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Abstract

Annual decreases in corn yield caused by diseases were estimated by surveying members of the Corn Disease Working Group in 22 corn-producing states in the United States and in Ontario, Canada, from 2012 through 2015. Estimated loss from each disease varied greatly by state and year. In general, foliar diseases such as northern corn leaf blight, gray leaf spot, and Goss's wilt commonly caused the largest estimated yield loss in the northern United States and Ontario during nondrought years. Fusarium stalk rot and plant-parasitic nematodes caused the most estimated loss in the southernmost United States. The estimated mean economic loss due to yield loss by corn diseases in the United States and Ontario from 2012 to 2015 was $76.51 USD per acre. The cost of disease-mitigating strategies is another potential source of profit loss. Results from this survey will provide scientists, breeders, government, and educators with data to help inform and prioritize research, policy, and educational efforts in corn pathology and disease management.

Introduction

Corn (*Zea mays* L.) diseases reduce yield and grain quality in the United States and Canada every year. Diseases of importance vary annually and from location to location. Occurrence of corn diseases that cause yield loss are influenced by many factors, including environmental conditions, crop production practices, previous disease history, hybrid selection, and susceptibility to disease (Munkvold and White 2016).

Previous estimates of annual yield loss caused by corn diseases in the United States ranged from 2 to 15% (Munkvold and White 2016). Catastrophic losses due to disease in corn are rare but have occurred, notably in 1970 when Race T of *Bipolaris maydis* resulted in a southern corn leaf blight epidemic that reduced corn yield by 20% in the United States (Ullstrup 1972). Yield loss to diseases may also go unnoticed or not be recognized due to misdiagnosis. Under these circumstances, yield reduction from stalk rots can take place through reduced ear size, poor grain fill, and early eardrop (Jardine 2006), and plant-parasitic nematodes can cause aboveground symptoms that may be mistakenly attributed to environmental conditions (Norton and Nyvall 2011). Some ear and stalk rot causing pathogens such as *Aspergillus*, *Fusarium*, and *Gibberella* species produce secondary metabolites known as mycotoxins that can make grain unsafe for animal or human consumption (Wise et al. 2016; Bennett and Klich 2003). In the United States, certain field-corn disease symptoms are often observed on plants but generally cause only a small reduction in corn yield. Examples of frequently occurring diseases where yield reduction is considered negligible include common rust (*Puccinia sorghi*) or eyespot (*Aureobasidium zeae*) on hybrid field corn (Wise et al. 2016).

Corn diseases are important because resultant grain loss decreases food, feed, and fuel production. The total corn production in the entire United States and Ontario, Canada, from 2012 to 2015 was nearly 54 billion bushels, which was valued at over $244 billion (USDA-NASS; Kulasekera 2015). Consequently, even if only the lowest estimated annual yield loss of 2% was realized, the loss during these years would be more than 1 billion bushels, translating to nearly $5 billion in lost revenue.

Annual soybean (*Glycine max*) disease loss estimates began in 1974 in the southern United States and in 1996 for the northern United States (Wrather et al. 1995; Wrather and Koenning 2009). These data have been published, often as summaries for 3- to 4-year spans (Koenning and Wrather 2010; Wrather et al. 2003; Wrather and Koenning 2006). However, the authors are not aware of any published multiyear summary of estimated corn yield losses in the United States and Ontario, Canada.

The goal of this survey was to determine the relative importance of the various corn diseases regionally and over time, equipping researchers, breeders, government, and Extension specialists with data to help prioritize educational opportunities, research investigations, and funding requests. Thus, the objective of this survey was to determine the annual estimated disease losses in field corn for each of the top corn-producing states in the United States and Ontario, Canada.

Data Collection and Loss Estimate Determination

The disease loss estimates in this publication were provided by members of the United States and Canadian Corn Disease Working Group after the end of each growing season from 2012 to 2015. For the purpose of this survey, states and provinces were broken up into a "southern" and a "northern" geographic region. States and provinces included in the northern region were Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, Wisconsin, and Ontario, Canada. The southern region consisted of Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas. A list of diseases was provided to pathologists in these states and provinces each year, and respondents were asked to estimate losses for each disease listed, and to also include information about diseases not listed on the form. Respondents used various methods to obtain disease loss information, and most individuals relied on more than one. It is important to note that methods for estimating disease loss varied by state and province. The estimates are based on statewide or provincial disease surveys, feedback from university Extension, industry, and farmer representatives, plant disease diagnostic clinic samples, research plots, "pure guess," and/or personal experience with disease losses. Disease loss estimates include grain from hybrid corn. Data were unavailable for Missouri in 2013.

Yearly per-acre corn production totals and crop value for corn grown in each state or province were determined using data from the United States Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) and the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) (Kulasekera 2015). Total production for Ontario, Canada, in 2015 was estimated by OMAFRA; total Ontario crop value in 2015 was determined by applying the United States national marketing year corn price to the total estimated production value. Disease loss values were determined based on yield before estimated losses {[(*100 – percent estimated disease loss*)/*100*]/*bushels harvested*} for each state or province. Total bushels lost per disease (*percent loss* × *yield before estimated loss*) was then calculated for each state or province. Losses in crop value were also determined in a similar fashion.

