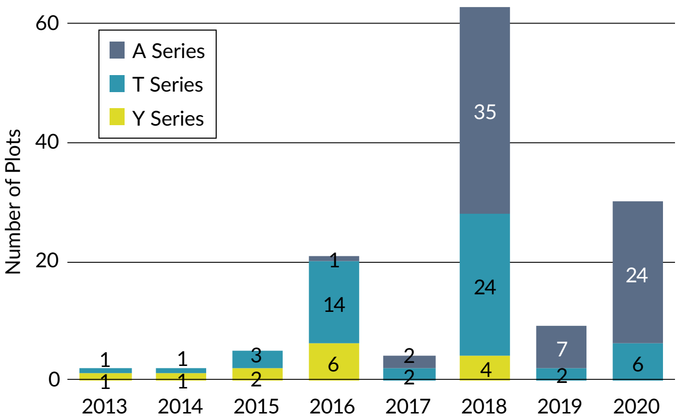

Figure 2. Series of Pioneer® brand soybean varieties used in eastern Canada Pioneer on-farm trial entries exceeding 75 bu/acre, 2013-2020.

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PIONEER ON-FARM TRIAL RESULTS

- A total of 67 on-farm soybean trials between 2018 and 2020 exceeded 75 bu/acre plot average, 66 of which contained Pioneer® brand A-Series soybean varieties (Figure 2).
- 75+ bu/acre was achieved with 49 different Pioneer brand varieties from maturity group 0.3 to 3.1 across those plots from 2018 to 2020 (Table 1).

Table 1. Pioneer brand soybean varieties used from 2018 to 2020 in eastern Canada Pioneer on-farm trial entries exceeding 75 bu/acre.

Variety/Brand[2]	Plots	Variety/Brand[2]	Plots
P03A26X (RR2X)	1	P18A98X (RR2X)	10
P04A60R (RR2X)	1	P19A14X (RR2X)	15
P05A35X (RR2X)	1	P19T39R2 (RR2Y)	5
P06A13R (R)	6	P20T95E (E3)	1
P06A51X (RR2X)	3	P21A20	1
P06T28R (R)	1	P21A28X (RR2X)	17
P07A18X (RR2X)	2	P23A15X (RR2X)	6
P08T96R (R)	10	P23A32X (RR2X)	9
P09A53X (RR2X)	19	P24A80X (RR2X)	12
P09A62X (RR2X)	16	P24T05R (R)	2
P09T74R2 (RR2Y)	6	P24T76E (E3)	2
P10T48R (R)	10	P25A54X (RR2X)	3
P11A10	2	P25A65R (R)	3
P11A44X (RR2X)	1	P26T57E (E3)	2
P11A67	1	P27A17X (RR2X)	11
P13T06L (LL)	1	P28A42X (RR2X)	8
P14A23L (LL)	1	P28A94X (RR2X)	7
P15A09X (RR2X)	4	P28T08R (R)	3
P15A63X (RR2X)	5	P28T14E (E3)	1
P15A88X (RR2X)	4	P28T62R (R)	2
P15T46R2 (RR2Y)	3	P29A25X (RR2X)	7
P15T83R (R)	1	93Y05 (R)	1
P16A13X (RR2X)	13	P31A22X (RR2X)	4
P16A84X (RR2X)	6	P31A95BX (BOLT, RR2X)	2
P16T71E (E3)	2		

AGRONOMIC PRACTICES FOR SOYBEANS

- 75+ bu/acre yields were achieved in a range of different environments and with a range of different agronomic practices.
- Analyses of management practices used in yield contest winners in other crops have produced similar findings (Jeschke, 2019), indicating that there is no single one-size-fits-all formula for achieving high yield potential.

Previous Crop

- The vast majority of 75+ bu/acre plots from 2013-2020 were planted to corn the prior season – 71 of 88 (80.7%) – while 8 (9.1%) were planted to soybeans, and 9 (10.2%) to another crop (data not shown).

Tillage

- The most common tillage system used at locations with 75+ bu/acre plots was conventional tillage, followed by conservation/min-till, followed by no-till. (Figure 3).

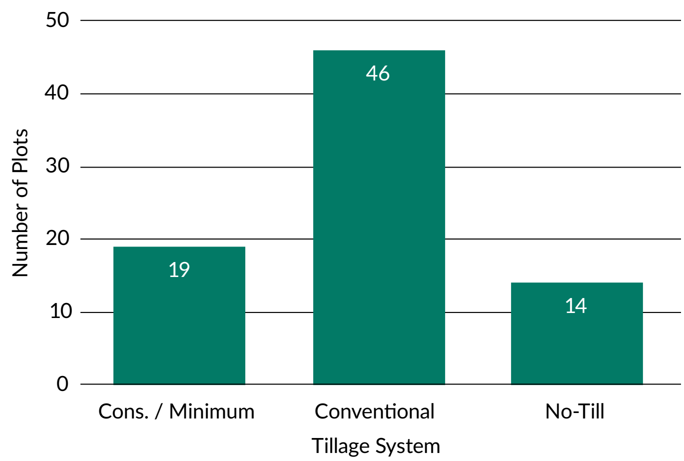

Figure 3. Tillage practices used in eastern Canada Pioneer on-farm trials with entries exceeding 75 bu/acre, 2013-2020.

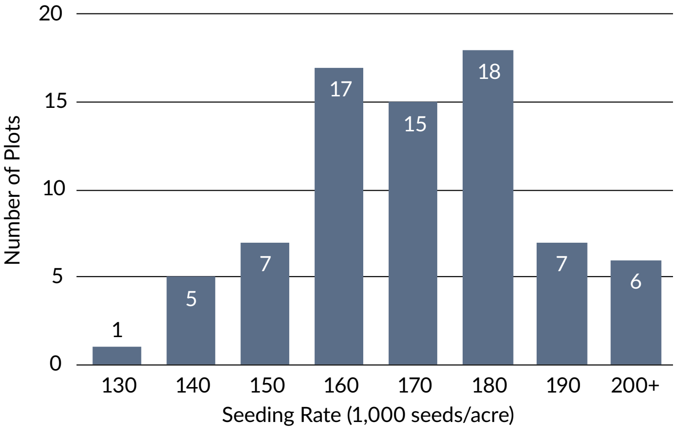

Figure 4. Seeding rate used in eastern Canada Pioneer on-farm trials with entries exceeding 75 bu/acre, 2013-2020.

Seeding Rate

- Seeding rates used in plots yielding greater than 75 bu/acre ranged from 130,000 seeds/acre to 225,000 seeds/acre, with an average of 173,000 seeds/acre (Figure 4).
- Average seeding rate was higher among no-till locations (180,000 seeds/acre) than conventional till locations (169,900 seeds/acre).
- Average seeding rates differed between Ontario and Quebec, where all of the 75+ bu/acre plots were located:
  - » The average seeding rate across Ontario locations was 174,000 seeds/acre.
  - » The average seeding rate across Quebec locations was 161,600 seeds/acre.

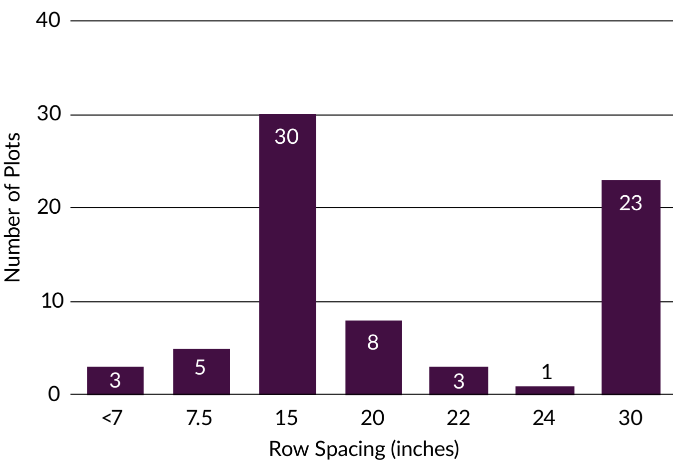

Figure 5. Row spacing used in eastern Canada Pioneer on-farm trials with entries exceeding 75 bu/acre, 2013-2020.

Row Spacing

- Where row spacing was recorded, there was an almost even split between locations with row spacing in 15-inch configurations or less, and 20- to 30-inch configurations (Figure 5).
- Geographic distribution of row spacing practices showed that all but one of Quebec's 75+ bu/acre locations was planted to a wide (20+ inch) row spacing, with the majority of those rows being in a 30-inch configuration. Ontario locations showed a wider variety of row spacing configurations, with 15-inch rows being the most common (data not shown).

Planting Date

- Some recent research has shown the importance of early planting for maximizing soybean yields (Van Roekel, 2019). However, most trial locations with 75 bu/acre plots in eastern Canada were planted in the mid to latter half of May (Figure 6), highlighting the importance of soil fitness at planting.

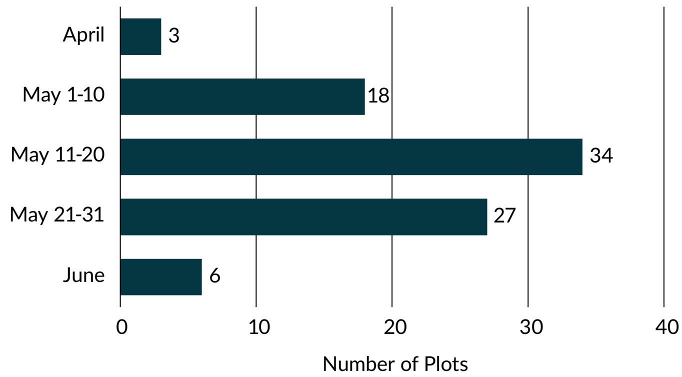

Figure 6. Planting date of eastern Canada Pioneer on-farm trials with entries exceeding 75 bu/acre, 2013-2020.

Other Practices

- Other management practices employed at locations with 75+ bu/acre plots included foliar fungicides (especially those aimed at white mold control), and foliar insecticides.

SOYBEAN WATER USE

Dan Berning,
Agronomy Manager

KEY POINTS:

- Seasonal soybean water use can range from 20 to 26 inches during the growing season, with more than 60% of total water use occurring during the R1 to R6 growth stages.
- The majority of soil water uptake by soybeans occurs within the top two to three feet of the soil profile.
- Adequate water is most critical during pod development and seed fill (R3-R6).

EVAPOTRANSPIRATION (ET)

Evaporation

- Early in the growing season, water loss from the soil occurs primarily through evaporation from the soil surface.
- As the crop grows and more leaf area shades the soil, evaporation will decline as transpiration increases.
- Crop residue on the soil surface can significantly reduce the amount of water lost through evaporation by reflecting solar radiation and protecting the soil from wind.

Transpiration

- In the process of transpiration, plants take up water from the soil and transport it to the leaves. Small openings in the leaves (stomata) allow water vapor to pass from the plant into the atmosphere, cooling the plant.
- The rate of transpiration increases with higher air temperature, solar radiation, and wind speed.
- High humidity levels reduce transpiration by decreasing the difference in water potential between the leaf airspace and the ambient air.

SOYBEAN WATER USE OVER THE GROWING SEASON

- Daily ET varies greatly throughout the growing season due to day-to-day variability in weather conditions.
- On average, daily ET increases through the vegetative growth stages, peaks during early pod fill, and declines as the crop approaches maturity. (Table 1).
- More than 60% of total water use occurs during the R1 to R6 reproductive growth stages.
- Seasonal soybean water use can range from 20 to 26 inches during the growing season (Kranz and Specht, 2012) compared to a typical range of 21 to 28 inches for corn.

SOYBEAN ROOTING DEPTH AND WATER UPTAKE

- Well-developed root systems are essential for soybean water uptake and growth.
- Soybean root systems that are unimpeded by soil factors can reach a maximum depth of more than 60 inches, similar to that of corn (Ordóñez et al., 2018).
- The majority of soil water uptake by soybeans occurs within the top two to three feet of the soil profile (Kranz and Specht, 2012).

Table 1. Average daily soybean water use (ETc), water use per growth stage, and cumulative water use over the course of the growth season.

