Research

Corn Yield Loss Estimates Due to Diseases in the United States and Ontario, Canada, from 2016 to 2019

Daren S. Mueller,[1,†] Kiersten A. Wise,[2] Adam J. Sisson,[1] Tom W. Allen,[3] Gary C. Bergstrom,[4] Kaitlyn M. Bissonnette,[5] Carl A. Bradley,[2] Emmanuel Byamukama,[6] Martin I. Chilvers,[7] Alyssa A. Collins,[8] Paul D. Esker,[9] Travis R. Faske,[10] Andrew J. Friskop,[11] Austin K. Hagan,[12] Ron W. Heiniger,[13] Clayton A. Hollier,[14] Tom Isakeit,[15] Tamra A. Jackson-Ziems,[16] Douglas J. Jardine,[17] Heather M. Kelly,[18] Nathan M. Kleczewski,[19] Alyssa M. Koehler,[20] Steve R. Koenning,[21] Dean K. Malvick,[22] Hillary L. Mehl,[23] Ron F. Meyer,[24] Pierce A. Paul,[25] Angie J. Peltier,[26] Paul P. Price,[27] Alison E. Robertson,[1] Gregory W. Roth,[28] Edward J. Sikora,[12] Damon L. Smith,[29] Connie A. Tande,[6] Darcy E. P. Telenko,[30] Albert U. Tenuta,[31] Lindsey D. Thiessen,[13] and William J. Wiebold[5]

[1] Department of Plant Pathology and Microbiology, Iowa State University, Ames, IA 50011, U.S.A.
[2] Department of Plant Pathology, University of Kentucky Research and Education Center, Princeton, KY 42445, U.S.A.
[3] Delta Research and Extension Center, Mississippi State University, Stoneville, MS 38776, U.S.A.
[4] Plant Pathology and Plant-Microbe Biology Section, Cornell University, Ithaca, NY 14853, U.S.A.
[5] Division of Plant Sciences, University of Missouri, Columbia, MO 65211, U.S.A.
[6] Department of Agronomy, Horticulture, and Plant Science, South Dakota State University, Brookings, SD 57007, U.S.A.
[7] Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI 48824, U.S.A.
[8] Department of Plant Pathology and Environmental Microbiology, The Pennsylvania State University Southeast Agricultural Research and Extension Center, Manheim, PA 17545, U.S.A.
[9] Department of Plant Pathology and Environmental Microbiology, The Pennsylvania State University, University Park, PA 16802, U.S.A.
[10] Lonoke Extension Center, University of Arkansas Division of Agriculture, Lonoke, AR 72086, U.S.A.
[11] Department of Plant Pathology, North Dakota State University, Fargo, ND 58102, U.S.A.
[12] Department of Entomology and Plant Pathology, Auburn University, Auburn, AL 36849, U.S.A.
[13] Department of Crop Science, North Carolina State University, Plymouth, NC 27962, U.S.A.
[14] Department of Plant Pathology and Crop Physiology, Louisiana State University, Baton Rouge, LA 70803, U.S.A.
[15] Department of Plant Pathology and Microbiology, Texas A&M University, College Station, TX 77843, U.S.A.
[16] Department of Plant Pathology, University of Nebraska–Lincoln, Lincoln, NE 68588, U.S.A.
[17] Department of Plant Pathology, Kansas State University, Manhattan, KS 66506, U.S.A.
[18] Department of Entomology and Plant Pathology, West Tennessee Research and Education Center, University of Tennessee, Jackson, TN 38301, U.S.A.
[19] Department of Crop Sciences, University of Illinois, Urbana, IL 61801, U.S.A.
[20] Department of Plant and Soil Sciences, University of Delaware, Georgetown, DE 19947, U.S.A.
[21] Department of Entomology and Plant Pathology, North Carolina State University, Raleigh, NC 27695, U.S.A.
[22] Department of Plant Pathology, University of Minnesota, St. Paul, MN 55108, U.S.A.
[23] Virginia Tech Tidewater Agricultural Research and Extension Center, Suffolk, VA 23437, U.S.A.
[24] Colorado State University Extension, Burlington, CO 80807, U.S.A.
[25] Department of Plant Pathology, The Ohio State University, Wooster, OH 44691, U.S.A.
[26] University of Minnesota Extension, Crookston, MN 56716, U.S.A.
[27] Macon Ridge Research Station, LSU AgCenter, Winnsboro, LA 71295, U.S.A.
[28] Department of Plant Science, The Pennsylvania State University, University Park, PA 16802, U.S.A.
[29] Department of Plant Pathology, University of Wisconsin–Madison, Madison, WI 53706, U.S.A.
[30] Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN 47907, U.S.A.
[31] Ontario Ministry of Agriculture, Food and Rural Affairs, Ridgetown, Ontario N0P 2C0, Canada

Accepted for publication 10 July 2020.

[†]Corresponding author: D. S. Mueller; dsmuelle@iastate.edu

The author(s) declare no conflict of interest.

Abstract

Annual reductions in corn (*Zea mays* L.) yield caused by diseases were estimated by university Extension-affiliated plant pathologists in 26 corn-producing states in the United States and in Ontario, Canada, from 2016 through 2019. Estimated loss from each disease varied greatly by state or province and year. Gray leaf spot (caused by *Cercospora zeae-maydis* Tehon & E.Y. Daniels) caused the greatest estimated yield loss in parts of the northern United States and Ontario in all years except 2019, and Fusarium stalk rot (caused by *Fusarium* spp.) also greatly reduced yield. Tar spot (caused by *Phyllachora maydis* Maubl.), a relatively new disease in the United States, was estimated to cause substantial yield loss in 2018 and 2019 in several northern states. Gray leaf spot and southern rust (caused by *Puccinia polysora* Underw.) caused the most estimated yield losses in the southern United States. Unfavorable wet and delayed harvest conditions in 2018 resulted in an estimated 2.5 billion bushels (63.5 million metric tons) of grain contaminated with mycotoxins. The estimated mean economic loss due to reduced yield caused by corn diseases in the United States and Ontario from 2016 to 2019 was US$55.90 per acre (US$138.13 per hectare). Results from this survey provide scientists, corn breeders, government agencies, and educators with data to help inform and prioritize research, policy, and educational efforts in corn pathology and disease management.