Results and Implications

This survey represents 96.7% of the total corn produced in the United States and Ontario between 2012 and 2015. Total annual production in these states and province ranged from a low of 10.68 billion bushels in 2012 to a high of 14.06 billion bushels in 2014 (Table 1). Individual state and provincial production values also varied widely from year to year.

Estimates of total corn production losses due to diseases differed greatly by state or province and year, from 0.02% in Colorado in 2015 to 25.08% in Ohio in 2012. States that produced more corn generally also had greater estimates of loss due to disease. The estimated corn production losses per year were 10.9%, 7.5%, 10.4%, and 13.5% for 2012, 2013, 2014, and 2015, respectively. Estimates do not account for potential grain contamination or rejection as a result of mycotoxins, thus the estimates presented here may be conservative.

Table 1. Total corn production (1,000 bu) in the United States and Ontario, Canada, from 2012 to 2015

State or province	2012	2013	2014	2015	Total
Arkansas	123,710	161,820	99,110	80,545	465,185
Colorado	134,330	128,380	147,460	134,900	545,070
Illinois	1,286,250	2,100,400	2,350,000	2,012,500	7,749,150
Indiana	596,970	1,031,910	1,084,760	822,000	3,535,640
Iowa	1,876,900	2,140,200	2,367,400	2,505,600	8,890,100
Kansas	375,250	504,000	566,200	580,160	2,025,610
Kentucky	104,040	243,100	225,940	225,320	798,400
Louisiana	91,690	115,910	71,370	66,690	345,660
Michigan	314,160	345,650	355,810	335,340	1,350,960
Minnesota	1,374,450	1,294,260	1,177,800	1,428,800	5,275,310
Mississippi	131,175	146,080	89,725	85,750	452,730
Missouri	247,500	435,200	628,680	437,360	1,748,740
Nebraska	1,292,200	1,613,950	1,602,050	1,692,750	6,200,950
New York	91,120	94,530	100,640	84,370	370,660
North Carolina	95,940	122,120	102,960	82,490	403,510
North Dakota	422,120	396,000	313,720	327,680	1,459,520
Ohio	438,000	649,020	610,720	498,780	2,196,520
Ontario	338,500	354,600	299,200	348,000	1,340,300
Pennsylvania	131,000	159,140	158,620	138,180	586,940
South Dakota	535,300	802,820	787,360	799,770	2,925,250
Tennessee	81,600	126,360	141,120	116,800	465,880
Texas	199,950	265,200	294,520	265,950	1,025,620
Wisconsin	396,000	439,350	485,160	492,000	1,812,510
Total	10,678,155	13,670,000	14,060,325	13,561,735	51,970,215
Southern U.S.[y]	1,585,185	2,248,170	2,367,085	2,075,965	8,276,405
Northern U.S.[z] and Ontario, Canada	9,092,970	11,421,830	11,693,240	11,485,770	43,693,810

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

A more useful indicator than percent production loss, is loss of bushels of corn. A 1% loss during a drought-affected year such as 2012 where mean yield per acre is reduced may be different than a 1% loss during a more productive year such as 2014. Similarly, a 1% loss in a major production state differs in total magnitude compared to a 1% loss in a state that produces less corn. Total estimated bushels lost were 1.3 billion in 2012, 1.1 billion in 2013, 1.6 billion in 2014, and 2.1 billion in 2015 (Table 2).

Table 2. Total estimated corn yield loss (bushels) due to diseases in the United States and Ontario, Canada, from 2012 to 2015, excluding grain contamination or rejection due to mycotoxins

State or province	2012	2013[x]	2014	2015	Total
Arkansas	3,432,857	1,222,821	930,375	1,972,160	7,558,214
Colorado	5,991,738	298,534	5,048,015	26,985	11,365,273
Illinois	214,625,146	200,147,645	230,999,451	218,652,993	864,425,235
Indiana	70,706,994	53,739,658	97,282,062	244,978,193	466,706,907
Iowa	180,427,633	163,815,502	622,118,879	801,686,167	1,768,048,181
Kansas	106,333,676	67,493,367	71,916,351	115,142,013	360,885,406
Kentucky	5,591,191	2,071,701	1,066,933	10,839,732	19,569,556
Louisiana	1,137,132	917,093	1,116,289	769,033	3,939,547
Michigan	68,961,951	45,356,787	80,285,110	66,312,893	260,916,741
Minnesota	44,703,330	161,928,119	162,436,686	111,685,175	480,753,310
Mississippi	2,472,478	1,700,959	1,307,223	2,710,519	8,191,179
Missouri	25,678,808	—	31,698,151	21,088,637	78,465,597
Nebraska	143,577,778	161,572,552	55,528,893	192,062,382	552,741,605
New York	6,178,452	7,224,575	3,845,050	3,478,813	20,726,889
North Carolina	2,419,647	2,251,117	2,955,029	5,555,683	13,181,476
North Dakota	4,565,535	4,121,249	9,902,860	6,687,347	25,276,991
Ohio	146,623,599	69,797,145	135,060,926	117,149,859	468,631,528
Ontario	24,152,668	25,179,372	28,726,348	35,175,512	113,233,900
Pennsylvania	12,310,360	25,071,136	16,611,993	12,671,528	66,665,017
South Dakota	134,830,195	43,768,632	19,857,552	92,631,250	291,087,629
Tennessee	5,393,603	3,014,424	3,292,607	3,525,538	15,226,173
Texas	1,571,871	425,000	353,849	319,523	2,670,243
Wisconsin	89,889,571	26,013,839	49,216,033	53,152,355	218,271,796
Total	1,301,576,212	1,067,131,227	1,631,556,663	2,118,274,291	6,118,538,393
Southern U.S.[y]	160,023,002	79,395,016	119,684,822	161,949,824	521,052,664
Northern U.S.[z] and Ontario, Canada	1,141,553,211	987,736,211	1,511,871,841	1,956,324,467	5,597,485,729