Growth Stage	Daily Water Use Rate	Water Use Per Stage	Cumulative Water Use
		inches	
2nd Trifoliate (V2)	0.08	0.56	1.00
4th Trifoliate (V4)	0.09	0.63	2.19
6th Trifoliate (V6)	0.14	0.98	3.17
Beginning Bloom (R1)	0.20	2.00	5.17
Full Bloom (R2)	0.25	1.75	6.92
Early Pod Development (R3)	0.28	1.96	8.88
Pod Elongation (R4)	0.32	3.20	12.08
Early Pod Fill (R5)	0.33	3.30	15.38
Mid Pod Fill	0.32	3.20	18.58
Full Pod (R6)	0.25	1.75	20.33
Lower Leaves Yellowing (R7)	0.15	1.50	21.83
Maturity (R8)	0.10	1.00	22.83

IMPACT OF WATER AVAILABILITY

- Soybeans can typically withstand moderate drought stress during vegetative growth with little effect on yield.
- Excessive rainfall during vegetative stages can cause the plants to put on more vegetative growth that will not necessarily lead to higher yields. Larger plants can be more susceptible to lodging during thunderstorms later in the season.
- Adequate water is most critical to soybeans during pod development and seed fill (R3-R6).
- Ample water during flowering followed by drought stress during seed fill will result in smaller seeds.

Mark Jeschke, Ph.D.,
Agronomy Manager

SYMPTOMS OF DICAMBA INJURY IN SOYBEANS

KEY POINTS:

- Dicamba use for post-emergence weed control has increased in both corn and soybeans in recent years to control glyphosate-resistant weeds.
- Soybeans without dicamba tolerance are extremely sensitive to dicamba and can be injured by off-target movement or contaminated spray equipment, which shows up as cupping of newly developed leaves.
- Other factors can also cause malformation of leaves in soybeans, so it is important to be able to distinguish symptoms associated with different causes.
- The potential for yield loss depends on the amount of dicamba and the growth stage of soybeans at the time of exposure.

INCREASING OCCURRENCE OF INJURY IN SOYBEANS

- With the increased use of dicamba herbicides for post-emergence weed control in soybeans, dicamba drift and volatilization have become a common cause of crop injury in non-dicamba-tolerant soybeans.
- Dicamba use has also increased in corn in response to the spread of waterhemp populations resistant to other herbicide modes of action.
- Soybeans are extremely sensitive to dicamba, and dicamba can move miles away from the site of application under certain atmospheric conditions, resulting in a high risk of crop injury.
- Other herbicides and non-herbicide factors can also cause malformation of leaves in soybeans, so it is important to be able to distinguish symptoms associated with different causes.

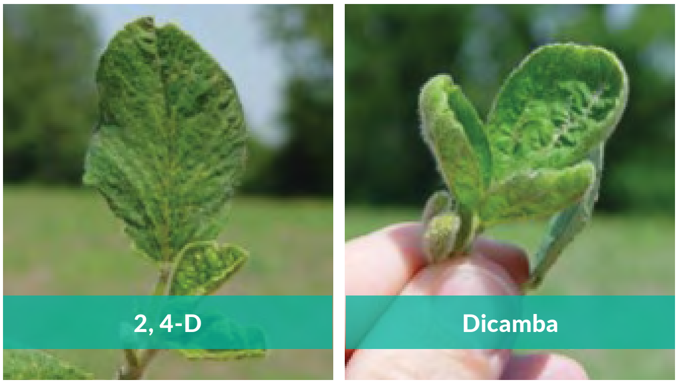

Figure 1. Side-by-side comparison of 2,4-D and dicamba symptoms from a Pioneer soybean herbicide response demonstration. Plants exposed to 2,4-D display leaf strapping, with the veins pulled into a more parallel orientation, while leaves exposed to dicamba show more of an upward cupping/drawstring effect.

PLANT GROWTH REGULATOR HERBICIDES

- At field application rates, injury symptoms of 2,4-D and dicamba to sensitive soybeans are often similar, with drooping leaves and stem twisting showing up within hours after application.
- At lower exposure levels, commonly associated with off-target movement, symptoms are generally more distinct and will also take a longer time after exposure to develop (Figure 1).

Dicamba

- Dicamba injury symptoms in soybeans include:
    - » Leaf cupping, often with whitish or yellowish color at the leaf margins (Figures 2 and 3).
    - » Height reduction and increased number of nodes. Plants may remain stunted for the rest of the season.
    - » Death of the apical meristem at higher rates of exposure.
- Symptoms typically appear on new growth 1-3 weeks following exposure. Leaves that were already fully developed at the time of exposure usually will not show injury symptoms.
- Soybeans are extremely sensitive to dicamba, so exposure to even a tiny amount can cause crop response. Less than 1/10,000x field rate has been shown to result in dicamba injury symptoms on susceptible plants (Gunsolus, 2018; Hager and Sprague, 2000).
- Dicamba is capable of moving long distances from treated fields, sometime well after application.
    - » Fine aerosol particles that remain suspended in the air during a temperature inversion can travel more than a mile from the site of application (Osipitan et al., 2019).
    - » Volatilization of dicamba from treated fields has been detected up to four days after application.

Figure 2. Soybean plants showing upward leaf cupping characteristics of dicamba injury. Symptoms are limited to newer growth, with older leaves unaffected.

Figure 3. Soybean plants in a field near Waterville, Kansas, showing symptoms of exposure to a low dose of dicamba. **Left:** Plants showing leaf crinkling, upward leaf cupping, and whitish leaf margins on new growth, all characteristics of dicamba injury. **Right:** Symptoms of a very low dose of dicamba exposure, including crinkling at the leaf tips and slight downward cupping.

- Dicamba injury symptoms that appear over an entire field of non-dicamba-tolerant soybeans can be indicative of either sprayer contamination or off-target movement.
- Sprayer Contamination
  - » Injury due to sprayer contamination is a risk whenever a sprayer used to apply dicamba is later used in non-dicamba-tolerant soybeans.
  - » Plant growth regulator herbicides readily adhere to plastic and rubber parts, making them difficult to clean from spray equipment.
  - » Some herbicides, such as glyphosate, can dissolve dicamba residues from the inside of spray tanks.
  - » The high sensitivity of soybeans to dicamba means that even a tiny amount left in a sprayer can cause injury over the entire area treated with the next sprayer load.
- Off-Target Movement
  - » Multiple university weed scientists have noted cases of relatively uniform injury across entire fields of non-dicamba-tolerant soybeans associated with off-target movement of dicamba.
  - » The scale of injury symptoms observed across the countryside in recent years suggests that off-target movement is likely the predominant cause of dicamba injury in soybeans (Hager, 2019).

Figure 4. Soybean trifoliate showing symptoms of 2,4-D injury. Leaflets are strapped, with parallel venation.

2,4-D

- Injury symptoms include:
  - » Leaf elongation and strapping, with parallel veins in affected leaves (Figure 4).
  - » Formation of callous tissue on stems.
- Soybeans are less sensitive to 2,4-D than to dicamba. It takes a higher dose to cause the same level of injury caused by off-target movement of dicamba.
- Plant height reduction generally doesn't occur unless exposure levels are high. Death of the apical meristem is also unlikely with 2,4-D injury.

Other Growth Regulator (Group 4) Herbicides

- Other plant growth regulator herbicides, such as clopyralid can also cause injury to soybeans.
- Carryover injury associated with clopyralid applied to corn the previous season will typically show up early in the season – around the V1 growth stage.
- Group 4 herbicides used in hay fields and pastures, such as picloram and aminopyralid, degrade slowly and can cause injury in soybeans via hay or manure brought into the field.

OTHER HERBICIDES MODES OF ACTION

- Foliar-Applied PPOs (Group 14)
  - » Foliar-applied PPO herbicides can cause leaf distortion in soybeans but can be distinguished by the accompanying leaf burning common with PPOs and a lower degree of cupping than is typical of dicamba (Figure 5).
  - » PPO response can also be distinguished from dicamba injury by the fact that symptoms will appear on all exposed leaves, while dicamba injury will show up only on new growth.
- Post-Emergence Applied Soil Residual Herbicides (Group 15)
  - » The post-emergence use of group 15 herbicides in soybeans has increased as a means to achieve better waterhemp control.
  - » These products can cause malformation of soybean leaves in cold and wet soil conditions, but symptoms differ from those associated with plant growth regulators (PRGs).
  - » Crop response to group 15 products can be distinguished by a shortening of the midrib of leaflets, resulting in a heart shape (Figure 6).

Figure 5. Soybean injury after foliar application of a PPO herbicide. Leaves show some degree of distortion and midrib shortening, which could be mistaken for other types of injury, but also show burning of leaves exposed at the time of application characteristic of PPO damage.

Figure 6. Soybean plants showing characteristic symptoms of Group 15 herbicide injury. The midribs are shortened, resulting in heart-shaped leaflets.

Factors NOT Shown to Cause Soybean Injury

- Ammonium Sulfate (AMS) – Observations of leaf cupping across entire fields of non-dicamba-tolerant soybeans has led to speculation that AMS applied with glufosinate or another post-emergence herbicide could be the cause of the crop response.
- However, multiple university weed scientists have noted that leaf cupping has never been a crop response associated with AMS over the many years of its use as a spray additive (Hager, 2019; Hartzler and Anderson, 2018).

GENERAL CONSIDERATIONS FOR DIAGNOSING HERBICIDE INJURY

- **Plant Symptoms** – The nature of injury to the plants and when/where they appear (new growth vs. old growth).
- **Spatial Pattern of Symptoms** – Spatial differences in the severity of symptoms can often provide a clue as to how the herbicide exposure occurred.
- **Timing of Symptoms** – When the symptoms appear relative to the timing of herbicide applications.
- **Application History** – Records of herbicides applied in the field, in neighboring fields, and the use of the same sprayer.

NON-HERBICIDE FACTORS

- Several factors other than herbicide exposure are known to cause malformation of soybean leaves, although they can generally be distinguished from symptoms of herbicide injury.
- **Spider mites** and **piercing/sucking insects,** such as potato leaf hopper or soybean aphids, can cause curling of soybean leaves (Figures 7 and 8).
- **Periods of rapid growth** can cause a wrinkled or blistered appearance of newly emerged leaves that the plant will quickly grow out of.
- **Viral infections**, such as bean pod mottle, soybean mosaic, and tobacco streak viruses, can all cause wrinkling and downward cupping of soybean leaves.
- **Drought stress** will cause soybean leaves to fold in and/or flip over to help the plant conserve water (Figure 9).

YIELD IMPACTS OF DICAMBA INJURY

- Soybean exposure to dicamba resulting in minor symptoms typically will not impact yield; however, the potential for yield loss increases at higher levels of exposure (Werle et al., 2018).
- The potential for yield loss depends on the amount of dicamba and the growth stage of soybeans at the time of exposure.
- Soybeans exposed during vegetative growth are more likely to recover and not experience yield loss.
- Yield loss is more likely when exposure to dicamba occurs after flowering has begun.

Figure 7. Curling and stippling of soybean leaves caused by spider mites.

Figure 8. Curling of soybean leaves caused by potato leaf hopper feeding.

Figure 9. Soybeans with leaves folded in and flipped over in response to drought stress.

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GALL MIDGE IN SOYBEANS

SUMMARY

- Soybean gall midge is a new insect pest of soybeans first found in Nebraska in 2011 and has now spread to parts of Iowa, Missouri, South Dakota, and Minnesota.
- Gall midge injury in soybean is a result of larval feeding, which occurs near the base of the plant. Prolonged feeding can cause the stem to break, resulting in plant death.
- Injury is generally most severe at field edges, which suggests that populations are moving in from adjacent fields planted to soybeans the previous season.
- Yield loss reports have ranged from a one or two bu/acre to nearly total yield loss depending on how early injury occurs and the severity of the infestation in certain areas of a field.
- In 2019, populations of a second gall midge species that feeds specifically on white mold-infected plant tissue were found in soybeans in Minnesota.
- Management recommendations for soybean gall midge are still in the process of being developed. Research on soybean variety susceptibility, as well as foliar insecticide and seed treatment efficacy, is currently underway.

GALL MIDGE – A NEW PEST OF SOYBEAN

Soybean gall midge is a relatively new insect pest of soybean. Gall midge was first observed in soybeans in Nebraska in 2011. Initially, it appeared to be a relatively minor pest of soybeans, mostly confined to field margins and feeding on soybean plants that were already damaged or diseased. However, instances of greater infestation levels and damage to soybeans were observed beginning in 2018, with populations extending further into field interiors and feeding on otherwise healthy plants.

Very little was known up to this point about the biology of soybean gall midge, including exactly what species it was. Initial investigations identified gall midge observed in soybeans as belonging to the genus *Resseliella*, which included 15 species known to exist in the U.S., none of which were known to infest soybeans. Genetic and morphological analyses subsequently confirmed soybean gall midge to be a previously undescribed *Resseliella* species, now named *Resseliella maxima* (Gagne et al., 2019).