Keywords: corn, maize, disease, yield loss, economic loss

Corn (*Zea mays* L.) diseases reduce grain yield and quality each year in the United States and Ontario, Canada. Occurrence of corn diseases that reduce yield is influenced by many factors, including environmental conditions, crop production practices, previous disease history, and hybrid susceptibility to disease (Munkvold and White 2016). For these reasons, diseases of economic importance vary annually and across locations. In order to estimate the impact of corn diseases, the specific objective of this survey was to determine annual estimated disease losses in field corn for each of 26 corn-producing states in the United States and for Ontario, Canada.

Recent estimates of annual yield loss caused by corn disease in individual states within the United States and in Ontario, Canada, were determined by university plant pathologists and ranged from 7.5 to 13.5% of grain production from 2012 to 2015 (Mueller et al. 2016). Prior to this, Munkvold and White (2016) estimated the range of annual yield losses caused by corn diseases in the United States to be from 2 to 15%. A recent survey conducted by Savary et al. (2019) estimated that corn yield losses due to disease in the Midwest United States and Canada align with the aforementioned previously reported estimates. Although rare, catastrophic losses caused by corn disease have occurred. In 1970, a southern corn leaf blight (caused by *Bipolaris maydis* [Y. Nisik. & C. Miyake] Shoemaker) epidemic resulted in a 20% corn yield reduction in the United States (Ullstrup 1972). Signs and symptoms of certain field corn diseases are often observed on plants yet result in minimal yield reductions. Frequently occurring diseases, for which yield reduction often is considered negligible, include common rust (caused by *Puccinia sorghi* Schwein) and eyespot (caused by *Kabatiella zeae* Narita & Y. Hirats.) on hybrid corn (Wise et al. 2016). Conversely, yield loss caused by diseases may also remain unnoticed or unrecognized due to misdiagnosis. Examples include yield reduction through reduced ear size, poor grain fill, and early eardrop from stalk rots (Jardine 2006), or plant-parasitic nematodes that can cause aboveground symptoms mistakenly attributed to environmental conditions or nutritional deficiencies (Norton and Nyvall 2011). Additionally, pathogens that cause ear and stalk rots, such as *Aspergillus* and *Fusarium*, produce mycotoxins that can make grain unsafe or of lower quality for animal or human consumption (Bennett and Klich 2003; Wise et al. 2016).

The total corn production across the entire United States and Ontario, Canada, from 2016 to 2019 was 59.1 billion bushels (1.5 billion metric tons), which was valued at US$210.7 billion (OMAFRA 2020; USDA-NASS 2020). Consequently, even if only the lowest estimated annual yield loss of 2% was realized, the loss during these four years would total nearly 1.2 billion bushels (30.5 million metric tons), equating to more than US$4.2 billion in lost revenue. Grain loss caused by corn diseases results in decreased food, feed, and fuel production.

The goal of this survey was to determine the relative importance of multiple corn diseases regionally and temporally, equipping researchers, government, breeders, industry, and Extension specialists with data to aid prioritization of educational needs, research investigations, and funding requests.

Data Collection and Loss Estimate Determination

Disease loss estimates were provided by U.S. and Canadian members of the Corn Disease Working Group after the end of each growing season from 2016 to 2019. States and the Canadian province of Ontario were divided up into a "southern" and a "northern" geographic region. The northern region consisted of Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, Wisconsin, and Ontario, Canada. The southern region consisted of Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia. A list of diseases was provided to plant pathologists annually. Respondents were asked to estimate percent losses for each disease and to include information about any relevant diseases not listed. Respondents used various methods to estimate corn yield losses caused by diseases, and most individuals relied on more than one method to obtain the most accurate estimate possible for each state. The methods used for estimating corn yield losses caused by diseases varied by state or province as well as year and included estimates based on statewide or provincial disease surveys, feedback from university Extension, industry, and farmer representatives, plant disease diagnostic laboratory samples, research plots, personal experience with disease losses, and/or other methods. Disease loss estimates were primarily for hybrid corn harvested for grain. Estimates for losses from bacterial leaf streak (caused by *Xanthomonas vasicola* pv. *vasculorum*, [Cobb] comb. nov.) and tar spot (caused by *Phyllachora maydis* Maubl.) began in 2017 and 2018, respectively, as these diseases became more important risks to corn production. Estimates for Virginia and Alabama began in 2017 and 2019, respectively.

Yearly production in bushels (yield), crop value in U.S. dollars (USD), and number of planted acres for corn grown in each state or province were obtained from the U.S. Department of Agriculture – National Agricultural Statistics Service (USDA-NASS) and the Ontario Ministry of Agriculture, Food and Rural Affairs

(OMAFRA), available at the time of writing. Total Ontario crop value in each year was determined by applying the U.S. national marketing year corn price to the total estimated production value in bushels from Ontario. Disease loss values (bushels per acre) were determined based on yield before estimated losses as follows for each state or province: {bushels harvested/[(100 – percent estimated disease loss)/100]}. Total bushels lost per disease was then calculated for each state or province: [(percent loss/100) × yield before estimated loss]. Losses in crop value in USD were determined similarly. Total per-acre losses in USD for each state or province were determined by dividing total estimated crop value losses by the number of acres planted.

Results and Implications

The current survey represents 98.0% of the total corn produced in the United States and Ontario between 2016 and 2019. Total annual production in the states and province covered by this survey ranged from a low of 13.8 billion bushels (350.5 million metric tons) in 2019 to a high of 15.2 billion bushels (386.1 million metric tons) in 2016 (Table 1). Individual state and provincial production values varied widely from year to year.

The estimated corn production losses per year across all states and Ontario, Canada, combined were 10.8, 6.7, 10.9, and 6.8% for 2016, 2017, 2018, and 2019, respectively. The average of these values is slightly lower than the average of yearly production losses reported from 2012 to 2015, which ranged from 7.5 to 13.5% (Mueller et al. 2016). Estimates of total corn production losses due to diseases differed greatly by state or province and year, from negligible yield loss in Mississippi in 2017 to 22.8% in Ohio in 2016 (Table 2). States that produced more corn generally had greater estimates of loss due to disease. Indiana, Kansas, and Ohio were observed to have the greatest estimated average percent yield losses from the states that provided data for all four years of this study, whereas estimates from Mississippi, Texas, and Arkansas were the lowest. Yield loss estimates do not account for potential grain contamination or rejection as a result of mycotoxins because contaminated or rejected grain is likely still used in some capacity, but it may be discounted or used in ways other than originally intended (Munkvold et al. 2012).