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Estimated corn yield loss due to root rots, seedling blights, and plant-parasitic nematodes can be found in Table 3, while corn yield losses due to foliar and aboveground diseases can be found in Table 4. Corn yield losses due to stalk rots and ear rots can be found in Tables 5 and 6, respectively. Finally, estimates of mycotoxin-contaminated grain can be found in Table 7. The estimated impact that each specific disease had on corn production in the United States and Ontario, Canada, was highly variable by disease and year, ranging from approximately 21,000 bushels yield loss due to Stewart's disease (*Pantoea stewartii*) in 2014 to more than 551 million bushels lost due to northern corn leaf blight (*Setosphaeria turcica*) in 2015 (Table 8).

Table 3. Estimated corn yield loss (bushels) from root rots, seedling blights, and plant-parasitic nematodes[w] in the United States and Ontario, Canada, from 2012 to 2015

State or province	2012	2013[x]	2014	2015	Total
Arkansas	63,571	81,521	60,024	90,769	295,886
Colorado	701,609	77,207	0	0	778,816
Illinois	22,513,127	27,606,572	11,614,498	14,502,494	76,236,691
Indiana	14,355,055	17,370,395	20,094,715	7,682,243	59,502,408
Iowa	63,777,157	115,200,775	17,937,113	16,536,431	213,451,476
Kansas	24,127,342	28,631,818	19,207,302	34,765,101	106,731,563
Kentucky	0	147,103	136,204	354,240	637,547
Louisiana	46,414	58,414	362,431	337,295	804,554
Michigan	34,480,976	25,415,441	34,887,609	32,132,231	126,916,257
Minnesota	2,128,730	42,229,455	25,464,497	17,715,580	87,538,262
Mississippi	13,365	29,556	19,117	1,769	63,807
Missouri	6,829,470	—	6,603,782	6,876,730	20,309,981
Nebraska	14,357,778	28,408,361	9,945,473	15,078,499	67,790,111
New York	972,985	559,650	156,728	878,488	2,567,850
North Carolina	1,780,310	1,019,843	677,856	2,482,888	5,960,897
North Dakota	0	0	3,268,591	1,671,837	4,940,428
Ohio	6,021,623	71,882	2,311,921	3,141,242	11,546,668
Ontario	5,874,973	6,076,470	6,230,601	6,897,159	25,079,203
Pennsylvania	429,931	36,842	403,034	316,788	1,186,595
South Dakota	268,052	253,977	161,444	13,386,019	14,069,491
Tennessee	8,699	38,812	28,883	24,065	100,459
Texas	100,761	79,688	0	0	180,448
Wisconsin	24,294,479	7,026,994	3,206,256	4,633,795	39,161,524
Total	223,146,406	300,420,775	162,778,077	179,505,663	865,850,921
Southern U.S.[y]	33,671,541	30,163,962	27,095,599	44,932,856	135,863,958
Northern U.S.[z] and Ontario, Canada	189,474,865	270,256,813	135,682,478	134,572,807	729,986,963

w. Diseases include those caused by *Fusarium* spp.; *Pythium* spp.; *Rhizoctonia* spp.; *Phoma terrestris*; and plant-parasitic nematodes (*Belonolaimus longicaudatus*, *Helicotylenchus* spp., *Heterodera zeae*, *Hoplolaimus* spp., *Longidorus breviannulatus*, *Meloidogyne* spp., *Paratrichodorus* spp., *Pratylenchus* spp., *Tylenchorhynchus* spp.)

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 4. Estimated corn yield loss (bushels) from foliar and other aboveground diseases[w] (not including stalk and ear rots) in the United States and Ontario, Canada, from 2012 to 2015

State or province	2012	2013[x]	2014	2015	Total
Arkansas	1,106,143	586,954	530,214	1,592,581	3,815,892
Colorado	2,483,695	92,649	472,775	13,493	3,062,611
Illinois	96,056,009	138,032,859	160,021,966	152,833,980	546,944,814
Indiana	6,009,093	27,684,066	53,546,505	147,563,084	234,802,749
Iowa	21,807,673	18,662,526	320,177,472	480,548,680	841,196,350
Kansas	288,950	3,371,811	6,956,106	23,431,678	34,048,545
Kentucky	1,918,546	1,605,875	749,123	9,611,701	13,885,244
Louisiana	997,892	683,438	732,112	411,500	2,824,942
Michigan	17,240,488	12,903,224	36,675,599	26,107,438	92,926,749
Minnesota	14,191,533	73,100,644	95,424,852	54,687,224	237,404,253
Mississippi	1,764,147	1,361,063	1,195,253	2,485,829	6,806,291
Missouri	5,463,576	—	11,226,429	7,564,403	24,254,407
Nebraska	80,403,556	80,963,828	44,257,356	134,764,085	340,388,826
New York	3,512,474	4,538,254	2,256,877	1,537,354	11,844,959
North Carolina	560,650	1,019,843	1,895,879	2,280,383	5,756,755
North Dakota	4,352,192	4,041,225	6,569,544	3,343,673	18,306,635
Ohio	70,271,757	58,943,006	93,222,616	86,291,773	308,729,151
Ontario	13,128,027	12,798,565	13,379,395	21,304,558	60,610,545
Pennsylvania	10,934,580	22,565,864	15,192,614	12,234,059	60,927,117
South Dakota	87,519,004	26,413,565	10,332,385	65,591,492	189,856,445
Tennessee	2,705,501	2,755,675	3,047,106	3,320,985	11,829,267
Texas	1,390,501	239,063	265,386	239,643	2,134,592
Wisconsin	29,153,374	9,586,495	37,726,948	30,474,017	106,940,834
Total	473,259,360	501,950,491	915,854,511	1,268,233,613	3,159,297,975
Southern U.S.[y]	18,679,600	11,716,370	27,070,383	50,952,195	108,418,548
Northern U.S.[z] and Ontario, Canada	454,579,760	490,234,120	888,784,129	1,217,281,418	3,050,879,427