Figure 1. Gall midge larvae feeding in soybean stems. Iowa, August 3, 2018. *Photo: Jessie Alt, Corteva Agriscience* .

Soybean gall midge has now been confirmed in five states and has proven capable of causing significant crop damage and reductions in yield. There is still much to be learned about the biology and life cycle of this pest, as well as effective management practices. The situation was further complicated in 2019 with the discovery of a second gall midge species affecting soybeans in parts of Minnesota.

FIELD OBSERVATIONS IN SOYBEANS

Gall midge damage in soybeans was first reported in Nebraska in 2011 in isolated cases mostly associated with damaged or diseased stems. Sporadic infestations were observed in subsequent years, but damage generally was not severe enough to impact yield. While remaining a relatively minor concern for soybean production, gall midge populations began to spread, with feeding in soybeans first reported in South Dakota in 2015 and western Iowa in 2016.

Pioneer agronomists and scientists at the University of Nebraska, Iowa State University, and South Dakota State University all noted increased infestations in 2018, with infestations occurring earlier in the season and causing higher levels of damage to soybeans. Numerous infestations were observed by Pioneer agronomists in 2018 on otherwise healthy soybean plants, indicating that damaged or diseased tissue is not a necessary prerequisite for gall midge infestation. Economic levels of damage were observed again in 2019. The spread of soybean gall midge has continued, with populations reported in Minnesota in 2018 and Missouri in 2019 and expansion of affected areas in Nebraska, Iowa, and South Dakota (Figure 2).

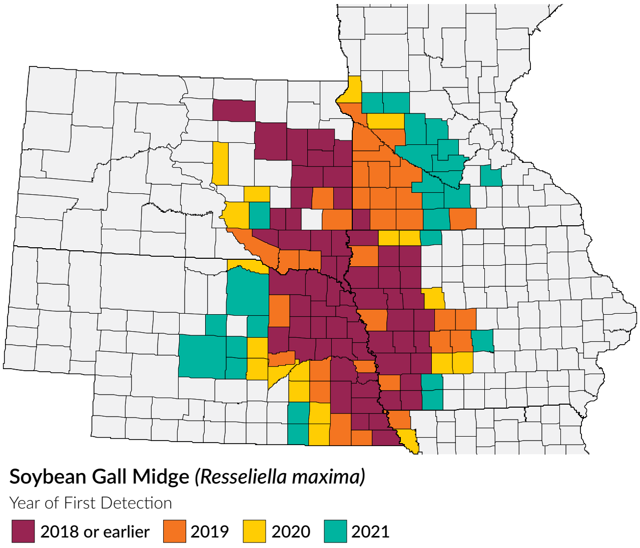

Figure 2. Counties with documented infestations of soybean gall midge and year of first detection. (Source: www.soybeangallmidge.org)

CHARACTERISTICS AND PLANT INJURY

Larvae are very small and start out white, turning bright red or orange as they mature (Figure 3). Adult midges are small (two to three mm in length) and have long antennae and hairy wings (Figure 4). Gall midge injury in soybean is a result of larval feeding, which occurs near the base of the plant. Multiple larvae can infest a plant. Larvae feed inside the stem, causing swelling and abnormal growth (galls). Infested portions of the stem will appear swollen and brown (Figure 5). Discolorations of the stem often begin near the soil surface and can extend up to the unifoliate node. Prolonged feeding can cause the stem to break off, resulting in plant death.

Figure 3. Gall midge larvae feeding in a soybean stem at the soil surface, South Dakota, August 8, 2018. *Photo: Curt Hoffbeck, Pioneer Field Agronomist.*

Figure 4. Gall midge adults.

Figure 5. Galls on a soybean stem due to gall midge infestation (left). Stem girdling from prolonged feeding (right). *Photos: Jessie Alt, Corteva Agriscience.*

GALL MIDGE SPECIES

Hessian fly *(Mayetiola destructor)*, an agricultural pest in the *Cecidomyiidae* family. *Photo courtesy of Scott Bauer, USDA-ARS.*

- The term *midge* is used to refer to a broad group of small fly species, encompassing several taxonomic families. Gall midge refers to species of flies in the family Cecidomyiidae.
- Gall midges are characterized by larvae that feed inside plant tissue, resulting in abnormal plant growth (galls).
- More than 6,000 species of gall midge have been described worldwide, although the total number of species in existence is believed to be much larger. More than 1,100 species have been described in North America.
- The gall midge family includes numerous species that are economically important pests of agricultural crops, including Hessian fly *(Mayetiola destructor)*, wheat blossom midge *(Sitodiplosis mosellana)*, and sunflower midge *(Contarinia schulzi)*.
- Some species of gall midge are known to feed primarily on decaying organic matter, fungi, and molds; therefore, they tend to be attracted to damaged or diseased areas on plants.

INJURY PATTERNS IN SOYBEANS

Infestation can occur during vegetative and reproductive stages. Injury is generally most severe at field edges (Figure 6). Injury on field margins suggests fly movement from previous crop residue to new crop. Research has shown that overwintering generation adult emergence comes almost entirely from fields infested the previous year, with very low rates of emergence observed in fencerows and other non-crop areas (McMechan et al., 2021a). Injury has been observed next to CRP, pastures, and tree lines in some cases. In severe cases, infestation can extend into the interior of the field.

Depending on the severity of gall midge infestation, some soybean plants may wilt, die, or simply show signs of poor pod development and small seed size, especially in the upper ⅓ of the canopy on "healthy-appearing" green plants. Yield loss varies depending on how early injury occurs and the severity of the infestation in certain areas of a field. Yield losses in soybean gall midge-infested fields can be up to 100% within 100 ft from the field edge and losses of 17-31% further into the field (McMechan et al., 2021c).

Figure 6. Dead soybean plants due to gall midge injury along the edge of a soybean field. South Dakota, August 8, 2018; *Photo: Curt Hoffbeck, Pioneer Field Agronomist.*

SOYBEAN GALL MIDGE LIFE CYCLE

Soybean gall midge undergoes complete metamorphosis, with egg, larva, pupa, and adult stages. Gall midge larvae overwinter in larval cocoons in the soil, similar to wheat midge (*Sitodiplosis mosellana*) (Figure 7).

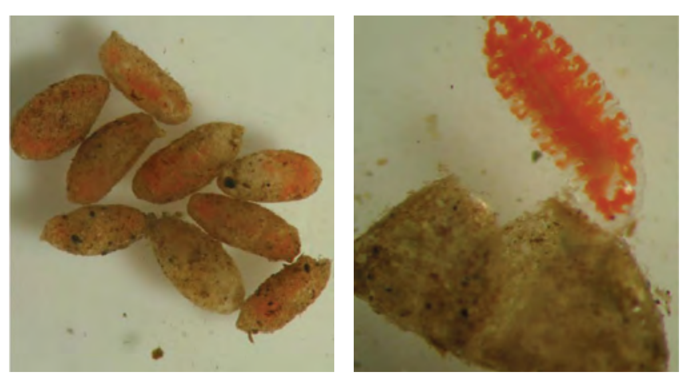

Figure 7. Soybean gall midge larval cocoons found in soil samples taken in a field with high soybean gall midge pressure (left). A soybean gall midge larvae extracted from a larval cocoon (right). *Photos courtesy of Kirk Anderson and Marion Harris, Dept. of Entomology, North Dakota State University.*

Timing of adult emergence from the soil varies by geography, with first adult emergence observed in mid-June in Nebraska and early July in Minnesota (Knodel, 2019). Adults have a long emergence window – overwintering generation adult emergence extended over a 17-day period in a Corteva Agriscience study in 2019 and as long as 37 days in a 2021 study (Figure 8). Adults live three to five days and do not feed on soybean plants (Calles-Torrez et al., 2020).

Females lay eggs in cracks and fissures in soybean stems. Females do not pierce the stem tissue when laying eggs. Larval infestation of soybean plants has not been observed prior of the V2-V3 growth stage. At this stage of soybean growth, the stem diameter expands, creating small fissures allowing the overwintering generation adults to deposit eggs into the stem (McMechan et al., 2021c). Prior to V3, the soybean stems do not have these fissures.

Newly hatched larvae feed under the epidermis of the stem and go through three instars. Larvae drop off the plant to the soil, where they form larval cocoons and pupate (Calles-Torrez et al., 2020). Adults then emerge and repeat the cycle. Adults are not strong fliers, so are limited in their mobility. The effect of wind in dispersing adults is under investigation.

Based on observations so far, soybean gall midge appears to go through two or three overlapping generations per season. The substantial overlap between generations makes it difficult to detect discrete generations within the growing season, and larvae can be present in an infested field continually over the majority of the growing season. The timing of adult emergence cessation in the fall appears to be relatively consistent from year to year (McMechan et al., 2021a).

Two other host species for soybean gall midge have been identified – alfalfa and sweet clover. There is no apparent need for management in these alternate hosts. Populations observed in alfalfa have been relatively low (McMechan et al., 2021a).

Figure 8. Trap set up following soybean planting to measure soybean gall midge adult emergence from the soil in 2019.

A SECOND GALL MIDGE SPECIES IN SOYBEAN

In 2019, populations of a second gall midge species were observed in soybeans in Minnesota. These populations were identified as belonging to a different species in the gall midge family (Cecidomyiidae), *Karshomyia caulicola*, known to exist in North America and northern Europe (Koch et al., 2019). Observations of *Karshomyia caulicola* have been in fields infected with white mold and, within the context of soybean management, it is now being referred to as white mold gall midge (WGM). *Karshomyia caulicola* is known to be a fungus feeder on other plant species and appears to only feed on white mold fungus in soybeans and not on the soybean plants. There is no evidence so far of white mold gall midge causing or spreading white mold infection.

Populations of white mold gall midge have been found in soybean fields in Minnesota, Wisconsin, and North Dakota. White mold gall midge appears to be widespread in the North Central region of the U.S. (Calles-Torrez et al., 2020).

Larvae of white mold gall midge are very similar in appearance to those of soybean gall midge. The most effective way to distinguish between the two species is based on the timing and location of larval feeding. White mold gall midge feeding is specifically associated with the presence of white mold infection, so it has only been observed after flowering when infected tissue is present. White mold gall midge feeding can occur anywhere in the field where there are infected plants and anywhere on the plant where there is infected tissue.

MANAGEMENT CONSIDERATIONS

Management recommendations for soybean gall midge are still in the process of being developed. Preliminary investigations into foliar insecticide treatments have shown some promise for suppressing gall midge populations when applied at the time of pre- or early post-emergence herbicide applications to control egg-laying adults. However, these types of insecticide applications still need more thorough evaluation, and careful consideration is needed to avoid insect resistance issues with midge or other insects, and potential harm to beneficial insects.

The long emergence window of soybean gall midge adults poses a significant challenge for timing and effectiveness of insecticide application. Foliar treatments later in the season when larval feeding in the stems is already underway are not likely to be effective since the larvae are protected from exposure to the insecticide. More insecticide treatment timings, active ingredients, and rates need to be fully evaluated to determine what options are effective.

Tillage of previously infested fields has been investigated as a way to potentially reduce adult emergence by disturbing the larval cocoons in the soil. Spring tillage has shown some effectiveness in reducing emergence rates and also appears to shift emergence earlier, possibly due to the quicker warming of the soil (McMechan et al., 2021b). Ridging soil around the stems of soybean plants has also been investigated as a way to impede egg laying in stem fissures. This technique has shown some effectiveness but is not likely to be a practical management tactic for many growers.

In general, the best opportunity for managing soybean gall midge is to limit the overwintering generation's ability to infest soybean plants. Research on differences in soybean variety susceptibility to gall midge damage and insecticide seed treatment effects on gall midge is ongoing. Scouting recommendations for adult flies have not yet been developed. Scouting for adults will be challenging due to the small size of adult midges.

REFOCUSING ON SOYBEAN CYST NEMATODE MANAGEMENT

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SOYBEAN CYST NEMATODE IN NORTH AMERICA

- Soybean cyst nematode (SCN; *Heterodera glycines*) is a major yield-reducing pathogen of soybean production in North America.
- SCN was likely introduced to the U.S. from Japan. The first report of SCN in the U.S. was in North Carolina in 1954.
- This tiny worm-like parasite has now spread to practically all important soybean production areas of the U.S. and Canada (Figure 1), and is reaching economic levels in more areas.
- SCN may decrease yields substantially without inducing obvious symptoms. Studies have shown that in SCN-infested fields, yields can be reduced by over 30% without visible above-ground symptoms.