Loss of bushels of corn is a more useful indicator than percent production loss. A 1% loss during a year with lower production is different than a 1% loss during a more productive year. Similarly, a

TABLE 1
Total corn production (bushels in thousands) in the United States and Ontario, Canada, from 2016 to 2019

State/province	2016	2017	2018	2019	Total
Alabama	37,800	39,245	38,220	44,835	160,100
Arkansas	127,395	108,885	116,745	126,875	479,900
Colorado	160,290	185,900	154,700	159,900	660,790
Delaware	27,880	32,319	24,070	28,980	113,249
Illinois	2,255,650	2,200,950	2,268,000	1,846,200	8,570,800
Indiana	946,310	936,000	967,680	814,580	3,664,570
Iowa	2,740,500	2,605,800	2,499,000	2,583,900	10,429,200
Kansas	698,640	686,400	642,420	800,660	2,828,120
Kentucky	222,600	217,160	213,500	245,050	898,310
Louisiana	90,750	90,160	77,850	89,925	348,685
Maryland	60,800	72,240	55,480	74,060	262,580
Michigan	320,280	300,510	289,170	239,890	1,149,850
Minnesota	1,544,000	1,480,220	1,357,720	1,263,240	5,645,180
Mississippi	119,520	94,500	85,100	107,880	407,000
Missouri	570,500	552,500	466,200	463,450	2,052,650
Nebraska	1,699,900	1,683,300	1,785,600	1,785,420	6,954,220
New York	73,530	78,085	97,785	86,110	335,510
North Carolina	121,260	119,280	93,790	103,230	437,560
North Dakota	516,660	448,970	448,290	455,430	1,869,350
Ohio	524,700	557,550	617,100	421,480	2,120,830
Ontario	317,000	344,000	345,176	340,164	1,346,340
Pennsylvania	122,550	148,120	124,600	162,180	557,450
South Dakota	825,930	736,600	777,600	566,950	2,907,080
Tennessee	125,330	121,410	112,560	161,070	520,370
Texas	323,850	313,600	189,000	285,950	1,112,400
Virginia	50,320	47,600	47,450	54,720	200,090
Wisconsin	573,160	509,820	545,240	450,240	2,078,460
Total	**15,197,105**	**14,711,124**	**14,440,046**	**13,762,369**	**58,110,644**
Southern U.S.A.[a]	1,878,005	1,808,899	1,519,965	1,786,025	6,992,894
Northern U.S.A.[b] and Ontario, Canada	13,319,100	12,902,225	12,920,081	11,976,344	51,117,750

[a] Southern United States includes Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.

[b] Northern United States includes Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

1% loss in a major production state differs in total magnitude compared with a 1% loss in a state with lower corn production. Total estimated bushels lost for each year was 1.8 billion (45.7 million metric tons) in 2016, 1.1 billion (27.9 million metric tons) in 2017, 1.8 billion (45.7 million metric tons) in 2018, and 1.0 billion (25.4 million metric tons) in 2019 (Table 3). Yearly estimated bushel losses were substantially greater in 2016 and 2018 than in 2017 and 2019, with losses appearing cyclical in nature. Greater estimated losses in 2016 and 2018 had much to do with Iowa, which reported greater bushel losses than any other state because Iowa produces more grain than any other state and disease was severe. To illustrate this, the average reported percent yield losses to corn diseases across all states and Ontario were 7.9% in 2016 and 6.9% in 2018, whereas yield losses reported in Iowa were 16.4% for 2016 and 18.6% for 2018 (Table 2). The Iowa values were more than twice the average percent loss during these two years. Furthermore, Iowa values were 60% greater when compared with the average reported losses from the top four corn-producing states (Illinois, Iowa, Minnesota, and Nebraska), which also border Iowa. Iowa values were closer to the average percent loss for all states and Ontario, Canada, in 2017 and 2019, although they were still greater. However, there were other states that reported greater percent losses than Iowa in all years except 2018.

The estimated impact that each specific disease had on corn production in the United States and Ontario was highly variable by disease and year, ranging from approximately 5,000 bushels (127 metric tons) of yield loss due to crazy top (caused by *Sclerophthora macrospora* [Sacc.] Thirum., C.G. Shaw & Naras.) in 2017, to more than 482 million bushels (12.2 million metric tons) lost due to gray leaf spot (caused by *Cercospora zeae-maydis* Tehon & E.Y. Daniels) in 2018 (Table 4). Gray leaf spot also caused the greatest estimated yield loss out of all diseases, followed by Fusarium stalk rot (caused by *Fusarium* spp.). Most diseases cause some amount of yield loss every year, and certain years have increased disease development. Examples include anthracnose leaf blight (caused by *Colletotrichum graminicola* [Ces.] G.W. Wilson) and eyespot, which had much greater reported losses in 2016 compared with 2017 through 2019.

TABLE 2
Total estimated percent losses due to corn diseases in the United States and Ontario, Canada, from 2016 to 2019, excluding grain contamination or rejection due to mycotoxins

State/province	2016	2017	2018	2019	Average
Alabama[a]	…	…	…	0.02	0.02
Arkansas	1.94	1.87	0.23	0.03	1.02
Colorado	4.23	5.01	3.05	0.04	3.08
Delaware	6.09	7.64	7.23	3.06	6.00
Illinois	8.93	7.93	9.65	6.62	8.29
Indiana	15.95	7.84	11.78	14.64	12.55
Iowa	16.36	6.80	18.62	8.17	12.49
Kansas	13.64	16.73	17.32	13.35	15.26
Kentucky	7.82	3.30	1.19	2.06	3.59
Louisiana	1.62	4.48	0.86	0.22	1.79
Maryland	6.09	7.64	7.23	3.06	6.00
Michigan	10.24	4.70	10.31	18.00	10.81
Minnesota	2.78	6.17	2.24	3.18	3.59
Mississippi	0.28	0.00	0.04	0.03	0.09
Missouri	12.63	2.56	1.92	4.10	5.30
Nebraska	12.70	5.84	15.12	5.72	9.85
New York	3.56	5.85	8.49	3.57	5.37
North Carolina	13.00	3.70	3.24	2.69	5.66
North Dakota	1.70	2.70	1.71	0.51	1.65
Ohio	22.80	10.70	14.90	7.23	13.91
Ontario	6.15	7.35	8.17	5.22	6.72
Pennsylvania	8.73	8.70	10.68	6.70	8.70
South Dakota	4.69	1.69	1.83	2.49	2.68
Tennessee	2.48	2.36	1.08	1.11	1.76
Texas	0.76	0.88	0.33	0.46	0.61
Virginia[b]	…	6.50	9.10	7.22	7.61
Wisconsin	11.13	8.13	14.16	11.51	11.23
Average	**7.85**	**5.66**	**6.94**	**4.85**	**6.13**
Southern U.S.A.[c] average	5.27	3.72	2.95	2.00	3.29
Northern U.S.A.[d] and Ontario average	9.57	7.08	9.87	7.13	8.41