w. Diseases include those caused by *Bipolaris maydis*; Brome mosaic virus; *Cercospora zea maydis*; *Clavibacter michiganensis* subsp. *nebraskensis*; *Cochliobolus carbonum*; *Colletotrichum graminicola*; *Kabatiella zeae*; Maize chlorotic mottle virus; Maize dwarf mosaic virus + Maize chlorotic dwarf virus complex; *Pantoea stewartii*; *Peronosclerospora sorghi*; *Physoderma maydis*; *Pseudomonas syringae*; *Puccinia polysora*; *Puccinia sorghi*; *Sclerophthora macrospora*; *Setosphaeira turcica*; *Sphacelotheca reiliana*; *Stenocarpella macrospora*; Sugarcane mosaic virus; *Ustilago maydis*; and Wheat streak mosaic virus.

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 5. Estimated corn yield loss (bushels) from stalk rot diseasesw in the United States and Ontario, Canada, from 2012 to 2015

State or province	2012	2013[x]	2014	2015	Total
Arkansas	2,237,714	505,433	300,121	255,803	3,299,071
Colorado	2,806,435	102,943	4,575,240	13,493	7,498,111
Illinois	34,520,128	23,005,476	25,809,995	22,311,530	105,647,129
Indiana	3,605,456	4,342,599	16,548,589	74,688,474	99,185,117
Iowa	30,859,915	27,648,186	179,371,133	281,119,324	518,998,557
Kansas	77,053,388	34,289,602	45,051,014	56,736,644	213,130,649
Kentucky	2,740,780	73,552	68,102	401,472	3,283,905
Louisiana	92,827	175,241	21,746	20,238	310,051
Michigan	5,746,829	1,173,020	4,360,951	4,016,529	15,297,330
Minnesota	28,383,067	43,685,644	33,505,917	39,282,372	144,856,999
Mississippi	681,602	310,340	91,943	222,036	1,305,921
Missouri	4,644,040	—	9,905,672	5,730,608	20,280,320
Nebraska	27,279,778	11,008,240	828,789	38,261,691	77,378,498
New York	1,080,013	1,546,670	846,329	711,575	4,184,587
North Carolina	19,672	136,808	190,647	132,069	479,196
North Dakota	85,337	80,024	64,725	1,671,837	1,901,923
Ohio	23,560,331	7,188,171	8,203,590	12,318,597	51,270,690
Ontario	2,937,487	2,886,323	4,099,079	4,023,343	13,946,232
Pennsylvania	902,855	2,247,376	490,650	90,511	3,731,392
South Dakota	40,341,838	17,101,090	9,121,558	13,475,259	80,039,745
Tennessee	2,644,606	168,187	101,089	84,228	2,998,109
Texas	40,304	53,125	29,487	26,627	149,544
Wisconsin	21,865,031	4,700,175	5,557,511	16,899,723	49,022,439
Total	314,129,431	182,428,224	349,143,877	572,493,982	1,418,195,514
Southern U.S.[y]	92,961,368	35,815,230	60,335,062	63,623,217	252,734,876
Northern U.S.[z] and Ontario, Canada	221,168,064	146,612,994	288,808,815	508,870,765	1,165,460,638

w. Diseases include those caused by *Colletotrichum graminicola*; *Erwinia* spp.; *Fusarium* spp.; *Gibberella zeae*; *Macrophomina phaseolina*; *Physoderma maydis*; *Pythium aphanidermatum*; and *Stenocarpella maydis*.