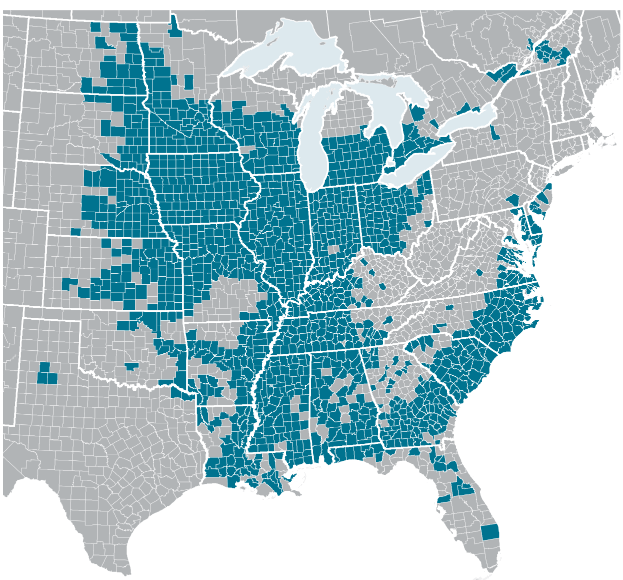

Figure 1. Known distribution of soybean cyst nematode in the United States and Canada as of 2017 (from Marett and Tylke, 2017).

GENETIC RESISTANCE TO SCN

- The most important management tactic for SCN during the years since its establishment as a yield-limiting pest in North America has been the selection of soybean varieties with genetic resistance to SCN (Figure 2).
- Researchers have identified a number of soybean lines that have the ability to resist nematode reproduction on their roots.
- Currently, there are three main sources for genetic resistance to SCN in commercially-available soybean varieties: PI88788, PI548402 (Peking), and PI437654 (Hartwig and CystX).
- The PI 88788 source is used in the vast majority of existing SCN-resistant varieties marketed in the U.S.
- Only a small number of varieties currently use the PI548402 (Peking) source, and even fewer use the PI437654 source.

Figure 2. Strips of SCN-resistant and non-resistant soybean varieties in a SCN-infested field, showing damage to the non-resistant varieties.

SCN HG TYPES

- SCN populations are genetically diverse and have historically been separated into races by their ability to reproduce on soybean tester lines.
- The most commonly used system separated SCN into 16 races.
- More recently, a new classification system called the HG Type test has been widely adopted. The HG Type test is similar to an SCN race test, but includes only the seven sources of resistance in available SCN-resistant soybean varieties.
- Results are shown as a percentage, indicating how much the nematode population from a soil sample increased on each of the seven lines.
- The HG Type test indicates which sources of resistance would be suited for the field being tested. For example, if an HG type contains the number 2, this indicates that PI88788 would not be an effective source of SCN resistance (Table 1).

Table 1. Indicator lines for HG Type classification of SCN.

Indicator Line		Indicator Line	
1	PI548402 (Peking)	5	PI209332
2	PI88788	6	PI89772
3	PI90763	7	PI548316
4	PI437654 (Hartwig)		

DECREASED EFFICACY OF PI88788 RESISTANCE

- Beginning in the 1990s, the widespread availability of soybean varieties with PI88788 SCN resistance provided a largely effective management tool for SCN in North America.
- In recent years however, PI88788 has been losing its effectiveness as an SCN management tool.
  - A recent survey in Nebraska showed almost half (47%) of the fields tested had SCN populations that reproduced on PI 88788 (HG type 2) (Wilson, 2018).
  - A recent University of Missouri study of 28 SCN populations representing different regions of the state found that all of them showed reproduction on PI 88788 varieties (Mitchum and Howland, 2018).
  - Studies in other states have found similar results, showing that SCN populations able to reproduce on PI88788 varieties have become widespread in many areas.
- The PI88788 source of SCN resistance no longer provides effective control in many fields, meaning that SCN once again poses a significant threat to soybean yield that requires grower attention and management.

SCN MANAGEMENT RECOMMENDATIONS

- The SCN Coalition provides the following recommendations for developing a plan to manage SCN (www.thescncoalition.com):
  - Test your fields to know your numbers.
  - Rotate resistant varieties.
  - Rotate to non-host crops.
- Consider using a nematode protectant seed treatment.
- Consult your university soybean extension specialist for specific management recommendations for your state.

Test Your Fields

- The first step in developing an 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 two cups of soil in a plastic bag and label with a permanent marker. Paper bags allow soil to dry excessively and are not recommended for SCN.
  - Do not store samples in direct sun or allow them to overheat. Ship as soon as possible to the lab you choose.

Rotate Resistant Varieties

- If your SCN populations are found to be increasing, select varieties with sources of resistance other than PI 88788.
- The most common source of resistance other than PI88788 is PI548402 or "Peking" resistance.
  - The Peking source of SCN resistance was identified from an older soybean cultivar and has been associated with yield drag.
  - Pioneer has been using precision molecular breeding methods to isolate the Peking genes and eliminate yield drag associated with the trait.
- Pioneer is currently offering 17 high yield potential soybean varieties with the Peking source of resistance.
- As a leader in SCN breeding, we continue to breed with Peking and Hartwig sources of resistance to provide additional modes of action for a variety of SCN races.
  - The complexity of the Hartwig trait makes it more challenging to bring into high yield potential varieties, but Pioneer anticipates introducing new varieties with the Hartwig source in the next few years.

Rotate to Non-Host Crops

- Rotation to a non-host crop to reduce SCN pressure.
- Corn, alfalfa and small grains are the most common non-host crop choices for reducing SCN numbers.
- However, since SCN persists in the soil for many years, it cannot be totally eradicated by rotation.

Seed Treatments

- Several nematicide seed treatments with activity against SCN are currently available and can provide added protection when used with an SCN-resistant soybean variety.
- Nematicide seed treatments are intended to supplement current SCN management strategies, not replace them. Seed treatments should therefore be used in coordination with SCN-resistant varieties and rotation to non-host crops (Bissonnette and Tylka, 2017).
- The LumiGEN® system offering includes ILEVO® fungicide/nematicide seed treatment, which has activity against SCN.
- A Pioneer study including 193 on-farm trial locations found an average yield response of 4.9 bu/acre in high SCN fields when ILEVO fungicide/nematicide seed treatment was added to the standard fungicide and insecticide seed treatment package (O'Bryan and Burnison, 2016).

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DIAGNOSING COMMON IN-SEASON ISSUES IN SOYBEANS

Mark Jeschke, Ph.D.,
Agronomy Manager

BROWN STEM ROT

Disease Facts

- Caused by *Phialophora gregata*, a fungus that survives in soybean residue.
- Fungus infects roots early in the season, but symptoms of vascular system damage usually appear in mid-summer, during reproductive development.
- Brown stem rot (BSR) development is greatest between 60–80°F and when soil moisture is near field capacity.
- BSR may be more severe in fields where soybean cyst nematode (SCN) is also a problem.

Identification and Symptoms

- BSR infection causes vascular and pith tissues to turn brown to reddish-brown, which is a distinguishing symptom.
  - » Split stems longitudinally to inspect for BSR, checking at and between nodes near the soil line (Figures 1 and 2).
  - » When disease is severe, discoloration is continuous from the base of the plant upward.
  - » When disease is less severe, discoloration only occurs at nodes, with healthy, white tissue between nodes.

Management

- **Select Resistant Varieties:** Pioneer® brand soybean varieties have been continually improved for resistance to BSR (Figure 3).
- **Crop Rotation:** Effective in reducing disease inoculum – two years away from soybeans is more effective than one.
- **Tillage:** Some tillage may be necessary to bury infected residue – the rate of inoculum decline is directly related to the rate of soybean residue decomposition.
- **Manage SCN:** Plant varieties resistant to both sudden death syndrome (SDS) and SCN.

Figure 1. Split soybean stems showing BSR symptoms mid-season (top) and in a mature plant (bottom).

Figure 2. Split soybean stems showing BSR symptoms in the plant. The pith is dark brown while cortex remains green in infected plants.

Figure 3. BSR symptoms on a susceptible soybean variety (left) compared to a resistant variety (right). Note wilting, premature defoliation, and lodging. Symptoms occur after pod fill begins and are more severe with dry soil conditions.

PHYTOPHTHORA ROOT AND STEM ROT

Disease Facts

- Caused by the soil-borne fungus *Phytophthora sojae* (also known as *Phytophthora megasperma* f. sp. *glycinea*).
- Pathogen has many races, and multiple races may occur in a field.
- Disease favors extended wet field conditions and temperatures between 60–80°F (15–27°C).
- May infect soybeans at any time during the growing season.
- Above-ground symptoms may not be evident for several weeks after initial infection.

Identification and Symptoms

- Symptoms begin in the root.
  - Taproot and secondary roots are brown and discolored and have less root mass.
  - Nodulation is often minimal, leading to chlorotic, nitrogen deficient plants.
  - Affected plants may be stunted, so fields have an uneven appearance.
- Symptoms may spread to the stem (Figure 4).
  - Brown discoloration develops at the soil line.
  - Dark-brown to red-brown lesions may progress up the stem (key diagnostic feature of the stem rot phase).
  - Diseased tissues quickly become soft and water-soaked, and wilting and plant death may soon follow, especially during stress periods (Figure 5).

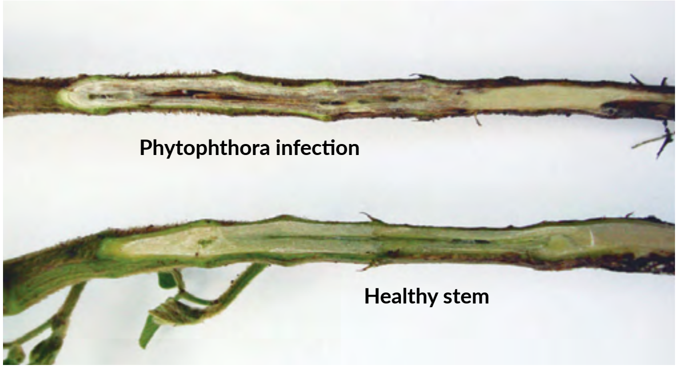

Figure 4. Split stem showing brown discoloration due to Phytophthora infection compared to a healthy stem.

Figure 5. Wilted plants surrounded by healthy plants are a common sign of Phytophthora.

Management

- Variety selection and seed treatments are the most effective means of managing Phytophthora.
- Corteva Agriscience uses molecular breeding to develop varieties with resistant genes and field tolerance to Phytophthora.
- Improve field drainage and remediate compaction and hardpan layers if possible.

SUDDEN DEATH SYNDROME (SDS)

Disease Facts

- Fungal disease caused by *Fusarium virguliforme*.
- Fungus colonizes on only the crown and roots of the plant.
- Above-ground symptoms are caused by a toxin produced by the fungus and translocated throughout the plant.
- Cool, moist conditions early in the growing season often result in higher disease incidences.
- Favorable disease conditions may result from early planting, high rainfall and/or low-lying, poorly drained or compacted field areas.
- Infection occurs early in the season, but symptoms usually do not appear until mid-summer.

Identification and Symptoms

- A blue coloration may be found on the outer surface of taproots due to the large number of spores produced.
- These fungal colonies may not appear if the soil is too dry or too wet.
- Splitting the root reveals cortical cells have turned a milky gray-brown color while the inner core, or pith, remains white.
- General discoloration of the outer cortex can extend several nodes into the stem, but its pith also remains white (Figure 6).
- Leaf symptoms first appear as yellow spots (usually on the upper leaves) in a mosaic pattern.
- Yellow spots coalesce to form chlorotic blotches between the leaf veins (Figures 7 and 8).
- Affected leaves twist, curl, and fall from plants prematurely.

Management

- Select SDS-resistant varieties.
  - Corteva Agriscience has developed elite soybean varieties with improved SDS resistance.
  - Soybean breeders have selected for genetic resistance in multiple environments with high levels of natural SDS infection.
- Manage soybean cyst nematode (SCN).
- Improve field drainage and reduce compaction.

Figure 6. Split soybean stem on top shows symptoms of sudden death syndrome infection. Split stem on bottom is healthy.