[a] Data collection from Alabama began in 2019.
[b] Data collection from Virginia began in 2017.
[c] Southern United States includes Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.
[d] Northern United States includes Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

The most destructive diseases in the 14 northern United States and Ontario, Canada, varied little by year (Table 5). Gray leaf spot caused the greatest yield loss among all diseases from 2016 to 2018 and caused the second greatest yield loss in 2019. Fusarium stalk rot was always in the top three most destructive diseases and caused the highest estimated yield loss of any disease in 2019. Gray leaf spot and Fusarium stalk rot were particularly devastating in 2018, with yield loss estimates substantially greater than any other disease across all years. Neither gray leaf spot nor Fusarium stalk rot were the greatest cause of estimated annual yield loss from 2012 to 2015, although they were always ranked within the top 10 most destructive diseases in the northern region (Mueller et al. 2016). Other diseases commonly present in the top 10 most destructive diseases from 2016 to 2019 were anthracnose stalk rot and top dieback (caused by *Colletotrichum graminicola*), Fusarium ear rot (caused by *Fusarium* spp.), plant-parasitic nematodes (multiple genera), Goss's wilt (caused by *Clavibacter nebraskensis* [Davis, Gillaspie, Vidaver & Harris] Nouioui et al.), and northern corn leaf blight (caused by *Setosphaeria turcica* [Luttr.] K.J. Leonard & Suggs). Tar spot, a recently observed disease in the United States, caused the third greatest yield loss in 2018. Some diseases, such as southern rust (caused by *Puccinia polysora* Underw.) or Diplodia ear rot (caused by *Stenocarpella maydis* (Berk.) B. Sutton), were estimated to substantially reduce corn yield on an intermittent basis.

Trends also emerged in the 12 southern United States (Table 6). Foliar diseases such as gray leaf spot and southern rust caused the most estimated yield loss annually. Several other diseases such as anthracnose stalk rot and top dieback, northern corn leaf blight, Fusarium ear rot, Fusarium stalk rot, plant-parasitic nematodes (multiple genera), and root rots (caused by multiple genera) commonly ranked among the top 10 most destructive diseases each year from 2016 to 2019.

Environmental conditions fluctuated from year to year and greatly impacted final yield, as well as disease incidence and severity. For example, in 2018, the midwestern United States experienced its fifth wettest fall since 1895 (NOAA 2018b), and Ontario, Canada, also experienced a wet fall in 2018. Wet weather created harvest difficulties for many farmers and likely contributed

TABLE 3
Total estimated loss due to corn diseases (bushels in thousands) in the United States and Ontario, Canada, from 2016 to 2019, excluding grain contamination or rejection due to mycotoxins

State/province	2016	2017	2018	2019	Total
Alabama[a]	…	…	…	10	10
Arkansas	2,523	2,077	264	40	4,904
Colorado	7,080	9,805	4,867	58	21,809
Delaware	1,809	2,672	1,876	914	7,271
Illinois	221,263	189,672	242,321	130,883	784,139
Indiana	179,579	79,625	129,227	139,754	528,184
Iowa	536,042	190,003	571,673	229,794	1,527,513
Kansas	110,346	137,908	134,576	123,379	506,208
Kentucky	18,884	7,420	2,576	5,159	34,039
Louisiana	1,494	4,225	675	196	6,590
Maryland	3,944	5,972	4,324	2,337	16,577
Michigan	36,538	14,824	33,241	52,662	137,265
Minnesota	44,167	97,335	31,110	41,504	214,116
Mississippi	339	2	32	27	401
Missouri	82,478	14,516	9,131	19,824	125,949
Nebraska	247,294	104,459	318,133	108,362	778,247
New York	2,714	4,852	9,072	3,188	19,826
North Carolina	18,119	4,583	3,141	2,857	28,700
North Dakota	8,935	12,459	7,799	2,325	31,518
Ohio	154,963	66,806	108,047	32,848	362,664
Ontario	20,773	27,290	30,710	18,735	97,507
Pennsylvania	11,722	14,114	14,898	11,646	52,381
South Dakota	40,642	12,663	14,495	14,484	82,284
Tennessee	3,187	2,929	1,228	1,805	9,149
Texas	2,480	2,784	626	1,321	7,212
Virginia[b]	…	3,309	4,750	4,258	12,318
Wisconsin	71,782	45,116	89,942	58,563	265,403
Total	**1,829,098**	**1,057,420**	**1,768,732**	**1,006,933**	**5,662,184**
Southern U.S.A.[c]	135,258	50,489	28,622	38,749	253,118
Northern U.S.A.[d] and Ontario, Canada	1,693,840	1,006,931	1,740,110	968,184	5,409,066

[a] Data collection from Alabama began in 2019.
[b] Data collection from Virginia began in 2017.
[c] Southern United States includes Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.
[d] Northern United States includes Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

to higher-than-normal concentrations of mycotoxin contamination compared with other years (Table 4). Another example is that of southern rust, which caused the greatest or second greatest estimated yield losses in the southern region in all years except 2018, when it was not even ranked among the top 10 yield-reducing diseases (Table 6). Much of the estimated yield losses due to southern rust in the southern region occur in Missouri, which experienced severe drought conditions during the summer of 2018

TABLE 4
Total estimated corn yield losses (bushels in thousands) caused by disease or type of disease in 26 United States[a] and Ontario, Canada, from 2016 to 2019

