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Potential wheat yield loss due to weeds in the United States and Canada

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Abstract

Yield losses due to weeds are a major threat to wheat production and economic well-being of farmers in the United States and Canada. The objective of this Weed Science Society of America (WSSA) Weed Loss Committee report is to provide estimates of wheat yield and economic losses due to weeds. Weed scientists provided both weedy (best management practices but no weed control practices) and weed-free (best management practices providing >90% weed control) average yield from replicated research trials in both winter and spring wheat from 2007 to 2017. Winter wheat yield loss estimates ranged from 2.9% to 34.4%, with a weighted average (by production) of 25.6% for the United States, 2.9% for Canada, and 23.4% combined. Based on these yield loss estimates and total production, the potential winter wheat loss due to weeds is 10.5, 0.09, and 10.5 billion kg with a potential loss in value of US$2.19, US$0.19, and US$2.19 billion for the United States, Canada, and combined, respectively. Spring wheat yield loss estimates ranged from 7.9% to 47.0%, with a weighted average (by production) of 33.2% for the United States, 8.0% for Canada, and 19.5% combined. Based on this yield loss estimate and total production, the potential spring wheat loss is 4.8, 1.6, and 6.6 billion kg with a potential loss in value of US$1.14, US$0.37, and US$1.39 billion for the United States, Canada, and combined, respectively. Yield loss in this analysis is greater than some previous estimates, likely indicating an increasing threat from weeds. Climate is affecting yield loss in winter wheat in the Pacific Northwest, with percent yield loss being highest in wheat-fallow systems that receive less than 30 cm of annual precipitation. Continued investment in weed science research for wheat is critical for continued yield protection.

Introduction

Weeds are the most significant pest in wheat worldwide (Oerke 2006). Previous estimates of global wheat yield loss due to weeds were 9.8% (Cramer 1967) and 12.3% (Oerke et al. 1994). In 2006, Oerke estimated the worldwide potential wheat loss to be 23.0% with a range of 18% to 29% and actual loss of 7.7% with a range of 3% to 13%. The Weed Science Society of America (WSSA) Weed Loss Committee generated reports in 1984 (Chandler et al.) and 1992 (Bridges) that summarized crop losses due to weeds across the United States and Canada. Chandler et al. (1984) reported an estimated 9% to 20% wheat yield loss with an average of 13% across the United States and 5% to 15% wheat yield loss across Canada due to weeds. Bridges (1992) reported 1% to 20% wheat yield loss due to weeds across the United States using then-current management (i.e., best management practices [BMPs] with herbicides); BMPs but no herbicides resulted in 3% to 60% wheat yield loss. In a summary of yield loss due to weeds in Canada, Swanton et al. (1993) reported 5% to 15% wheat yield loss.

Wheat was harvested from more than 218.5 million ha in 2017, the largest area of any crop in the world (FAO 2017). Wheat production is second only to corn, with 771.7 billion kg produced worldwide in 2017 (FAO 2017). Canada and the United States accounted for 4.1% and 8.3%, respectively, of the world's wheat production between 2007 and 2017 (Figures 1 and 2), with an average production value of US$6.02 and US$12.7 billion, respectively (FAO 2017). A significant proportion of wheat production in North America is exported. In 2018 to 2019, the United States exported 27.2 billion kg of wheat (about 50% of production), whereas Canada exported 18.2 billion kg (about 90% of production). Export partners demanded that North American wheat remain free of transgenic varieties (Paarlberg 2014). As a consequence, no transgenic herbicide-resistant wheat is produced in North America, in stark contrast to corn, soybean, and cotton.