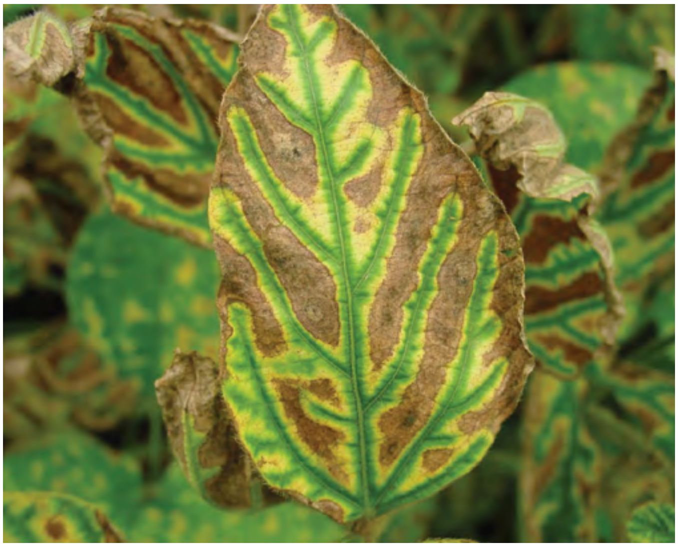

Figure 7. Soybean leaf showing symptoms of sudden death syndrome infection. Drying of necrotic areas can cause curling of affected leaves.

Figure 8. Soybean plants infected with sudden death syndrome. Necrotic areas of leaves dry rapidly. Leaves drop from the plant prematurely, but leaf petioles remain firmly attached to the stem.

SOYBEAN CYST NEMATODE

Nematode Facts

- Soybean cyst nematode (SCN; *Heterodera glycines*) is a small plant-parasitic roundworm that attacks the roots of soybeans.
- 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.
- The PI88788 source of SCN resistance no longer provides effective control in many fields, meaning SCN once again poses a significant threat to soybean yield and requires grower attention and management.

Identification and Symptoms

- Above-ground symptoms of SCN are not distinct and can be mistaken for soil compaction, nutrient deficiency, or other factors.

Figure 9. Strips of SCN-resistant and non-resistant soybean varieties in an SCN-infested field, showing damage to the non-resistant varieties.

- SCN damage can appear as stunting and yellowing, often in circular or oval-shaped patches in the field (Figure 9).
- SCN is best diagnosed by carefully digging up plants and looking for females and cysts on the roots (Figure 10).
- The bodies of the females are white and easily visible during early and mid-summer but turn brown and become more difficult to see late in the season.

Management

- Take samples and send to a diagnostic laboratory to determine the HG type of the SCN population in the soil.
- Rotate resistant varieties – the most common source of resistance other than PI88788 is PI548402 or “Peking” resistance.
- Rotate to a non-host crop to reduce SCN pressure.
- Use nematicide seed treatments with activity against SCN, which can provide added protection when used with an SCN-resistant soybean variety.

Figure 10. Lemon-shaped cysts of SCN visible on soybean roots.

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FUSARIUM WILT AND ROOT ROT OF SOYBEANS

Laura Sharpe,
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DISEASE FACTS

- Fusarium Wilt is a disease complex associated with several soil-borne *Fusarium* species.
- More than 10 *Fusarium* species are known to infect soybeans.
- Different species can favor different conditions; some prefer warm and dry soils, while others prefer cool and wet soils.
- Host range also differs among species, with some species capable of infecting corn, wheat and other host plants.
- *Fusarium spp.* can infect soybeans as the primary pathogen or alongside other soybean pathogens, such as *Pythium*, *Phytophthora*, and *Rhizoctonia*.
- Infection often occurs during a wet period but becomes noticeable under hot, dry conditions.

Figure 1. Stand loss due to Fusarium infection. Note the patchy nature of infection occurring in a specific area of the field.

SYMPTOMS

- Infection causes reddish to brown discoloration of vascular tissue in the roots and stems.
- External light to dark brown lesions may spread over much of the root system but will not extend above the soil line.
- Fusarium-infected roots often have red, orange, or white mycelium visible.
- Infection of the taproot can promote adventitious root growth near the soil surface. Fusarium may also degrade lateral roots but usually does not cause seed rot.
- Foliar symptoms can appear if root and stem rot is sufficiently severe, including wilting of stem tips, stunting, and chlorosis.
- Upper leaves may appear scorched while leaves in the middle and lower canopy turn chlorotic and wilt, eventually dropping from the plant, leaving petioles behind.

Figure 2. Foliar symptoms of fusarium wilt.
Photo by Daren Mueller, Iowa State University, Bugwood.org

DISEASE CYCLE

- *Fusarium* spp. can survive in the soil as spores or mycelium in plant residue.
- Fungus can infect plants at any stage but especially when plants are weakened by stress.
- After infection, roots are compromised and will show more symptoms during dry conditions.

Figure 3. Dead plants due to Fusarium infection, with healthy plants in the background. Less severe infections may degrade roots without resulting in plant death.

MANAGEMENT

- **Variety Selection** - There are no resistant varieties available.
- **Seed Treatment** - Fungicide seed treatments may protect seedlings.
- **Stress Factors** - Reduce stress factors, such as herbicides that cause crop injury, high pH, wet soils, and soybean cyst nematode (SCN).
- **Field Drainage and Soil Structure** - Improve field drainage and remediate compaction and hardpan layers if possible.
- **Planting Date** - Problematic fields should be planted when soils are warmer.

CERCOSPORA LEAF BLIGHT AND PURPLE SEED STAIN OF SOYBEANS

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DISEASE FACTS

- Caused by a fungal pathogen, *Cercospora kikuchii*.
- Infection favors humid conditions and temperatures of 75 to 80°F or higher.
- Can be found throughout the U.S. and Canada. The disease is becoming more common in the midwestern U.S.
- Generally occurs during pod filling stages (August), affecting both leaves and seeds of soybeans.

DISEASE DEVELOPMENT

- Disease organism survives as mycelia on soybean residue and on the seed coat of infected seed.
- 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.
- Lesions develop on leaves during hot, humid conditions. Sporulation from lesions results in secondary infections.
- Seeds become infected when the fungus invades the pod and grows through the upper vein. The hilum and eventually the seed coat become infected.
- Infected plants and seeds provide inoculum for the next soybean crop.

Figure 1. Leaf symptoms of *Cercospora kikuchii,* which causes purple seed stain of soybean seeds. Leaf symptoms begin as a light purple color that extends over the leaf and develops a leathery appearance.

DISEASE SYMPTOMS – LEAF BLIGHT

- The Cercospora leaf blight phase generally begins in August at the start of pod fill on late-planted soybeans.
- Sun-exposed leaves on the upper part of the plant develop a reddish-purple to bronze discoloration (Figure 1).
- Discoloration results from numerous irregular-shaped lesions that range from small specks to half-inch spots, and may extend to the upper stems, petioles and pods.
- Lesions form large necrotic blotches as the disease progresses and lesions merge.
- As plants mature, infected leaves develop a leathery appearance.
- Severely affected upper leaves may drop but the petioles remain on the plant. Lower leaves of the plant remain green and attached (Figure 2).
- Infection sites on petioles and stems are sunken red lesions that can be up to ¼ inch in length.

Figure 2. Field infected with cercospora leaf blight of soybeans. The pathogen overwinters on infested debris or seed.

IMPACT ON CROP

- Plants infected early from diseased seed may lose their cotyledons, become stunted, or die.
- Loss of leaf tissue or entire leaves may occur. Extensive blighting of fields is common with severe infections.
- Defoliation may reduce yield if disease occurs early relative to pod fill. Significant yield loss is more common in southern states than in northern and central states.
- Purple seed stain may reduce quality and marketability of soybeans. Severely stained seed may be docked at the elevator, depending on the percent of seed affected.

SYMPTOMS – PURPLE SEED STAIN

- Lesions and a purplish discoloration are symptoms of infected pods. Seeds are infected through their attachment to the pod, the hilum (Figure 3).
- Infected seeds may show a pink or pale to dark-purple discoloration, which varies in size from specks to blotches that cover the entire seed coat.
- Seed discoloration extends from the seed hilum in all cases. However, seed is sometimes infected without showing obvious symptoms.

Figure 3. Close-up of soybean seeds with purple seed stain caused by a fungal disease, *Cercospora kikuchii*. Infected seeds have a pink-to-purple discoloration on their seed coats.

MANAGEMENT

Rotation and Tillage

- A one- to two-year rotation to corn or small grains will reduce inoculum levels. Other legumes should not be included in the rotation.
- Tillage, where practical, can be used to incorporate and hasten the decomposition of crop residue on which Cercospora pathogens survive.

Genetic Resistance

- Soybean varieties vary in their response to Cercospora, but a high level of resistance is not currently available. Nevertheless, many commercial varieties demonstrate at least some degree of tolerance.
- Resistance to the leaf blight and seed infection stages are thought to be under different genetic control.

Seed Treatments

- The fungicide component of seed treatments can help protect against early infection of seedlings that may result in cotyledons shriveling, turning dark purple, and dropping early, or plants that die or become stunted.

Fungicides

- Many commonly used foliar fungicides are labeled for Cercospora leaf blight on soybeans; however, research has shown efficacy to often be variable (Table 1).
- Single applications at R2 to R4 (full-flower to full-pod stages) tend to perform better in reducing the leaf blight phase of this disease than applications made at R5 (beginning-seed stage).
- Single applications at R4 to R5 (full-pod to beginning-seed stages) can reduce the incidence of purple seed stain, but may or may not improve soybean yield.
- The cost-effectiveness of multiple applications has not been proven.

Table 1. Efficacy of select foliar fungicides for control of Cercospora leaf blight (Smith, 2020).

Fungicide	Active Ingredient(s)	Efficacy*
Aproach® Prima 2.34SC	cyproconazole, picoxystrobin	P-G
Domark® 230ME	tetraconazole	P-G
Headline® 2.09EC/SC	pyraclostrobin	P
Miravis® Top 1.67SC	pydiflumetofen, difenoconazole	P-G
Priaxor® 4.17SC	pyraclostrobin, fluxapyroxad	P-G
Quadris® 2.08SC	azoxystrobin	P
Quadris Top® 2.72SC	azoxystrobin, difenoconazole	P-G
Quilt Xcel® 2.2SE	azoxystrobin, propiconazole	F
Stratego® YLD 4.18SC	trifloxystrobin, prothioconazole	F
Topguard® 1.04SC	flutriafol	P-G
Trivapro®	benzovindiflupyr 2.9% azoxystrobin 10.5% propiconazole	P-G

* E=Excellent; VG=Very Good; G=Good; F=Fair; P=Poor;

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RHIZOCTONIA ROOT AND STEM ROT

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DISEASE FACTS

- Caused by the soil-borne fungus *Rhizoctonia solani*.
- Pathogen causes damping-off, root and stem rot, and foliage blight.
- Disease favors heavy, poorly drained soils and delayed emergence.
- May attack soybeans from planting to mid-season.
- Most prevalent on seedlings and young plants when prolonged wet periods are followed by warm and dry weather.
- Yield reductions can range from as little as 5% to more than 50% depending on severity.

CONDITIONS FAVORING DISEASE DEVELOPMENT

- This pathogen is favored with high soil moisture and warm soil temperatures, around 81°F (27°C).
  - Because of this, it is common in late-planted soybean fields.
- Commonly occurs in heavy, poorly drained or compacted soils.

RHIZOCTONIA SYMPTOMS

- Infects young seedlings, causing damping off.
- Infection is characterized by shrunken, reddish-brown lesions on the hypocotyl at or near the soil line.
- Infections may be superficial, causing no noticeable damage, or these firm, dry, brick-red lesions can join to girdle the stem and kill or stunt plants.
- Soybeans can also appear stunted, chlorotic, and wilted as a result of root decay.
- Severely affected plants may lose their leaves.
- Wilted and/or dead plants often occur in small patches.
- Stems weakened by infection can cause plants to break at the soil line under stormy conditions.

DISEASE CYCLE

- Disease-causing fungus survives as resting mycelium or sclerotia in the soil.
- When soils warm, the fungus becomes active and infection can occur.
- At optimum temperatures, 77-84°F (25-29°C), disease severity increases.
- Infection occurs under wet conditions but symptoms become evident under drought stress.

Figure 1. Soybean plants showing symptoms of damping off due to rhizoctonia root rot disease. *Rhizoctonia solani* can cause seed rot, root rot, and reddish-brown lesions on hypocotyls at the soil line.

MANAGEMENT

- **Seed Treatments** - Offer some measure of protection and increase emergence.
- **Crop Rotation** - Limited in its effectiveness, as many strains of Rhizoctonia can infect corn, alfalfa, dry bean, and cereals.
- **Field Drainage and Soil Structure** - Improve field drainage and remediate compaction and hardpan layers if possible.
- **Planting** - Avoid planting under cool, wet conditions.