Disease common name	Latin binomial	2016	2017	2018	2019	Total
Root rots	Various	23,270	26,933	18,754	35,091	104,048
Seedling blights	Various	17,462	67,680	23,659	25,343	134,145
Plant-parasitic nematodes[b]	Various	58,382	69,693	75,974	65,464	269,512
Anthracnose leaf blight	*Colletotrichum graminicola*	8,803	2,042	757	2,642	14,245
Bacterial leaf streak[c]	*Xanthomonas vasicola* pv. *vasculorum*	...	22,991	51,852	19,288	94,131
Carbonum leaf spot	*Cochliobolus carbonum*	4,823	1,655	4,974	12,035	23,487
Common rust	*Puccinia sorghi*	18,964	20,850	4,615	5,020	49,449
Common smut	*Ustilago maydis*	1,731	569	364	2,568	5,232
Crazy top	*Sclerophthora macrospora*	333	5	19	102	458
Eyespot	*Kabatiella zeae*	36,311	2,789	9,066	2,878	51,043
Goss's wilt	*Clavibacter nebraskensis*	90,773	70,532	68,226	9,821	239,352
Gray leaf spot	*Cercospora zeae-maydis*	235,331	187,795	482,145	146,308	1,051,579
Head smut	*Sphacelotheca reiliana*	314	248	270	287	1,119
Holcus spot	*Pseudomonas syringae*	3,576	75	70	347	4,067
Northern corn leaf blight	*Setosphaeria turcica*	151,318	43,818	43,177	64,047	302,360
Physoderma leaf spot	*Physoderma maydis*	63,097	31,317	34,030	21,264	149,708
Southern corn leaf blight	*Bipolaris maydis*	46	365	650	707	1,767
Southern rust	*Puccinia polysora*	158,638	107,546	3,121	28,973	298,278
Stewart's disease	*Pantoea stewartii*	0	23,907	251	198	24,356
Tar spot[d]	*Phyllachora maydis*	...	...	183,579	45,367	228,946
Maize dwarf mosaic	*Maize dwarf mosaic virus*	42	0	0	0	42
Other virus/virus-like diseases[e]	Various	0	3	0	0	3
Other foliar/aboveground diseases[f]	Various	42,795	275	22	264	43,355
Anthracnose stalk rot/top dieback	*Colletotrichum graminicola*	197,815	81,355	130,008	54,100	463,278
Bacterial stalk rot	*Erwinia* spp.	173	118	118	391	800
Charcoal rot	*Macrophomina phaseolina*	10,399	8,927	1,440	2,076	22,841
Diplodia stalk rot	*Stenocarpella maydis*	29,941	599	7,577	8,546	46,664
Fusarium stalk rot	*Fusarium* spp.	185,123	128,702	300,741	193,373	807,938
Gibberella stalk rot	*Fusarium graminearum*	80,842	23,971	71,524	34,095	210,431
Other stalk rots[g]	Various	32,765	1,426	7,955	4,634	46,781
Aspergillus ear rot	*Aspergillus flavus/A.* spp.	2,138	1,305	2,318	551	6,311
Diplodia ear rot	*Stenocarpella maydis*	173,230	49,518	33,090	17,988	273,825
Fusarium ear rot	*Fusarium* spp.	95,851	52,104	90,374	107,405	345,735
Gibberella ear rot	*Fusarium graminearum*	61,336	25,684	87,869	59,131	234,020
Other ear rots[h]	Various	43,476	2,623	30,145	36,632	112,876
Mycotoxin contamination[i]	—	128,544	120,962	2,464,239	881,751	3,595,497

[a] The states included Alabama (2019 only), Arkansas, Colorado, Delaware, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maryland, Michigan, Minnesota, Mississippi, Missouri, Nebraska, New York, North Carolina, North Dakota, Ohio, Pennsylvania, South Dakota, Tennessee, Texas, Virginia (2017 to 2019 only), and Wisconsin.

[b] Plant-parasitic nematodes includes *Belonolaimus*, *Helicotylenchus*, *Hoplolaimus*, *Longidorus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, *Tylenchorhynchus*, and *Xiphinema* spp.

[c] Data collection for bacterial leaf streak as a separate disease category began in 2017.

[d] Data collection for tar spot as a separate disease category began in 2018.

[e] Injury from other virus/virus-like diseases was reported in 2017, but no specific causal organism was indicated.

[f] Other foliar/aboveground diseases include bacterial leaf streak (2016 only; *Xanthomonas vasicola* pv. *vasculorum*), Curvularia leaf spot (*Curvularia lunata*), Diplodia leaf streak (*Stenocarpella macrospora*), and red root rot (*Phoma terrestris* and other fungi). Yield losses in 2016 in this category were primary caused by bacterial leaf streak in Nebraska (38,943,872 bushels).

[g] Other stalk rots include primarily reports of Physoderma stalk rot (*Physoderma maydis*).

[h] Other ear rots include Cladosporium ear rot (*Cladosporium herbarum*), Nigrospora ear rot (*Nigrospora oryzae*), Penicillium ear rot (*Penicillium* spp.), and Trichoderma ear rot (*Trichoderma viride*).

[i] Values are for contamination of grain only, not yield loss.

(NOAA 2018a). These dry conditions likely contributed to a reduction in southern rust risk that year, because the causal pathogen requires moisture for infection (Hollier and King 1985).

Overall, from 2016 to 2019 the total estimated economic loss due to disease was US$20.1 billion in the United States and Ontario, Canada (Table 7). Economic losses averaged approximately

TABLE 5
The 10 most destructive diseases and associated estimated corn yield losses (bushels in thousands) by disease or type of disease in the northern United States[a] and Ontario, Canada, from 2016 to 2019

	2016		2017		2018		2019	
Rank	Disease	Loss	Disease	Loss	Disease	Loss	Disease	Loss
1	Gray leaf spot	213,884	Gray leaf spot	175,650	Gray leaf spot	474,273	Fusarium stalk rot	192,664
2	Anthracnose stalk rot and top dieback	183,273	Fusarium stalk rot	127,644	Fusarium stalk rot	299,129	Gray leaf spot	130,433
3	Fusarium stalk rot	177,640	Southern rust	93,215	Tar spot	183,579	Fusarium ear rot	105,533
4	Diplodia ear rot	162,778	Anthracnose stalk rot and top dieback	80,445	Anthracnose stalk rot and top dieback	127,012	Plant-parasitic nematodes[b]	64,728
5	Northern corn leaf blight	145,215	Goss's wilt	70,438	Fusarium ear rot	88,422	Northern corn leaf blight	62,646
6	Southern rust	137,855	Plant-parasitic nematodes[c]	67,958	Gibberella ear rot	87,623	Gibberella ear rot	58,965
7	Goss's wilt	89,913	Seedling blights	67,432	Plant-parasitic nematodes[d]	74,770	Anthracnose stalk rot and top dieback	53,483
8	Fusarium ear rot	86,787	Fusarium ear rot	49,072	Gibberella stalk rot	70,205	Tar spot	45,367
9	Gibberella stalk rot	74,264	Diplodia ear rot	48,893	Goss's wilt	68,217	Other ear rots[e]	36,573
10	Physoderma leaf spot	63,031	Northern corn leaf blight	36,627	Bacterial leaf streak	51,833	Gibberella stalk rot	33,766