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 6. Estimated corn yield loss (bushels) from ear rot diseases[w] in the United States and Ontario, Canada, from 2012 to 2015

State or province	2012	2013[x]	2014	2015	Total
Arkansas	25,429	48,913	40,016	33,007	147,364
Colorado	0	25,736	0	0	25,736
Illinois	61,535,881	11,502,738	33,552,993	29,004,989	135,596,601
Indiana	46,737,390	4,342,599	7,092,252	15,044,393	73,216,633
Iowa	63,982,889	2,304,016	104,633,161	23,481,732	194,401,797
Kansas	4,863,995	1,200,136	701,928	208,591	6,974,650
Kentucky	931,865	245,172	113,503	472,319	1,762,860
Louisiana	0	0	0	0	0
Michigan	11,493,659	5,865,102	4,360,951	4,056,694	25,776,406
Minnesota	0	2,912,376	8,041,420	0	10,953,796
Mississippi	13,365	0	910	885	15,160
Missouri	8,741,722	—	3,962,269	916,897	13,620,888
Nebraska	21,536,667	41,192,123	497,274	3,958,106	67,184,170
New York	612,980	580,001	585,116	351,395	2,129,493
North Carolina	59,016	74,623	190,647	660,343	984,628
North Dakota	128,006	0	0	0	128,006
Ohio	46,769,888	3,594,086	31,322,799	15,398,246	97,085,019
Ontario	2,212,181	3,418,014	5,017,273	2,950,451	13,597,920
Pennsylvania	42,993	221,053	525,696	30,170	819,913
South Dakota	6,701,302	0	242,165	178,480	7,121,947
Tennessee	34,797	51,750	115,530	96,260	298,338
Texas	40,304	53,125	58,975	53,254	205,658
Wisconsin	14,576,687	4,700,175	2,725,318	1,144,820	23,147,000
Total	291,041,015	82,331,737	203,780,197	98,041,033	675,193,982
Southern U.S.[y]	14,710,493	1,699,454	5,183,779	2,441,556	24,035,281
Northern U.S.[z] and Ontario, Canada	276,330,522	80,632,283	198,596,418	95,599,477	651,158,701

w. Diseases include those caused by *Aspergillus flavus* and other *Aspergillus* spp.; *Cladosporium* spp.; *Fusarium graminearum*; *Fusarium* spp.; *Nigrospora oryzae*; *Penicillium* spp.; *Stenocarpella maydis*; and *Trichoderma viride*.

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 7. Estimated grain contamination (bushels) by mycotoxins in the United States and Ontario, Canada, from 2012 to 2015.[w]

State or province	2012	2013[x]	2014	2015	Total
Arkansas	12,714	16,304	0	0	29,019
Colorado	0	0	0	0	0
Illinois	525,306,301	57,513,691	51,619,989	44,623,060	679,063,041
Indiana	200,303,098	16,284,745	1,182,042	213,396	217,983,281
Iowa	123,439,658	0	2,989,519	330,729	126,759,906
Kansas	409,346,124	5,714,934	63,812	0	415,124,870
Kentucky	3,288,936	1,225,859	1,135,035	1,180,799	6,830,628
Louisiana	9,283	11,683	0	0	20,965
Michigan	0	0	43,610	0	43,610
Minnesota	0	0	1,340,237	0	1,340,237
Mississippi	1,336	1,478	0	885	3,699
Missouri	27,317,881	—	0	0	27,317,881
Nebraska	1,220,411,111	1,509,194,169	0	0	2,729,605,281
New York	48,649	50,877	52,243	43,924	195,693
North Carolina	19,672	24,874	21,183	440,228	505,958
North Dakota	0	0	0	0	0
Ohio	0	0	1,491,562	0	1,491,562
Ontario	181,326	1,139,338	6,558,527	3,831,755	11,710,947
Pennsylvania	14,331	0	17,523	0	31,854
South Dakota	0	0	80,722	0	80,722
Tennessee	8,699	0	0	0	8,699
Texas	73,353,961	53,125,000	88,462,155	66,567,381	281,508,496
Wisconsin	24,294,479	4,653,638	534,376	54,515	29,537,008
Total	2,607,357,560	1,648,956,590	155,592,532	117,286,671	4,529,193,354
Southern U.S.[y]	513,358,606	60,120,131	89,682,184	68,189,293	731,350,214
Northern U.S.[z] and Ontario, Canada	2,093,998,953	1,588,836,459	65,910,348	49,097,379	3,797,843,140

w. w In 2013–2015, values are for contamination of grain only, not necessarily yield loss. Data from 2012 may represent either contamination, direct losses due to contamination, or both.

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 8. Total estimated corn loss (bushels) by disease or type of disease in the United States and Ontario, Canada, from 2012 to 2015