Figure 2. Red discoloration at soil line due to *Rhizoctonia solani* (left). Close up of red discoloration due to *Rhizoctonia solani* (right).

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ALTERNATE FORAGE OPTIONS FOR HIGH ROOTWORM PRESSURE FIELDS

KEY POINTS

- Corn is increasingly the preferred forage crop for dairy production because of its high yield potential and energy content.
- Continuous production of corn for grain or silage in the same field can lead to corn rootworm problems.
- Forage programs that combine a winter cover crop followed by an alternative spring-seeded forage crop can come close to replacing the value of a corn crop, particularly if corn rootworm damage is limiting corn yields.
- Use this article as a starting point for introducing rotation into a feed production operation using some of the easier-to-manage forage alternatives to corn.

CORN ROOTWORM PROBLEMS IN CONTINUOUS CORN

Corn is king in much of dairy country and is displacing alfalfa acres in the rotation because it supplies high forage quantity and quality. However, planting corn in the same fields year after year may lead to challenges in managing corn rootworm. Continuous corn fields can favor higher corn rootworm populations, even when using Bt corn products (Pilcher et al., 2018). Relying on a single corn rootworm management tactic can result in reduced efficacy over time.

Rotating fields with historically high levels of corn rootworm pressure out of corn can greatly aid in reducing corn rootworm populations and maintaining the efficacy of corn rootworm control options. However, there is no single crop that can completely replace the tonnage and feed value of corn silage.

Figure 1. Corn rootworm larvae feeding on corn roots and lodging caused by root damage.

Alternatively, by leveraging multiple crops in the growing season, a producer can come close to replacing the value of a corn crop. This is particularly true if corn rootworm damage is limiting corn yields. Table 1 summarizes the comparative values for various forage crops. Combining a winter cereal with a summer forage crop results in similar feed value to corn silage when corn yields are challenged.

IDENTIFY AN ALTERNATIVE FORAGE SYSTEM

Developing an alternative forage cropping plan that uses multiple crop species can help meet the feed needs of a dairy or livestock operation while also effectively managing corn rootworm. An effective plan involves two key steps:

Step 1 – Start with a small grain cover crop planted shortly after corn silage harvest.

Step 2 – In the spring, follow the small grain cover crop with an alternate forage crop. Common spring-planted options discussed in this article include:

- Forage sorghum
- Sorghum-sudangrass
- Clear-seeded alfalfa

START WITH A COVER CROP

Many fall cover crop options are available, but winter rye or winter triticale are currently the most common. They are widely available; are able to establish stands and overwinter in cold conditions; and have relatively low seed cost. Small grain forages are widely used by many dairy operations and growers who have integrated cover crops into their management systems.

Table 1. Relative yield and feeding value of forage crops.

Crop	Yield	DM	Starch	Protein	NDFd 30[1]	uNDF 240[2]	Starch Value	Protein Value	pdNDF Value[3]	NDFd Milk Adj[4]	Total Value[5]
	tons/acre	**%**					*$/acre*				
Corn silage	26	35	34.70	8.04	58.91	10.02	296.82	542.15	290.25	176.94	**1,306.16**
CRW-damaged corn silage (20% yield loss)	20	35	27.76	8.04	58.91	10.02	182.66	417.03	223.27	136.11	**959.07**
BMR sorghum silage	18	35	16.00	10.30	54.80	15.40	94.75	480.83	307.77	19.96	**903.31**
Grain sorghum silage	12	35	26.00	8.93	48.36	19.24	102.65	277.92	175.39	(93.80)	**462.16**
Sorghum-sudan silage	14	35	2.95	9.79	55.00	14.10	13.59	355.47	246.89	19.40	**635.35**
Alfalfa silage	6	40	0.00	20.64	47.89	17.01	-	367.06	58.00	(58.07)	**366.99**
Soybean silage	7	35	0.10	19.62	46.43	17.30	0.23	356.19	63.95	(73.44)	**346.93**
Small grain silage	8	35	0.01	12.30	54.95	16.41	0.03	255.20	116.53	10.53	**382.29**
Small grain + BMR sorghum silage											**1,285.60**
Small grain + grain sorghum silage											**844.45**
Small grain + sorghum-sudan silage											**1,017.64**
Small grain + alfalfa silage											**749.28**
Small grain + soybean silage											**729.22**

[1] NDFd30 = NDF digestibility measured at 30 hours. [2] uNDF240 = undigestible NDF measured at 240 hours. [3] pdNDF = potentially digestible NDF (NDF-uNDF240).
[4] NDFd Milk Adj = 0.55# milk per NDFd point (Jung MN Nut Conf 2004) - $18 milk, 18# DM inclusion rate in TMR. [5] Total Value = Sum of Starch, Protein, pdNDF +/- NDFd milk adjustment.

Nutritional values from Dairyland Summaries. The starch levels for BMR sorghum were changed to more closely reflect current varieties. Corn cost $3.50/bu. Protein calculated from $350/ton SBM. pdNDF from $150 soy hulls.

Figure 2. Newly emerged fall-seeded cereal rye cover crop.

How to Manage Small Grain Cover Crops

- **Planting**
  - » Plant winter rye (or winter triticale) in the fall after corn silage harvest.
  - » Target a seeding rate of around 100 lbs/acre. Seeding rate should be higher under challenging seeding conditions or when broadcasting. Seeding rate can be lower (75 to 80 lbs/acre) when planting conditions are favorable.
  - » Planting is best accomplished using a drill with a seeding depth of ¾ to 1 inch.
  - » Plant as soon as possible after corn silage harvest. If applying manure prior to planting, a tillage pass may be necessary to incorporate the manure and prepare the field for planting.
  - » Consider broadcast seeding in late August (corn dent stage) if harvest will occur after early October.
- **Management**
  - » Weed control is not typically needed for a fall-seeded crop with adequate stands, but watch for winter annuals, such as chickweed and henbit. Yield can be reduced if weeds are not adequately controlled.
  - » Apply 50 to 75 lbs of nitrogen/acre at green-up in the spring to encourage tillering and increase forage yields. Higher rates of nitrogen can improve crude protein levels in the harvested forage, and a summer annual crop can use any remaining nitrogen.
- **Harvest**
  - » Harvest small grain crops in the late-boot to early heading stage to optimize forage quality and energy content.
  - » Apply Pioneer® brand inoculant 11G22 when harvesting for silage to reduce dry matter losses during fermentation and feed out.

CHOOSE A FOLLOW CROP

Option 1: Forage Sorghum

Hybrid forage sorghum types grow 8 to 10 ft tall and have thick stems. Like corn grown for silage, they are designed to be harvested a single time during the grain maturation stage for forage.

- **Hybrid Selection**
  - » Pioneer® hybrid 845F is a 68 relative maturity forage sorghum widely adapted across the U.S.
  - » Pioneer hybrid 849F is a slightly fuller season choice with increased plant height.
- **Planting**
  - » Plant at a rate of 7 to 8 lbs/acre (90,000 to 100,000 seeds/acre) in 30-inch rows to optimize forage harvest for silage. If planting with a drill or broadcasting, increase seeding rate to 10 to 15 lbs/acre.
  - » Forage sorghum should be planted after the over-wintering cover crop is harvested and when the soil temperature has reached 65°F.
  - » Sorghum is sensitive to cool soils; adequate soil temperatures at planting are necessary to ensure rapid emergence.
- **Management**
  - » Forage sorghum requirements for nitrogen, phosphorus, and potassium are like those of corn silage. Use a yield target of 80 to 90% of a typical corn silage crop for the area.
  - » When applying manure, incorporate it prior to planting, and credit the available manure nutrients when calculating fertility needs.
  - » Metolachlor or s-metolachlor products (contained in the herbicide brands Bicep® and Dual®) can be used for grass weed control when safened seed is used. Pioneer forage sorghum hybrids are available with Concep® III seed safener to help protect against phytotoxic effects of s-metolachlor herbicides.
  - » Atrazine, dicamba, and 2,4-D can be used for broadleaf weed control in sorghum crops.
  - » Check state labels for herbicide products, and consult local advisors for all potential herbicide options, including pre-harvest intervals for use as forage.
- **Harvest**
  - » Harvest at mid-dough to mature-grain color stage to optimize tonnage and quality.
  - » Maturity can change quickly, so close monitoring of grain maturity and whole plant forage moisture is necessary for proper fermentation and to optimize feed quality. Starting early is preferable to delayed harvest for best quality and can help avoid lodging.
  - » Using a BMR forage sorghum hybrid improves fiber digestibility of the forage, though there may be reduced dry matter yields and agronomic concerns like standability.
  - » Apply Pioneer® brand 11G22 inoculant when harvesting as silage to reduce fermentation and feed-out losses.

Option 2: Sorghum-Sudangrass

Sorghum-sudangrass hybrids have high yield potential provided adequate rainfall or irrigation. They are designed for multiple harvests and can be stored as silage or hay when properly wilted or dried down.

- **Hybrid Selection**
  - » Pioneer® 877F sorghum-sudangrass is widely adapted and suitable for planting across the U.S.

Figure 3. Field of sorghum-sudangrass

- **Planting**
  - » Plant at a rate of 8 to 12 lbs/acre (100,000 seeds/acre) in rows or at 15 to 20 lbs/acre when seeding with a drill or broadcasting.
  - » Sorghum-sudangrass should be planted after the overwintering small-grain crop is harvested and when soil temperature has reached 60°F (16°C).
  - » Sorghum-sudangrass is sensitive to cool soils. Adequate soil temperatures at planting are necessary to ensure rapid emergence.
- **Management**
  - » Sorghum-sudangrass requirements for nitrogen, phosphorus, and potassium are similar to those of a corn silage crop.
  - » Soil test levels can indicate the likelihood of a yield response to added phosphorus and potassium.
  - » Nitrogen response is similar to that of corn. Yield target with sorghum-sudangrass should be 60 to 70% of a good corn silage crop.
  - » Metolachlor and alachlor products (contained in the herbicide brands Dual® and Lasso®) can be used for grass weed control when safened seed is used. Pioneer sorghum-sudangrass hybrids are available with Concep® III seed safener to help protect against phytotoxic effects of s-metolachlor herbicides.
  - » Atrazine, dicamba, and 2,4-D can be used for broadleaf weed control in sorghum crops.
  - » Check state labels for herbicide products, and consult local advisors for all potential herbicide options.
- **Harvest**
  - » Two cuttings are often achievable in a 75- to 90-day growth period. Take the first cutting at boot stage to optimize tonnage and quality. Leave 4 to 7 inches of stubble when harvesting to encourage rapid regrowth.
  - » A second cut is typically ready 30 to 35 days after the first cut. Ensure that the crop is at least 26 inches tall before cutting.
  - » Apply Pioneer® brand 11G22 inoculant when harvesting as silage to reduce fermentation and feed out losses.

Option 3: Summer-Seeded Alfalfa

Alfalfa is a highly digestible, high-protein forage source for all livestock classes. It is a perennial crop that is harvested frequently to maximize tonnage and quality.

- **Variety Selection**
  - » Pioneer offers a range of alfalfa varieties adapted to your local growing conditions. Consult with your local Pioneer sales professional for both conventional and Roundup® Ready choices.
  - » If planning on a short alfalfa rotation (<2 years), an economical variety, such as Pioneer® brand 54B66™, minimizes seed cost.
- **Planting**
  - » Plant alfalfa after harvest of the small-grain cover crop at a rate of 15 to 18 lbs/acre (60 to 80 seeds/ft^2).
  - » Prepare a firm seedbed to ensure good seed-to-soil contact for rapid germination and seedling growth.
  - » Maintaining soil moisture is key for late spring plantings. Consider no-till seeding in areas with low rainfall or irrigation potential to prevent surface soil from rapidly drying with tillage.

Figure 4. Field of alfalfa.

- **Management**
  - » Ensure soils have a pH of 6.5 to 6.8 or greater, and apply lime during the preceding season if necessary. Apply phosphorus and potassium based on recent soil tests.
  - » Weed competition is typically higher with later seeding dates and warmer soils.
  - » Consider herbicide options that control weeds, and allow the alfalfa to establish stands. Alfalfa with Roundup® Ready technology can help establish weed-free stands with high forage yield and quality potential.
  - » If no pre-emergent herbicide is planned, consider increasing seeding rates by up to 10 lbs/acre, and take an earlier cutting to reduce early weed competition.
- **Harvest**
  - » Harvest from bud to early bloom stage.
  - » Use Pioneer® brand 11H50 inoculant when harvesting and storing as silage (haylage) to reduce dry matter losses and retain high nutrient content.