[a] Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.
[b] Plant-parasitic nematodes in 2019 include *Belonolaimus*, *Helicotylenchus*, *Hoplolaimus*, *Longidorus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, *Tylenchorhynchus*, and *Xiphinema* spp.
[c] Plant-parasitic nematodes in 2017 include *Helicotylenchus*, *Hoplolaimus*, *Longidorus*, *Paratrichodorus*, *Pratylenchus*, *Tylenchorhynchus*, and *Xiphinema* spp.
[d] Plant-parasitic nematodes in 2018 include *Belonolaimus*, *Helicotylenchus*, *Hoplolaimus*, *Longidorus*, *Paratrichodorus*, *Pratylenchus*, *Tylenchorhynchus*, and *Xiphinema* spp.
[e] Other ear rots in 2019 include Cladosporium ear rot (*Cladosporium herbarum*), Nigrospora ear rot (*Nigrospora oryzae*), Penicillium ear rot (*Penicillium* spp.), and Trichoderma ear rot (*Trichoderma viride*).

TABLE 6
The 10 most destructive diseases and associated estimated corn yield losses (bushels in thousands) by disease or type of disease in the southern United States[a] from 2016 to 2019

	2016		2017		2018		2019	
Rank	Disease	Loss	Disease	Loss	Disease	Loss	Disease	Loss
1	Gray leaf spot	21,448	Southern rust	14,331	Gray leaf spot	7,872	Gray leaf spot	15,875
2	Southern rust	20,783	Gray leaf spot	12,145	Northern corn leaf blight	3,145	Southern rust	7,896
3	Anthracnose stalk rot and top dieback	14,542	Northern corn leaf blight	7,191	Anthracnose stalk rot and top dieback	2,997	Root rots	3,124
4	Diplodia ear rot	10,452	Fusarium ear rot	3,032	Fusarium ear rot	1,952	Seedling blights	2,206
5	Charcoal rot	10,088	Root rots	2,030	Root rots	1,743	Fusarium ear rot	1,872
6	Diplodia stalk rot	9,986	Plant-parasitic nematodes[b]	1,736	Fusarium stalk rot	1,612	Northern corn leaf blight	1,400
7	Fusarium ear rot	9,064	Common rust	1,611	Physoderma leaf spot	1,381	Diplodia stalk rot	883
8	Fusarium stalk rot	7,483	Fusarium stalk rot	1,058	Gibberella stalk rot	1,318	Plant-parasitic nematodes[c]	736
9	Gibberella stalk rot	6,578	Gibberella ear rot	1,057	Plant-parasitic nematodes[b]	1,204	Fusarium stalk rot	708
10	Plant-parasitic nematodes[d]	6,332	Anthracnose stalk rot and top dieback	910	Seedling blights	1,137	Southern leaf blight	707

[a] Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.
[b] Plant-parasitic nematodes in 2017 and 2018 include *Belonolaimus*, *Hoplolaimus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, and *Tylenchorhynchus* spp.
[c] Plant-parasitic nematodes in 2019 include *Belonolaimus*, *Helicotylenchus*, *Hoplolaimus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, *Tylenchorhynchus*, and *Xiphinema* spp.
[d] Plant-parasitic nematodes in 2016 include *Hoplolaimus*, *Meloidogyne*, and *Paratrichodorus* spp.

US$5.02 billion annually during the survey period. Because economic losses are tied to bushel losses, the pattern of estimated monetary losses was similar to that observed with bushel losses.

The estimated mean economic loss due to reduced yield caused by corn diseases in the United States and Ontario from 2016 to 2019 was US$55.90 per acre (US$138.13 per hectare) (total estimated losses in USD divided by total acres planted). The corresponding value is considerably less than the estimated mean economic loss per acre from 2012 to 2015, which was US$76.51 (US$189.06 per hectare) (A. Sisson, *unpublished data*). A greater estimated loss per acre can be partially explained by national corn marketing year prices from 2012 to 2015, which averaged US$4.67 per acre (US$11.54 per hectare), whereas the average from 2016 to 2019 was US$3.55 per acre (US$8.77 per hectare) (USDA-NASS 2020). The average estimated annual yield losses due to disease from 2012 to 2015 were also slightly greater than those reported from 2016 to 2019 (Mueller et al. 2016). Individual estimated per acre losses from corn disease varied across year and region, ranging from US$0.02 (US$0.05 per hectare) in Mississippi in 2017 to US$157.58 (US$389.39 per hectare) in Ohio in 2016 (Table 8). In general, per acre losses were greater in the northern region than in the southern region.

Per acre losses are important to note, because these values may be larger than, or approach, the profit margins per acre in some years. For example, average corn production expenses for Iowa in 2018 were US$623.36 per acre (US$1,540.35 per hectare), whereas crop value was US$681.00 per acre (US$1,682.79 per hectare) (Plastina 2019). When per acre production expenses are subtracted from per acre crop value, US$57.64 remains (US$142.43 per hectare), a value that is much lower than the 4-year average of estimated yield loss due to corn diseases (US$98.68 per acre; US$243.84 per hectare) in Iowa. Conversely, Mississippi average estimated disease losses were only US$0.53 per acre (US$1.31 per hectare), which is much lower than estimated per acre returns for corn production in Mississippi (MSU 2016).