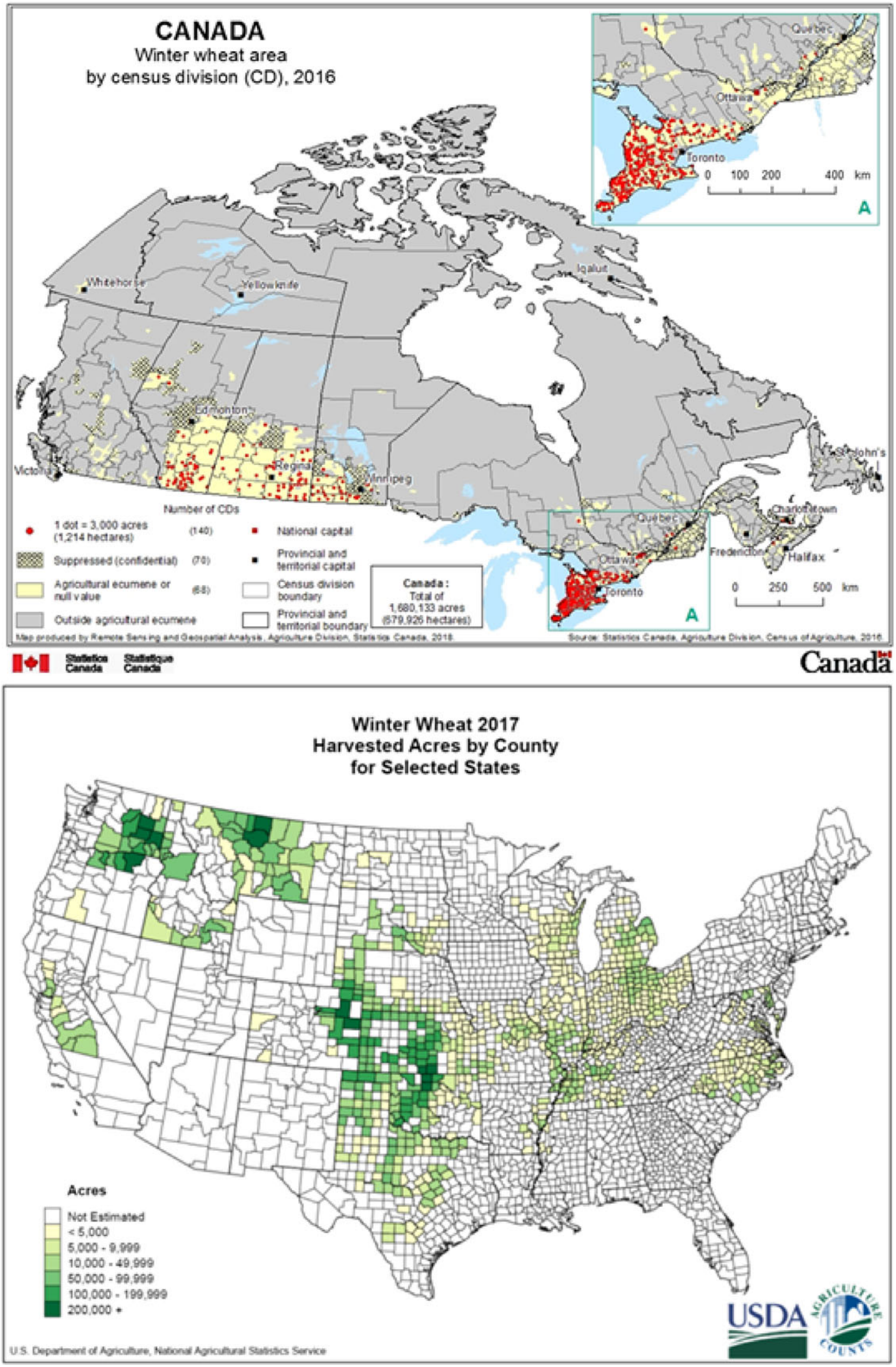

Figure 1. Distribution of winter wheat acres harvested in the United States (2017) and in Canada (2016). Images and data from USDA NASS 2017b and Statistics Canada 2017, respectively.