VERTICILLIUM STRIPE OF CANOLA

Kristie Sundeen,
Pioneer Field Agronomist

Photos courtesy of the Canola Council of Canada

KEY POINTS:

- Verticillium stripe is a soil-borne disease of canola first found in Manitoba, Canada, in 2014.
- Soil surveys conducted by the Canadian Food Inspection Agency in 2015 found *V. longisporum* throughout canola–growing provinces in Canada.
- Due to the late onset timing of the disease, verticillium stripe is less damaging than other diseases, such as blackleg or Sclerotinia stem rot.

DISEASE FACTS

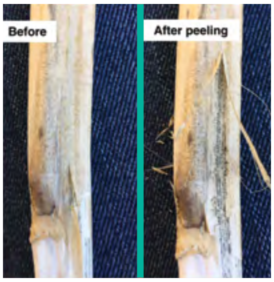
- Verticillium stripe of canola is caused by the fungal species *Verticillium longisporum*. This is related to, but not the same as, *Verticillium dahliae*, which is a pathogen of potato, tomato, sunflower, strawberry, cabbage, and maple.
- Verticillium stripe is a soil-borne disease and as such will have similar management practices to clubroot (which is also a soil-borne disease). Fungal propagules called microsclerotia are present in soil or dead plant tissue.
- *V. longisporum* is known to infect numerous annual and perennial species in both temperate and subtropical zones.
- Its host range includes several crop species, including broccoli, cabbage, horseradish, radish, and canola, along with wild mustard in the mustard family. It has been an economically important pathogen of oilseed rape in northern Europe for more than 30 years and has also been found in cauliflower in California and horseradish in Illinois.
- The pathogen is taken up by the roots and moves up into the stem, plugging up the xylem.
- Verticillium stripe is a monocyclic disease, meaning it only goes through one cycle of the disease each year. However, if infected plants ripen prematurely, they can have reduced yield.
- Yield losses up to 50% have been observed in Europe, but the potential impact on spring-seeded canola in Canada does not appear to be as great.

CONDITIONS FAVORING DISEASE

- Verticillium stripe is favored by hot and dry conditions. Soil temperatures between 59° and 66°F and air temperatures around 73°F are optimal for disease development.
- The disease is less of an issue with high levels of soil moisture.
- Plants with damaged roots are more susceptible to the disease entering the vascular system.

SYMPTOMS

- Disease symptoms include leaf chlorosis, early ripening, stunting, and necrosis (shredding of the stem tissue).
- Symptoms are primarily visible on the stem and roots but can also be noticed on leaves and pods.
- Infection can occur in patches or across the entire field.
- The interference of water and nutrient uptake caused by verticillium stripe can cause the crop to show signs of stunting and premature senescence.
- Faint black vertical striping can be seen on the stems, which can appear darker or more obvious when rubbed.
- Peeling back the epidermis and outer cortex of the stem, the striping will become more obvious farther into the maturation process due to the tissue dying below the stem surface.
- Once the plant is fully ripe, the stem peels to reveal tiny black microsclerotia, which can resemble ground pepper in appearance.
- These microsclerotia remain on the plant stem or fall to the soil. Those in stems are released in the soil as the stems decay.
- Microsclerotia are hardy and can survive in the soil for many years.
- Microsclerotia can move with surface and ground water, through wind dispersal of infected soil or crop debris, equipment contaminated with infected soil or crop debris, seed contaminated with infested soil or crop debris, or with people from one field to another.



Before and after peeling epidermis to reveal microsclerotia

Peeling epidermis to reveal microsclerotia

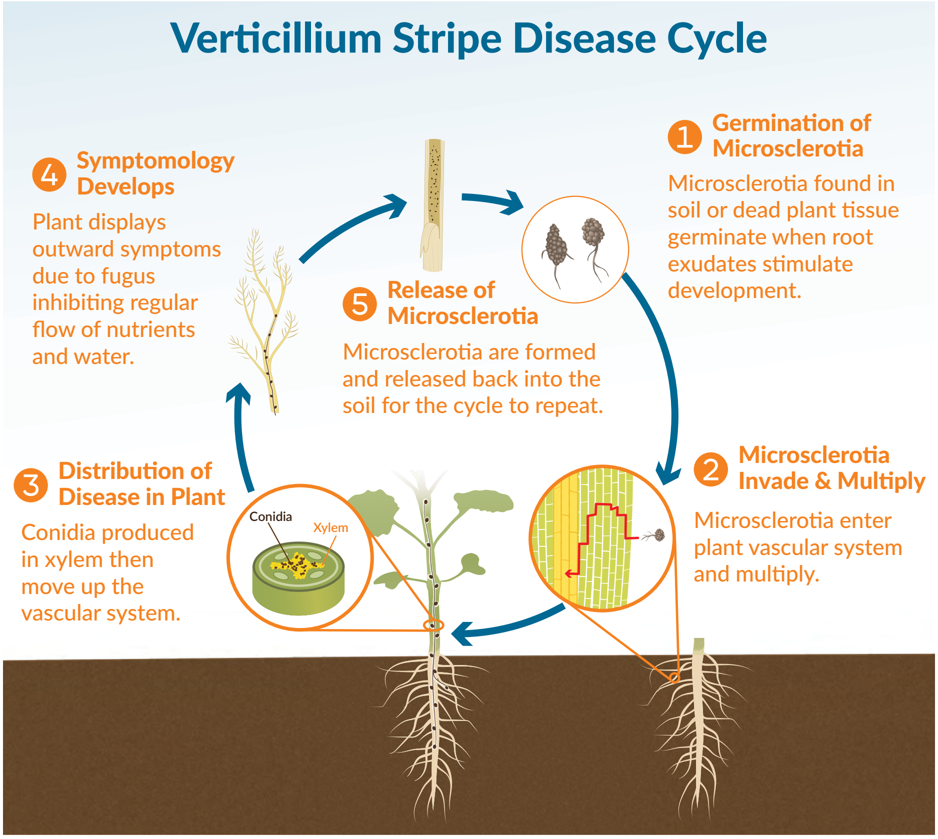


Figure 1. Verticillium stripe disease life cycle.

SCOUTING TIPS

- It is best to start looking for symptoms after flowering, although symptoms are not typically observed until later in the growing system, when plants are near maturation.
- Post-harvest or after swathing may be the best time to scout for this disease when you are also looking for blackleg, white mold, and clubroot.
- Verticillium stripe can easily be mistaken for other diseases, such as blackleg and Sclerotinia stem rot, at first.
- While shredding of the stem is similar to Sclerotinia stem rot, the large sclerotia and hollowing inside the stem of Sclerotinia is different than the tiny microsclerotia of verticillium stripe.
- Discolored stems and premature ripening can also be symptoms of blackleg. Cutting the stem at ground level and observing a cross-section of the stem can clarify. Blackening inside the stem will identify blackleg.

DISEASE LIFE CYCLE

- The rapid germination of microsclerotia in the soil is triggered by the root exudate (fluids emitted by the roots). This is necessary in order to successfully infect the roots at the most susceptible location of the fast-growing root tip.
- Additionally, the beginning of the flowering plant stage has been said to be important to the spread of *V. longisporum* in canola, as the plant is believed to be the most susceptible.
- The fungus can enter the vascular system by root directly or through an open wound in the root via fungal hyphae.
- After the hyphae multiply in the root, hyphae and single-cell spores called conidia are produced locally in the xylem and move through the vascular system of the plant to multiply.
- This inhibits the flow of water and nutrient up to the plant tissues, eventually causing the xylem to plug, turn black, collapse, and shrivel.
- The pathogen then moves into non-vascular tissue where microsclerotia are formed. The microsclerotia are released in the soil and the cycle repeats.

MANAGEMENT

- There are no foliar or seed treatment fungicides currently registered for control of Verticillium stripe in canola.
- At this time, there is no characterized host resistance in canola hybrids to *V. longisporum*; however, differences in susceptibility between hybrids have been reported.

Root cross-section of plants prior to harvest. Verticillium stripe (left), blackleg (middle), and healthy plant (right).

- In northern Europe, where this disease has been an important issue for more than 30 years, it is recommended that growers leave three years between canola crops. This allows the pathogen population to naturally decline in the soil, but due to the long-lived microsclerotia, rotation alone is not enough to manage this disease effectively.

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

THE PIONEER® YIELD PYRAMID™ DECISION TOOL

KEY POINTS

- The Pioneer® Yield Pyramid™ is a proprietary, data-driven decision tool that helps prioritize management practices most likely to increase corn yield potential.
- The tool is built on more than 10 years of site-specific weather, soil, fertility, and management data from over 56,000 locations.
- Advanced data science techniques were used to group locations with similar characteristics into 10 different genetic x environment x management (GEM) zones.
- Within each GEM zone, there are five yield levels, each with corresponding management factors.

INTRODUCTION

Many farmers ask, "Where should I invest money to continue to increase my corn yields?" For the 2022 growing season, this can be a tough question. With the costs of inputs rising, farmers must prioritize where they invest in their operations. A recent article from the University of Illinois shows that the price of a ton of anhydrous ammonia, DAP, and potash, increased 53%, 83%, and 71%, respectively, in 2021 (Schnitkey et al., 2021). Pioneer has developed a tool that can help farmers answer some of these questions. The Pioneer® Yield Pyramid™ decision tool is a new proprietary, data-driven tool designed to bring even more value to farmers. By identifying where a grower is currently with crop yield and then identifying certain management decisions and practices, this tool can help increase yield potential in specific areas.

Figure 1. The Pioneer® Yield Pyramid™ Levels

WHAT IS THE PIONEER® YIELD PYRAMID™ DECISION TOOL?

The Pioneer® Yield Pyramid™ is a decision tool that allows farmers to manage the complexity of crop management decisions by prioritizing those practices that increase corn yield potential in their area. The power of this tools lies in on-farm data collected by the Pioneer Agronomy team from 2011 to 2020. Site-specific weather, management, and soil data from more than 56,000 locations are grouped into 10 genetic x environment x management (GEM) zones. These GEM zones are the first step in the yield pyramid. There are five yield levels within each GEM zone, each with corresponding management factors: Level one

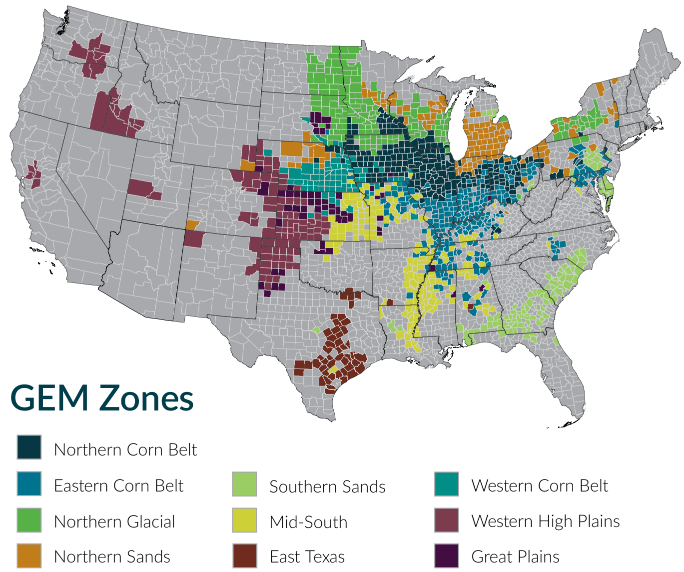


Figure 2. A map showing the locations of the 10 genetic x environment x management zones.

represents USDA county average corn yield, Levels two through four are based off internal Pioneer data. The fifth level represents the future and where corn yields are heading. Figure 1 provides a visual of each of the yield levels.

GENETIC X ENVIRONMENT X MANAGEMENT ZONES

When data is used to help make farming decisions, it is often assumed that fields closest to you are the ones that you should reference when making management decisions. However, locations closest to you may or may not be a good reference. For example, if you have a farm with sandy soil that is well drained, data from fields that are close by but have heavier silt loam soils and are somewhat poorly drained may not be helpful in making decisions. The first step to using the Pioneer® Yield Pyramid™ decision tool is to understand the environment that you are currently farming in.