Disease common name	Latin binomial	2012[s]	2013[t]	2014	2015	Total
Root rots	—		70,941,867	32,042,002	59,262,882	162,246,751
Seedling blights	—		148,739,829	69,900,871	48,019,326	266,660,026
Plant-parasitic nematodes	—	80,873,420	80,739,079	60,835,205	72,223,455	294,671,158
Fusarium seedling blight	*Fusarium* spp.	37,357,079	—	—	—	—
Rhizoctonia	*Rhizoctonia* spp.	10,468,470	—	—	—	—
Pythium damping off	*Pythium* spp.	93,407,422	—	—	—	—
Other root rots/ seedling blights[u]	—	1,040,014	—	—	—	—
Anthracnose leaf blight	*Colletotrichum graminicola*	8,158,404	7,392,039	13,450,393	11,165,969	40,166,805
Carbonum leaf spot	*Cochliobolus carbonum*	12,139,341	3,979,926	8,164,537	4,153,286	28,437,090
Common rust	*Puccinia sorghi*	49,707,925	52,441,997	109,937,337	18,179,858	230,267,117
Common smut	*Ustilago maydis*	83,537,963	24,934,358	13,084,489	7,362,035	128,918,845
Crazy top	*Sclerophthora macrospora*	139,938	367,224	350,666	528,826	1,386,654
Eyespot	*Kabatiella zeae*	13,808,658	12,634,760	14,043,426	68,849,094	109,335,939
Goss's wilt	*Clavibacter michiganensis* subsp. *nebraskensis*	61,839,925	102,808,589	196,964,925	139,795,799	501,409,237
Gray leaf spot	*Cercospora zea maydis*	84,807,249	84,941,890	143,981,508	258,727,101	572,457,747
Head smut	*Sphacelotheca reiliana*	1,657,664	423,166	649,251	222,324	2,952,404
Holcus spot	*Pseudomonas syringae*	8,219,192	596,851	925,130	684,226	10,425,399
Northern corn leaf blight	*Setosphaeira turcica*	73,993,728	131,554,916	350,068,129	551,054,156	1,106,670,929
Physoderma leaf spot	*Physoderma maydis*	1,472,043	12,948,855	32,697,398	56,260,881	103,379,177
Southern corn leaf blight	*Bipolaris maydis*	29,988	65,460	710,175	6,194,177	6,999,800
Southern rust	*Puccinia polysora*	53,394,080	57,373,993	23,665,110	138,814,598	273,247,781
Stewart's disease	*Pantoea stewartii*	11,437,901	113,255	21,183	44,023	11,616,362
Maize Dwarf Mosaic	Maize dwarf mosaic virus	2,956,805	2,388,425	3,193,218	2,376,599	10,915,046
Other virus/virus-like diseases[v]	—	2,936,653	4,682,762	2,657,138	2,398,524	12,675,077
Other foliar/above-ground diseases[w]	—	3,021,902	2,302,025	1,290,500	1,422,138	8,036,565
Anthracnose stalk rot	*Colletotrichum graminicola*	67,073,263	47,527,197	70,296,416	236,122,780	421,019,655
Bacterial stalk rot	*Erwinia* spp.	2,017,713	416,046	762,115	593,241	3,789,114
Charcoal rot	*Macrophomina phaseolina*	70,312,596	7,206,103	12,602,329	2,794,433	92,915,461
Diplodia stalk rot	*Stenocarpella maydis*	5,840,518	7,878,670	42,268,152	34,677,677	90,665,018
Fusarium stalk rot	*Fusarium* spp.	123,874,135	89,541,480	135,492,026	173,764,638	522,672,278

Gibberella stalk rot	*Gibberella zeae*	43,575,428	29,843,950	87,705,316	90,509,628	251,634,323
Other stalk rots[x]	—	1,435,778	14,778	17,523	34,031,585	35,499,665
Aspergillus ear rot	*Aspergillus flavus*/ *A.* spp.	109,957,414	4,214,329	149,519	90,934	114,412,196
Diplodia ear rot	*Stenocarpella maydis*	35,520,770	12,022,492	67,304,225	52,523,968	167,371,455
Fusarium ear rot	*Fusarium* spp.	91,386,214	52,127,712	51,647,176	18,921,537	214,082,640
Gibberella ear rot	*Fusarium graminearum*	38,334,993	13,722,470	81,615,500	25,753,873	159,426,836
Other ear rots[y]	—	15,841,624	244,734	3,063,777	750,721	19,900,855
Mycotoxin contamination[z]	—	2,607,357,560	1,648,956,590	155,592,532	117,286,671	4,529,193,354

s. In 2012, seedling and root rot disease losses were estimated using different categories than in 2013 to 2015.
t. In 2013, disease loss estimate data was not available in Missouri.
u. Other root rots/seedling blights includes loss due to *Phoma terrestris* and possibly other disease-causing pathogens.
v. Other virus/virus-like diseases includes loss due to Brome mosaic virus; Maize chlorotic mottle virus; Maize dwarf mosaic virus + Maize chlorotic dwarf virus complex; Sugarcane mosaic virus; Wheat streak mosaic virus; and possibly others.
w. Other foliar/aboveground diseases include losses due to *Peronosclerospora sorghi*; *Stenocarpella macrospora*; and possibly others.
x. Other stalk rots include *Physoderma maydis*; *Pythium aphanidermatum*; and possibly others.
y. Other ear rots includes *Cladosporium* spp.; *Nigrospora oryzae*; *Penicillium* spp.; *Trichoderma viride*; and possibly others.
z. In 2013–2015, values are for contamination of grain only, not necessarily yield loss. Data from 2012 may represent either contamination, direct losses due to contamination, or both.

The most destructive diseases in the 12 northern-most United States and Ontario, Canada, varied little by year (Table 9). Yield loss estimates for northern corn leaf blight were greatest in 2014 and 2015 and the second greatest in 2013, while estimates were lower in the drought year of 2012. Gray leaf spot (*Cercospora zeae-maydis*) and Goss's wilt (*Clavibacter michiganensis* subsp. *nebraskensis*) were in the top four most production-limiting diseases every year except 2012. Fusarium stalk rot (*Fusarium verticillioides*) was always the fifth or sixth greatest cause of disease-related yield loss, while Fusarium and Aspergillus ear rots (*Fusarium* and *Aspergillus* spp.) ranked as the top diseases causing yield loss in 2012. Trends also emerged in the 10 southern-most United States (Table 10). For example, Fusarium stalk rot was always ranked first or second in terms of causing the greatest estimated yield loss, while plant-parasitic nematodes always ranked in the top three most important pathogens causing yield loss.