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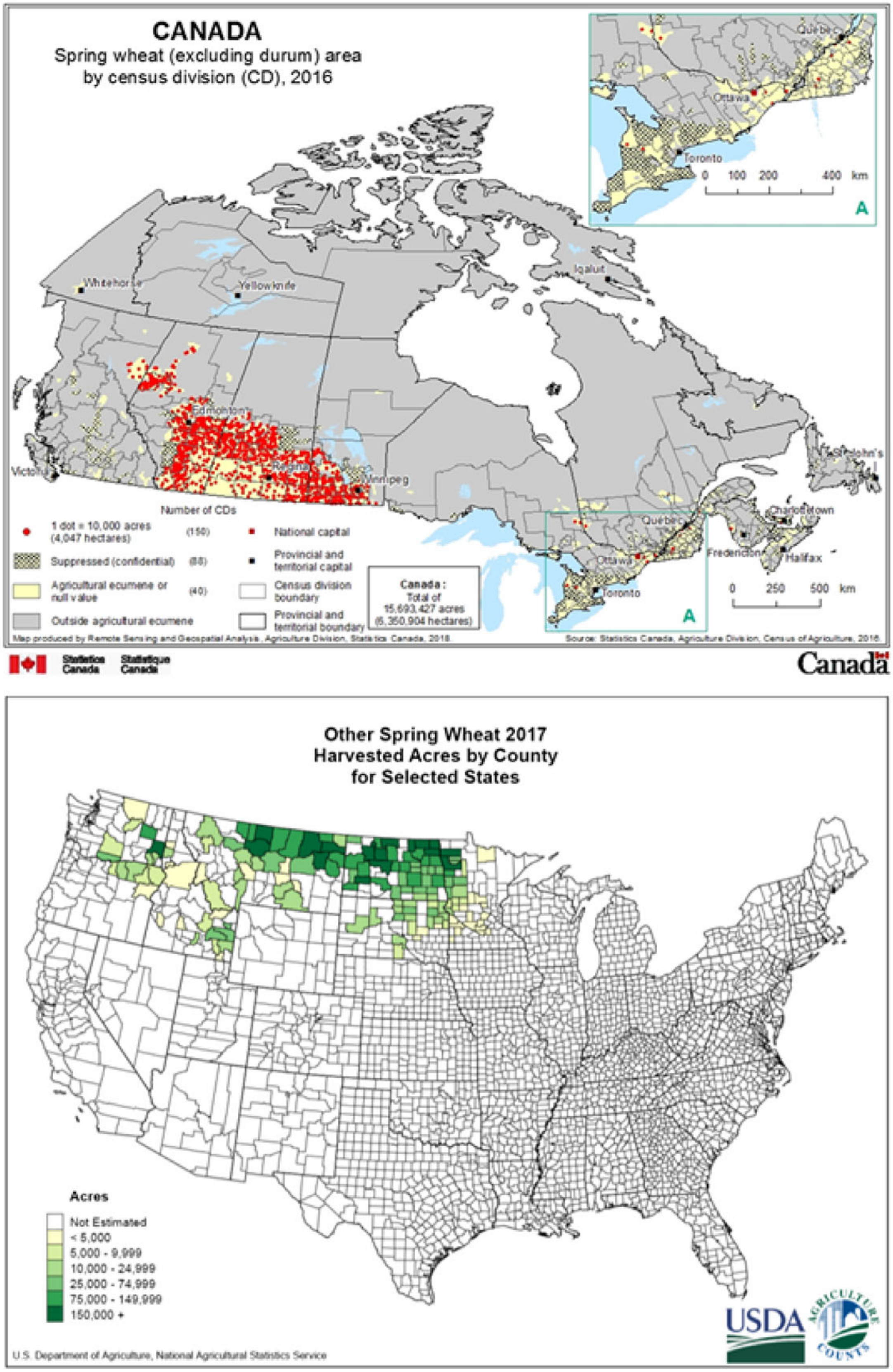

Figure 2. Distribution of spring wheat acres harvested in the United States (2017) and in Canada (2016). Images and data from USDA NASS 2017b and Statistics Canada 2017, respectively.