The concept of GEM zones was borne out of the idea that locations that have similar characteristics can be more useful for

Table 1. Features of each of the 10 GEM zones

GEM Zone	Average Yield		Seasonal Average			Soil Texture
	USDA	Pioneer	Temperature	Precipitation	Solar Radiation	
	bu/acre		°F	inches	MJ/m²	
East Texas	97	125	75.7	13	2,388	Clay
Eastern Corn Belt	169	208	74	16	2,344	Silt Loam
Great Plains	124	134	74.1	10.6	2,743	Silt Loam
Mid-South	163	205	73.3	20	2,537	Silt Loam
Northern Corn Belt	192	234	69.9	19.8	2,619	Silt Loam
Northern Glacial	188	214	66.8	18	2,602	Loam
Northern Sands	169	215	67.9	16.3	2,634	Sandy Loam
Southern Sands	165	203	74.7	18.5	2,424	Sandy Loam
Western Corn Belt	161	211	72.1	13.3	2,784	Silt Loam
Western High Plains	165	234	73.7	8.5	2,883	Silt Loam

decision making than locations that are in close proximity but have different characteristics. Grouping locations with similar weather patterns, soil types, fertility levels, and management practices can give us a better understanding how changes in these features affect corn yield, and ultimately give us thousands of locations to compare to better understand if a farmer should implement management changes or not.

To execute this concept, The Pioneer Agronomy team collected site-specific weather, soil, fertility, and management data from more than 56,000 locations from 2011 through 2020. Advanced data science techniques, such as data clustering, were used to determine how locations aligned with each zone. A map of the 10 GEM zones is shown in Figure 2, and a table of weather, soil, and yield levels are in Table 1. When the attributes of each zone are compared, you can better understand what makes an environment unique. For example, a farmer in northern Iowa has a high probability of falling in the Northern Corn Belt GEM zone. On average, the Northern Corn Belt zone has above average yields and precipitation, below average growing season temperatures, and is a predominantly silt loam soil texture. These specific features make this zone unique, and by finding other locations that have similar characteristics, we can better understand how changes in management in this environment can help a farmer in northern Iowa to increase their yields.

HOW DO I USE THE PIONEER® YIELD PYRAMID™ DECISION TOOL?

1. Select the GEM zone that best describes where you farm. The GEM zones are defined using data analytics and consider major climate conditions, soil types, and yield levels typical of that GEM zone.
2. Determine where your field or farm falls on the Yield Pyramid. There are five tiers to the Yield Pyramid, representing five different yield levels as well as the crop inputs and management practices commonly used within each level.
3. Compare your management practices and yields with the management practices associated with each yield level. Determine if there are differences or gaps in your current crop management program compared to management associated with each yield level.
4. Develop a plan for moving up the Yield Pyramid. To move up the pyramid requires attention to the foundational management practices while addressing additional factors that become important as yields increase. A fundamental concept is that each key factor must be addressed at each layer before you can move up the yield pyramid.
5. Crop management variables are ranked in order of importance for each GEM zone. Use this ranking to help decide what factors may need addressed first in a field. This prioritization can help decide where to spend input dollars to optimize return on investment.
6. A suggested list of action items is provided for you to consider as you move from one yield layer to the next. Work with your local Pioneer Agronomist to fine tune these actions to your farm operation.

THE PIONEER® YIELD PYRAMID™ DECISION TOOL IN ACTION

Consider, as an example, a farmer in central Indiana with an average corn yield of 200 bu/acre. The map in Figure 2, shows that central Indiana is in the Eastern Corn Belt GEM zone. Based on the information collected by Pioneer, the Eastern Corn Belt GEM zone is characterized by highly productive soils, though some may have drainage issues or periods of drought. Weather patterns within this zone include wet springs and hotter, drier weather during grain fill. High nighttime temperatures may increase grain fill stress. High humidity levels throughout the growing season in this zone also increase the likelihood of foliar diseases.

The crop management variable rankings indicate that population, drainage class, and hybrid comparative relative maturity (CRM) have the most influence on corn yield (Figure 3). In general, higher populations are associated with higher yields. Yields could be further improved by increasing population specifically according to the yield goal and hybrid population recommendations. Locations that have well-drained soils have the highest potential yields, as do hybrids with longer CRM.

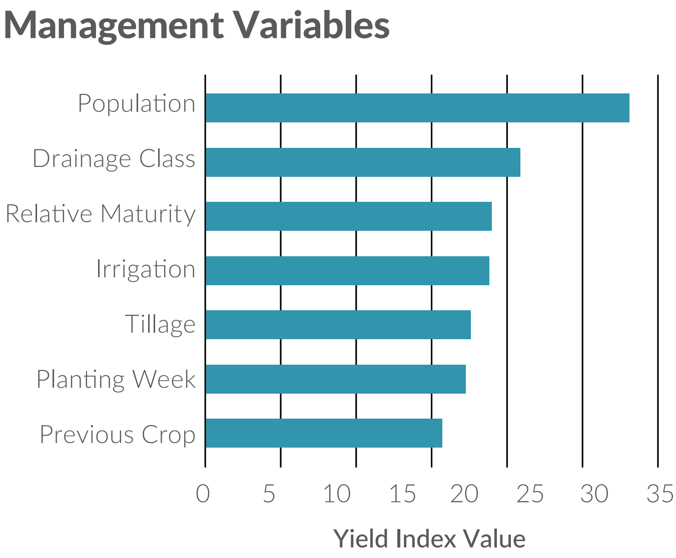


Figure 3. Rank order of most to least important management variables in the Eastern Corn Belt GEM zone.

Based on an average yield level of 200 bu/acre, this farm would be considered a Level 3 on the Pioneer® Yield Pyramid™, which has a corn yield range of 190 – 220 bu/acre. In this level, the focus will be managing the crop. Some key items that would specifically be targeted are:

- Fertilize to meet the nutrient replacement needs of the crop and possibly build soil test levels if they are below the soil test targets.
- Set population based on hybrid recommendations but target 32,800 plants/acre at a minimum.
- Plant a full-season hybrid as early as possible into fit soil conditions.
- Manage foliar diseases using a fungicide, such as Aproach® Prima.

Specific actions for Level 3 can be found in Figure 4.

Level 3 Management Practices

Eastern Corn Belt Zone

Level 3: Manage the Crop + Levels 1 & 2

1. Boost seeding rate to match yield goal according to Pioneer hybrid specific recommendations.
2. Use soil test targets and tissue sufficiency ranges to assess crop nutrient availability.
3. Build soil test to values within median range indicated for Level 3.
4. Focus on nitrogen (N) efficiency; split apply N with a preplant + an in-season application to improve efficiency to the crop.
5. Plant as early as possible into fit soil conditions.
6. Plant as late of comparative relative maturity hybrid as suited to your latitude
7. Scout and treat insects as well as foliar diseases according to university insect integrated pest management economic thresholds.
8. Diversify crop rotation.

Level 2 to Level 3

Level 2 Target = 188 bu/acre	Action	Level 3 Target = 222 bu/acre
N = 1.0-1.2 lbs/bu yield goal	267 lbs N/acre split applied, subtract credits	
P soil test = 38 ppm	90 lbs P_2O_5/acre**	P soil test = 40 ppm
K soil test = 132 ppm	85 lbs K_2O/acre**	K soil test = 143+ ppm
pH < 6.0 (BpH = 6.8)	Apply lime	pH = 6.0+
N to S ratio	15-20 lbs S/acre	N to S ratio 14:1
Population = 31,000 plants/acre	Consult Pioneer hybrid by yield level recommendations	Population = 32,500 plants/acre
Foliar fungicide	Aproach® Prima fungicide	

**Replace grain crop removal **Build (removal + 20)*

Figure 4. Level 3 management practices for the Eastern Corn Belt GEM Zone.

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AGRONOMY TEAM

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

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

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

Dan Berning, ***Agronomy Manager***

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

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

Danny leads Commercial UAS training and compliance for the field sales team. In addition, his work supports the execution, analysis and delivery of on-farm agronomy trials that drive Pioneer Agronomy innovation. Danny started his career with Corteva Agriscience in 2019, where he managed disease screening trials and supported precision phenotyping efforts for corn, soybean, and wheat breeding programs. He earned his B.S. in Agronomy and a M.S. in soil science both from Iowa State University. Danny completed his research in western Africa, studying agronomic applications of UAS technology. Danny is a native of central Illinois and is passionate about utilizing innovative technology to support agricultural production.

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

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

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

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

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

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

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

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

Darrin Malone, ***Agronomy Leader - MidSouth***

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

Luke Northway, M.S., ***Agronomy Systems Manager***

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

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

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

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

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

April Battani, ***Graphic Designer***

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

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FOOTNOTES AND ACKNOWLEDGMENTS

[1] All Pioneer products are hybrids unless designated with AM1, AM, AMRW, AML, AMT, AMX, AMXT and Q, in which case they are brands.

[2] All Pioneer products are varieties unless designated with LL, in which case some are brands.

[3] Data is based on 10-state broad-acre head-to-head strip trial comparing Lumialza™ nematicide seed treatment vs. non-nematicide seed treatment utilizing the same insecticide and fungicide recipe in seed-applied technology replicated and strip trial data. Yields ranged from 3 to 9 bu/A depending on nematode species and population, in 184 low stress and 54 moderate to high stress locations.

Photos on page 141 provided courtesy of Deere and Co.

Photos on pages 9, 63, and 75 provided courtesy of CNH.

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.

AMXT - Optimum® AcreMax® XTreme contains a single-bag integrated refuge solution for above- and below-ground insects. The major component contains the Agrisure® RW trait, a Bt trait, and the Herculex® XTRA genes. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax XTreme products.

YGCB,HX1,LL,RR2 (Optimum® Intrasect®) - Contains a Bt trait and Herculex® I gene for resistance to corn borer.

AMT - Optimum® AcreMax® TRIsect® Insect Protection System with RW,YGCB,HX1,LL,RR2. Contains a single-bag refuge solution for above and below ground insects. The major component contains the Agrisure® RW trait, a Bt trait, and the Herculex® I genes. In EPA-designated cotton growing counties, a 20% separate corn borer refuge must be planted with Optimum AcreMax TRIsect products.

Qrome® products are approved for cultivation in the U.S. and Canada. They have also received approval in a number of importing countries, most recently China. For additional information about the status of regulatory authorizations, visit http://www.biotradestatus.com/

Components of LumiGEN® seed treatments are applied at a Corteva Agriscience production facility, or by an independent sales representative of Corteva Agriscience or its affiliates. Not all sales representatives offer treatment services, and costs and other charges may vary. See your sales representative for details. Seed applied technologies exclusive to Corteva Agriscience and its affiliates.

Lumialza™ is registered for sale and use in several countries, with additional registrations in progress. The information provided here is not an offer for sale. Contact your country pesticide regulatory agency to determine if Lumialza is registered for sale or use in your country. Always read and follow label instructions.

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ALWAYS READ AND FOLLOW PESTICIDE LABEL DIRECTIONS. Roundup Ready® crops contain genes that confer tolerance to glyphosate, the active ingredient in Roundup® brand agricultural herbicides. Roundup® brand agricultural herbicides will kill crops that are not tolerant to glyphosate.

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Varieties with the Glyphosate Tolerant trait contain genes that confer tolerance to glyphosate herbicides. Glyphosate herbicides will kill crops that are not tolerant to glyphosate.

Always follow grain marketing, stewardship practices and pesticide label directions. Varieties with BOLT technology provide the highest degree of plant-back flexibility for soybeans following application of SU (sulfonylurea) herbicides such as DuPont™ LeadOff® or DuPont™ Basis® Blend as a component of a burndown program.

DO NOT APPLY DICAMBA HERBICIDE IN-CROP TO SOYBEANS WITH Roundup Ready 2 Xtend® technology unless you use a dicamba herbicide product that is specifically labeled for that use in the location where you intend to make the application. IT IS A VIOLATION OF FEDERAL AND STATE LAW TO MAKE AN IN-CROP APPLICATION OF ANY DICAMBA HERBICIDE PRODUCT ON SOYBEANS WITH Roundup Ready 2 Xtend® technology, OR ANY OTHER PESTICIDE APPLICATION, UNLESS THE PRODUCT LABELING SPECIFICALLY AUTHORIZES THE USE. Contact the U.S. EPA and your state pesticide regulatory agency with any questions about the approval status of dicamba herbicide products for in-crop use with soybeans with Roundup Ready 2 Xtend® technology.

ALWAYS READ AND FOLLOW PESTICIDE LABEL DIRECTIONS. Soybeans with Roundup Ready 2 Xtend® technology contain genes that confer tolerance to glyphosate and dicamba. Glyphosate herbicides will kill crops that are not tolerant to glyphosate. Dicamba will kill crops that are not tolerant to dicamba.

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