TABLE 7
Total estimated losses due to corn disease (USD[a] in thousands) in the United States and Ontario, Canada, from 2016 to 2019, excluding grain contamination or rejection due to mycotoxins

State/province	2016	2017	2018	2019	Total
Alabama[b]	…	...	...	43	43
Arkansas	9,310	7,561	1,001	155	18,028
Colorado	24,213	33,042	18,007	227	75,490
Delaware	7,397	10,740	7,710	3,932	29,779
Illinois	758,931	646,781	877,203	503,899	2,786,814
Indiana	651,873	283,465	488,476	572,990	1,996,804
Iowa	1,768,940	628,910	2,052,308	873,219	5,323,376
Kansas	353,106	452,340	481,781	456,501	1,743,727
Kentucky	70,626	27,380	9,890	21,153	129,050
Louisiana	5,529	15,716	2,607	772	24,624
Maryland	15,974	24,006	17,771	10,049	67,800
Michigan	125,691	51,291	123,655	210,649	511,286
Minnesota	141,776	309,526	107,951	151,489	710,742
Mississippi	1,269	9	123	108	1,509
Missouri	280,424	49,500	33,602	77,315	440,842
Nebraska	821,015	349,937	1,138,915	411,776	2,721,643
New York	10,586	19,747	37,740	13,612	81,685
North Carolina	73,746	19,432	13,787	12,713	119,677
North Dakota	26,895	37,874	25,893	8,255	98,917
Ohio	559,417	241,170	404,095	137,961	1,342,644
Ontario	69,797	91,694	110,863	72,128	344,482
Pennsylvania	47,357	54,623	62,871	51,244	216,095
South Dakota	125,585	39,127	48,994	53,589	267,295
Tennessee	11,665	10,400	4,616	7,128	33,810
Texas	9,201	10,301	2,584	5,682	27,769
Virginia[c]	…	13,104	19,286	17,672	50,062
Wisconsin	235,445	148,884	316,595	216,684	917,608
Total	**6,205,767**	**3,576,558**	**6,408,326**	**3,890,948**	**20,081,600**
Southern U.S.A.[d]	485,142	188,148	112,978	156,724	942,992
Northern U.S.A.[e] and Ontario, Canada	5,720,625	3,388,410	6,295,348	3,734,224	19,138,608

[a] U.S. dollars.
[b] Data collection from Alabama began in 2019.
[c] Data collection from Virginia began in 2017.
[d] Southern United States includes Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.
[e] Northern United States includes Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Economic losses caused by corn disease may be underestimated or overestimated. The costs to diagnose and manage diseases are additional corn production expenses that may not be considered in economic estimates of losses due to disease. Diagnostic costs include field scouting, fees for consultant or diagnostic services, and quantification of nematode population densities in soil samples. Management expenses for corn disease can include costs associated with crop rotation, tillage, fungicide and nematicide-treated seed, in-field nematicide application, and foliar fungicide (Munkvold and White 2016). For example, Wise et al. (2019) reported single foliar fungicide applications at VT (tasseling growth stage) averaged US$18.27 per acre (US$45.14 per hectare) and US$20.96 per acre (US$51.80 per hectare), for ground and aerial applications, respectively. Cost of fungicide application varies by region, supplier, product selected, and method of application (Wise et al. 2019). Other potential indirect expenses incurred as a result of corn diseases include refusal of seed for export due to contamination with a quarantined pathogen, costs associated with breeding corn for resistance to disease, grain quality reduction that results in livestock health issues (e.g., mycotoxins), and increased harvest difficulty from crop lodging (Munkvold and White 2016; Pataky 2003; Wise et al. 2016).

The risk of corn disease is not static and varies significantly over time and location based on numerous factors. Changing weather patterns that result in increased humidity, heavy rainfall frequency, and changes in temperature can increase the risk of some corn diseases (Arritt 2016; Todey 2014). Other factors that increase disease risk include reduced tillage and continuous corn production, and hybrid selection (Wise and Mueller 2011). Hybrid selection by farmers is often based on yield potential. Hybrids with high yield potential often have lower disease resistance (Brown and Rant 2013). Consequently, disease epidemics can occur when a large number of acres on a farm or within a region are planted to a popular, high yielding, but susceptible hybrid.

The yield reduction and costs associated with disease management continue to demonstrate the need for ongoing scientific research on disease-causing pathogens and farmer and agribusiness

TABLE 8
Total estimated losses due to corn diseases (USD[a]) per acre in the United States and Ontario, Canada, from 2016 to 2019, excluding grain contamination or rejection due to mycotoxins

State/province	2016	2017	2018	2019	Average by state/region
Alabama[b]	…	…	…	0.14	0.14
Arkansas	12.25	12.20	1.52	0.20	6.54
Colorado	18.07	22.63	12.33	0.15	13.30
Delaware	43.51	59.66	45.35	21.26	42.45
Illinois	65.43	57.75	79.75	47.99	62.73
Indiana	116.41	52.98	92.17	114.60	94.04
Iowa	127.26	47.29	155.48	64.68	98.68
Kansas	69.24	82.24	88.40	71.33	77.80
Kentucky	47.08	20.74	7.44	13.65	22.23
Louisiana	8.92	31.43	5.67	1.36	11.84
Maryland	34.73	50.01	40.39	19.70	36.21
Michigan	52.37	22.80	54.96	105.32	58.86
Minnesota	16.78	38.45	13.66	19.42	22.08
Mississippi	1.69	0.02	0.26	0.16	0.53
Missouri	76.83	14.56	9.60	24.16	31.29
Nebraska	83.35	36.64	118.64	40.77	69.85
New York	9.62	19.75	35.27	13.35	19.50
North Carolina	73.75	21.83	15.15	12.84	30.89
North Dakota	7.80	11.07	8.22	2.36	7.36
Ohio	157.58	70.93	115.46	49.27	98.31
Ontario	34.47	43.25	51.44	32.75	40.48
Pennsylvania	33.83	40.46	48.36	35.34	39.50
South Dakota	22.43	6.86	9.24	12.32	12.71
Tennessee	13.26	13.87	6.41	7.35	10.22
Texas	3.17	4.20	1.17	2.27	2.71
Virginia[c]	…	26.21	39.76	32.73	32.90
Wisconsin	58.13	38.18	81.18	57.02	58.63
Average by year	**47.52**	**32.54**	**43.74**	**29.72**	
Southern U.S.A.[d] average	31.52	23.16	15.70	11.32	18.99
Northern U.S.A. and Ontario[e] average	58.18	39.42	64.30	44.44	51.59

[a] U.S. dollars.

[b] Data collection from Alabama began in 2019.