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Herbicides are the most widely used pesticide in wheat. Herbicides are applied to 61% and 96% of planted acres of winter and spring wheat, respectively, production in the United States (USDA-NASS 2017a). Herbicides applied postemergence (POST) are the most common method of weed management in wheat. Tillage, where used, is conducted prior to or during planting, or in very low external input, wheat-fallow systems as part of a way to maintain the fallow (Schillinger 2005). Timely seeding is essential to optimize wheat yields, and nonselective herbicides are used in place of tillage and delayed seeding practices in most systems. Herbicide use in wheat varies regionally, with the southern Great Plains using the least amount of herbicides, due to the widespread use of intensive wheat grazing systems, low rainfall, and low yield potential (Burke 2018). By contrast, more than 97% of wheat in the Pacific Northwest and northern Great Plains are treated with an herbicide.

Herbicide resistance in wheat production is a global problem, and North America is no exception (Walsh and Powles 2014). Heavy reliance on POST herbicides for management of weeds in spring and winter wheat has selected for numerous biotypes of Asteraceae, Brassicaceae, cereal rye (*Secale cereale* L.), downy brome (*Bromus tectorum* L.), Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], foxtail (*Setaria* spp.), kochia [*Bassia scoparia* (L.) A.J. Scott], Russian thistle (*Salsola tragus* L.), or wild oat (*Avena fatua* L.; Heap 2021). As herbicide resistance increases, weed control suffers, potentially causing further reduced yields. Indeed, wheat yield loss in the long running Broadbalk Experiment in England is now greater than it was before herbicides were introduced (Storkey et al. 2021).

Previous WSSA crop loss reports in wheat are nearly 30 yr old (Bridges 1992; Chandler et al. 1984; Swanton et al. 1993) and were estimated based on the expert opinions of researchers, extension specialists, and farmers across the wheat growing regions of the United States and Canada. Crop loss reports in wheat determined using quantitative data from replicated research trials across North America do not exist. Such information is important to inform funders, policymakers, commodity groups, and other stakeholders on the importance and continued need for weed science research in wheat (Walker 1983, 1987). The objective of this report is to document the potential wheat yield and economic losses due to weeds in the United States and Canada.

Materials and Methods

Weed science specialists and researchers in primary wheat growing regions of the United States and Canada were asked to provide yield data from replicated small grains research trials conducted between 2007 and 2017. Up to 10 individual trials could be reported within a year for winter, spring, and durum wheat; barley (*Hordeum vulgare* L.); and oat (*Avena sativa* L.). Data were also obtained from weed control research reports published online for several states and provinces. The specific information requested from each trial included both weedy and weed-free yields. Weedy yield was the average yield from the nontreated weedy plot (yield using BMP but no weed control practices), whereas weed-free yield was the average yield from an herbicide control plot with >90% control for each weed species (yield with BMP and excellent weed control). Yield loss was determined for each individual trial, then averaged within a year, and averaged across years for each state or province, as follows:

Table 1. Average annual production and value of barley, oat, and durum wheat in Canada and the United States from 2007 to 2017.[a]

		Production		Value
		kg × 10^6	(bu × 1,000)	US$
Barley				
	Canada	8,922	(409,781)	2,086,158,820
	U.S.	4,334	(199,041)	1,013,299,174
Oat				
	Canada	3,412	(221,257)	632,191,077
	U.S.	1,127	(73,049)	208,719,617
Durum wheat				
	Canada	5,112	(187,841)	1,442,616,365
	U.S.	2,084	(76,580)	588,133,702

[a]Based on 2007 to 2017 average production from Statistics Canada 2017 and USDA-NASS 2017b and average price from USDA-NASS (2017b).

$$Yield\ Loss\ (\%) = \frac{(weed - free\ yield\ -\ weedy\ yield)}{weed - free\ yield} \times 100 \quad [1]$$

State- and province-level data for total winter and spring wheat acres harvested, average wheat yield, as well as total production, and yearly average commodity prices were obtained from USDA-NASS (2017b), OMAFRA (2017), and Statistics Canada (2017). The average commodity price for the period of 2007 to 2017 was US$208.71 and US$234.43 per 1,000 kg of winter and spring wheat, respectively, and was used to determine potential economic loss due to weeds (USDA-NASS 2017b). National and total (US + Canada) potential yield loss values were calculated using weighted average yield loss percentage based on the production of each state or province. These methods have been previously published by the WSSA Weed Loss Committee (Soltani et al. 2016, 2017, 2018a, 2018b).