Environmental conditions fluctuated widely from year to year and greatly impacted final yield as well as disease incidence and severity. This is most evident when comparing 2012, a drought year, to the 2013 to 2015 yield trends. Corn yield during 2012 was approximately 3 billion bushels less than that of any other year. Environment also influenced diseases and associated yield loss estimates. For example, 2015 summer precipitation in the Midwest was the fourth greatest on record, while foliar diseases in 2015 resulted in double the yield loss compared to 2013, despite the fact that total grain production was greater in 2013 than 2015 (NOAA 2015).

Table 9. Ten most destructive corn diseases and associated estimated yield losses (bushels) by disease or type of disease in the northern United States[z] and Ontario, Canada, from 2012 to 2015

	2012		2013		2014		2015	
Rank	Disease	Loss	Disease	Loss	Disease	Loss	Disease	Loss
1	Aspergillus ear rot	99,626,000	Seedling blights	148,580,920	Northern corn leaf blight	347,593,010	Northern corn leaf blight	547,671,336
2	Fusarium ear rot	89,646,682	Northern corn leaf blight	130,703,478	Goss's wilt	190,067,089	Anthracnose stalk rot	233,209,053
3	Pythium damping off	87,826,356	Goss's wilt	99,875,100	Gray leaf spot	136,701,632	Gray leaf spot	224,420,541
4	Common smut	82,843,148	Gray leaf spot	80,935,769	Common rust	109,820,815	Goss's wilt	139,642,127
5	Fusarium stalk rot	82,742,000	Root rots	70,766,630	Fusarium stalk rot	101,881,118	Southern rust	129,217,456
6	Gray leaf spot	80,748,571	Fusarium stalk rot	60,688,350	Gibberella stalk rot	86,127,279	Fusarium stalk rot	116,756,288
7	Northern corn leaf blight	70,891,165	Southern rust	54,588,852	Gibberella ear rot	80,237, 937	Gibberella stalk rot	89,298,666
8	Anthracnose stalk rot	65,590,484	Common rust	52,261,306	Diplodia ear rot	65,847,391	Eyespot	68,761,049
9	Goss's wilt	59,666,788	Plant-parasitic nematodes	50,909,263	Seedling blights	63,174,042	Physoderma leaf spot	56,237,177
10	Plant-parasitic nematodes	55,202,729	Fusarium ear rot	50,674,749	Anthracnose stalk rot	57,275,846	Root rots	55,007,881

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Table 10. Ten most destructive corn diseases and associated estimated yield losses (bushels) by disease or type of disease in the southern United States[y] and Ontario, Canada, from 2012 to 2015

	2012		2013[z]		2014		2015	
Rank	Disease	Loss	Disease	Loss	Disease	Loss	Disease	Loss
1	Charcoal rot	47,011,787	Plant-parasitic nematodes	29,829,816	Fusarium stalk rot	33,610,908	Fusarium stalk rot	57,008,350
2	Fusarium stalk rot	41,132,136	Fusarium stalk rot	28,853,130	Plant-parasitic nematodes	20,278,642	Plant-parasitic nematodes	35,960,126
3	Plant-parasitic nematodes	25,670,691	Gray leaf spot	4,006,121	Anthracnose stalk rot	13,020,569	Gray leaf spot	34,306,559
4	Aspergillus ear rot	10,330,815	Charcoal rot	3,822,729	Southern rust	9,288,075	Southern rust	9,597,142
5	Southern rust	7,357,960	Anthracnose stalk rot	2,994,775	Charcoal rot	8,183,997	Seedling blights	4,717,728
6	Pythium damping off	5,581,067	Goss's wilt	2,933,489	Gray leaf spot	7,279,876	Root rots	4,255,002
7	Gray leaf spot	4,058,678	Southern rust	2,785,140	Goss's wilt	6,897,836	Northern corn leaf blight	3,382,819
8	Northern corn leaf blight	3,102,563	Fusarium ear rot	1,452,963	Seedling blights	6,726,828	Anthracnose stalk rot	2,913,726
9	Goss's wilt	2,173,137	Northern corn leaf blight	851,437	Diplodia stalk rot	3,877,739	Diplodia stalk rot	1,401,456
10	Diplodia ear rot	1,936,114	Holcus spot	290,003	Northern corn leaf blight	2,475,120	Diplodia ear rot	1,379,932

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.
z. In 2013, disease loss estimate data was not available in Missouri.

Overall, from 2012 to 2015 the total estimated economic loss due to disease was $27.4 billion in the United States and Ontario, Canada (Table 11). Yearly estimated economic losses were almost twice as great in 2012 than in 2013, and averaged approximately $6.85 billion annually during this survey period. It is interesting to note that estimated economic loss was greatest in 2012, when production was reduced compared to 2013, 2014, or 2015, in part because of greater per bushel prices received during 2012. The next highest year in terms of economic loss was 2015, despite the fact that nearly 817 million more bushels were estimated to have been lost due to disease than in 2012. During this survey, the United States national corn marketing prices per bushel were as follows: $6.89 in 2012, $4.46 in 2013, $3.70 in 2014, and $3.60 in 2015 (USDA-NASS). Thus, the estimated economic losses due to diseases in corn were as follows: $94.71/acre in 2012, $53.26 /acre in 2013, $68.95/acre in 2014, and $88.35/acre in 2015. The average estimated yield loss due to corn diseases during the four years of this survey (2012 to 2015) was $76.32/acre. This is important to note, as 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 2014 were $722.21 per acre, while crop value was $793.00 per acre (Plastina and Johanns 2016). When production expenses are subtracted from crop value, $70.79 remains, a value that is similar to the four-year average of estimated yield loss due to corn diseases.