[c] Data collection from Virginia began in 2017.

[d] Southern United States includes Alabama, Arkansas, Delaware, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Tennessee, Texas, and Virginia.

[e] Northern United States includes Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

education regarding corn diseases. These survey results provide scientists, breeders, government agencies, and educators with data to help inform and prioritize research, policy, and educational efforts in corn pathology and disease management. For more disease loss information, including individual data points for specific diseases for each state or province, additional years of data, and estimates for other field crops, see the Crop Protection Network "Field Crop Disease Loss Calculator" at https://loss.cropprotectionnetwork.org/.

Authors' Note

The values in this publication are estimates of corn yield loss due to diseases. The members of the Corn Disease Working Group used the most appropriate means available to estimate disease losses and assume no liability resulting from the use of these estimates. Production values reported by USDA-NASS are refined as additional data are made available; thus, the values reported in this publication are based on the most current data available at the time of writing. The information contained in this publication should serve as only a guide. Additional disease loss information can be found at https://loss.cropprotectionnetwork.org/.

Acknowledgments

Special thanks to the many people and agribusinesses that supplied information to help inform the disease loss estimates made by members of the Corn Disease Working Group. Support was obtained from the Crop Protection Network to aid in compiling the disease loss estimates. Ontario participation was supported by the Grain Farmers of Ontario, who obtained funding, in part, through 'Growing Forward 2' (GF2), a federal-provincial-territorial initiative. The Agricultural Adaptation Council assists in the delivery of GF2 in Ontario. Thanks to Ethan Stoetzer for providing technical editing.

Literature Cited

Arritt, R. 2016. Climate Change in the Corn Belt. CSCAP-0193-2016. Cropping Systems Coordinated Agricultural Project (CAP): Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems. Iowa State University, Ames, IA.

Bennett, J. W., and Klich, M. 2003. Mycotoxins. Clin. Microbiol. Rev. 16: 497-516.

Brown, J. K. M., and Rant, J. C. 2013. Fitness costs and trade-offs of disease resistance and their consequences for breeding arable crops. Plant Pathol. 62:83-95.

Hollier, C. A., and King, S. B. 1985. Effect of dew period and temperature on infection of seedling maize plants by *Puccinia polysora*. Plant Dis. 69: 219-220.

Jardine, D. 2006. Stalk rots of corn and sorghum. L-741. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS.

Mississippi State University (MSU). 2016. Corn, Grain Sorghum & Wheat 2017 Planning Budgets. Department of Agricultural Economics. Budget Report 2016-03.

Mueller, D. S., Wise, K. A., Sisson, A. J., Allen, T. W., Bergstrom, G. C., Bosley, D. B., Bradley, C. A., Broders, K. D., Byamukama, E., Chilvers, M. I., Collins, A., Faske, T. R., Friskop, A. J., Heiniger, R. W., Hollier, C. A., Hooker, D. C., Isakeit, T., Jackson-Ziems, T. A., Jardine, D. J., Kelly, H. M., Kinzer, K., Koenning, S. R., Malvick, D. K., McMullen, M., Meyer, R. F., Paul, P. A., Robertson, A. E., Roth, G. W., Smith, D. L., Tande, C. A., Tenuta, A. U., Vincelli, P., and Warner, F. 2016. Corn yield loss estimates due to diseases in the United States and Ontario, Canada from 2012 to 2015. Plant Heath Prog. 17. doi: 10.1094/PHP-RS-16-0030.

Munkvold, G., Hurburgh, C., Meyer, J., Loy, D., and Robertson, A. 2012. Aflatoxins in Corn. PM 1800. Iowa State University Extension and Outreach, Ames, IA.

Munkvold, G. P., and White, D. G. 2016. Compendium of Corn Diseases, 4th Ed. American Phytopathological Society, St. Paul, MN.

National Oceanic and Atmospheric Administration (NOAA). 2018a. Quarterly Climate Impacts and Outlook. Midwest Region. September 2018.

National Oceanic and Atmospheric Administration (NOAA). 2018b. Quarterly Climate Impacts and Outlook. Midwest Region. December 2018.

Norton, D. C., and Nyvall, R. F. 2011. Review. Nematodes that attack corn in Iowa. PM 1027. Iowa State University Extension and Outreach, Ames, IA.

Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA). 2020. Area, yield, production and farm value of specified field crops 2012-2019. http://www.omafra.gov.on.ca/english/stats/crops/index.html. Accessed 25 February 2020.

Pataky, J. 2003. Stewart's wilt of corn. APSnet Features. doi: https://www.apsnet.org/edcenter/apsnetfeatures/Pages/StewartsWilt.aspx.

Plastina, A. 2019. 2018 Iowa Farm Costs and Returns. FM 1789. Iowa State University Extension and Outreach, Ames, IA.

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., and Nelson, A. 2019. The global burden of pathogens and pests on major food crops. Nat. Ecol. Evol. 3:430-439.

Todey, D. 2014. Climate change impacts in the Corn Belt. Resilient Agric. Aug. 2014:8-9.

Ullstrup, A. J. 1972. The impacts of the southern corn leaf blight epidemics of 1970-1971. Annu. Rev. Phytopathol. 10:37-50.

United States Department of Agriculture - National Agriculture Statistics Service (USDA-NASS). 2020. Quick Stats 2.0. https://www.nass.usda.gov/Quick_Stats/index.php. Accessed 25 February 2020.

Wise, K., and Mueller, D. 2011. Are fungicides no longer just for fungi? An analysis of foliar fungicide use in corn. APSnet Features. doi: https://www.apsnet.org/edcenter/apsnetfeatures/Pages/fungicide.aspx.

Wise, K. A., Mueller, D. S., Sisson, A. J., Smith, D. L., Bradley, C. A., and Robertson, A. E., eds. 2016. A Farmers' Guide to Corn Diseases. American Phytopathological Society Press, St. Paul, MN.

Wise, K. A., Smith, D., Freije, A., Mueller, D. S., Kandel, Y., Allen, T., Bradley, C. A., Byamukama, E., Chilvers, M., Faske, T., Friskop, A., Hollier, C., Jackson-Ziems, T. A., Kelly, H., Kemerait, B., Price, P., III, Robertson, A., and Tenuta, A. 2019. Meta-analysis of yield response of foliar fungicide-treated hybrid corn in the United States and Ontario, Canada. PLoS One 14: e0217510.