Table 11. Total estimated economic loss (USD) caused by corn disease in the United States and Ontario, Canada, from 2012 to 2015, excluding grain contamination or rejection due to mycotoxins

State or province	2012	2013[x]	2014	2015	Total
Arkansas	$23,377,754	$6,260,841	$3,842,448	$8,085,869	$41,566,912
Colorado	41,103,333	1,376,243	19,939,660	99,846	62,519,083
Illinois	1,474,474,835	904,667,356	857,007,963	798,083,426	4,034,233,580
Indiana	511,211,552	240,216,287	364,807,731	943,166,044	2,059,401,614
Iowa	1,248,559,224	735,531,605	2,308,061,040	2,805,901,584	7,098,053,452
Kansas	748,589,076	303,045,216	271,843,806	431,782,550	1,755,260,649
Kentucky	38,914,666	9,674,843	4,203,716	41,190,980	93,984,206
Louisiana	7,846,213	4,677,173	4,632,607	3,076,132	20,232,124
Michigan	461,355,366	189,591,371	293,040,763	232,095,124	1,176,082,624
Minnesota	298,171,227	696,290,911	581,523,337	379,729,596	1,955,715,070
Mississippi	17,159,009	8,589,842	5,542,624	10,842,075	42,133,551
Missouri	188,482,450	—	112,211,445	76,973,526	377,667,422
Nebraska	983,507,778	722,229,359	209,343,944	691,424,574	2,606,505,654
New York	41,889,930	32,655,109	15,803,140	14,784,976	105,133,154
North Carolina	18,098,957	11,165,538	12,381,561	23,889,435	65,535,491
North Dakota	29,493,355	16,114,083	33,075,557	21,399,510	100,082,506
Ohio	1,039,561,313	307,805,387	510,530,387	445,169,465	2,303,066,553
Ontario	159,666,044	148,558,297	134,152,046	126,631,843	569,008,230
Pennsylvania	88,757,695	112,068,007	64,786,772	48,151,808	313,764,283
South Dakota	906,058,912	177,262,961	66,324,213	301,051,620	1,450,697,705
Tennessee	39,265,433	14,680,241	12,544,830	13,573,322	80,063,825
Texas	11,191,719	2,184,500	1,564,010	1,326,023	16,266,252
Wisconsin	601,361,227	113,940,613	180,622,819	180,718,006	1,076,642,665
Total	$8,978,097,068	$4,758,585,782	$6,067,786,421	$7,599,147,333	$27,403,616,604
Southern U.S.[y]	$1,134,028,611	$361,654,437	$448,706,709	$610,839,759	$2,555,229,515
Northern U.S.[z] and Ontario, Canada	$7,844,068,458	$4,396,931,346	$5,619,079,712	$6,988,307,574	$24,848,387,089

x. In 2013, disease loss estimate data was not available in Missouri.

y. Southern United States includes Arkansas, Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Tennessee, and Texas.

z. Northern United States includes Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, New York, North Dakota, Ohio, Pennsylvania, South Dakota, and Wisconsin.

Losses due to disease may be underestimated. The costs to diagnose and manage diseases are additional disease-related corn production expenses that are often not included in economic estimates of losses due to disease. Disease diagnostic costs include scouting fields, fees for consultant or diagnostic services, quantification of nematode population densities from soil samples, and costs associated with misdiagnosis. Management for various corn diseases includes hybrid resistance, crop rotation, tillage, fungicide/nematicide-treated seed, nematicide, foliar fungicide, insect/vector and alternative host plant management, and proper post-harvest handling (Munkvold and White 2016). For example, estimated application cost for foliar fungicide from 2008 to 2012 was $28.25/acre (Liu et al. 2015). However, cost of fungicide product and application undoubtedly vary by region,

supplier, product selected, and method of application. Additional costs incurred because of corn disease include refusal of corn seed for export due to contamination with a quarantined pathogen, phyto-sanitary inspections, breeding corn for resistance, grain quality reduction that results in livestock health issues, and increased harvest difficulty due to lodging (Pataky 2003; Wise et al. 2016; Munkvold and White 2016).

Corn disease risk is not static, and varies greatly over time and by location based on many factors. For example, changing weather patterns that result in increased humidity, frequent and heavy rainfall events, and changes in temperature may heighten the risk of some corn diseases. Other factors increasing the risk of disease include: (i) reduced tillage and continuous corn production practices that increase inoculum-infested crop residue on the soil surface; (ii) increasing use of greater plant populations; and (iii) selecting hybrids based on high yield potential rather than disease resistance (Butzen and Jeschke 2013; Wise and Mueller 2011). Thus, it is possible that crop yield reduction and costs associated with disease management will increase, resulting in an increased need for ongoing scientific research on corn pathogens and farmer/agribusiness education regarding corn diseases. Our survey results will help scientists, government, and educators direct research, funding, and educational efforts in corn pathology and disease management.

Author's Note – The values in this publication are intended to be estimates of corn yield loss due to diseases. The members of the United States and Canadian 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. This information is only a guide.

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