Additionally, yield loss data from the inland Pacific Northwest was used to assess the effects of weed competition between winter and spring wheat by agroecological class. The Pacific Northwest is characterized by a substantial climate gradient (Karimi et al. 2017). Within areas with similar climate, there are similar crop production practices. Three agroecological classes dominate the inland Pacific Northwest wheat production area: an area of annual crop production where rainfall typically exceeds 45 cm of annual precipitation, an area of variable crop rotations that includes fallow and is typified by rainfall between 30 and 45 cm, and an area where the dominant crop rotation is winter wheat-fallow that has an annual precipitation of less than 30 cm.

Results and Discussion

Data were received from states and provinces that represented 52.0%, 60.0%, and 52.6% of U.S., Canadian, and combined winter wheat production, respectively, and 93.3%, 82.4%, and 87.1% of U.S., Canadian, and combined spring wheat production. Data could not be obtained from states such as Colorado and Texas, which have significant winter wheat production, which potentially limits our findings. Sufficient data were not available for barley, oat, or durum wheat for yield loss analyses, despite a combined value in the U.S. + Canada of US$5.97 billion (Table 1; Statistics Canada 2017; USDA-NASS 2017b). Harker (2001) previously estimated yield loss in barley in Alberta, but reports for

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Table 2. Potential annual winter wheat yield and monetary loss due to weeds for each state or province that provided data for the period of 2007 to 2017.[a]

State or province	Area harvested		Average yield		Yield loss[b]	Potential loss in production		Potential loss in value
	ha × 1,000	(ac × 1,000)	kg ha^{-1}	(bu ac^{-1})	%	kg × 10^{6}	(bu × 1,000)	US$ × 1,000
Kansas	3,410	(8,427)	2,720	(40)	25.8	2,391	(87,845)	498,960
Michigan	223	(550)	5,010	(75)	3.0	33.6	(1,235)	7,017
Missouri	289	(715)	3,660	(54)	5.3	56.0	(2,059)	11,694
Montana	861	(2,126)	2,810	(42)	32.0	773.1	(28,408)	161,355
Nebraska	575	(1,422)	2,970	(44)	34.0	581.3	(21,358)	121,315
North Carolina	238	(588)	3,520	(52)	23.0	193.1	(7,096)	40,306
Oklahoma	1,444	(3,568)	1,980	(29)	24.3	695.1	(25,552)	145,062
Ontario	364	(900)	5,340	(79)	2.9	55.7	(2,046)	11,621
South Dakota	511	(1,263)	3,170	(47)	34.4	557.8	(20,495)	116,410
Tennessee	146	(360)	4,190	(62)	30.1	184.0	(6,762)	38,409
Washington	682	(1,684)	4,380	(65)	17.1	511.1	(18,780)	106,672

[a]Harvested acres, average yield, and yearly average commodity price were obtained from USDA-NASS (2017b) and OMAFRA (2017).
[b]Standard error for each state or province was <7.0 where it was possible to calculate.

Table 3. Potential annual spring wheat yield and monetary loss due to weeds for each state or province that provided data for the period of 2007 to 2017.[a]

State or province	Area harvested		Average yield		Yield loss[b]	Potential loss in production		Potential loss in value
	ha × 1,000	(ac × 1,000)	kg ha^{-1}	(bu ac^{-1})	%	kg × 10^{6}	(bu × 1,000)	US$ × 1,000
Alberta + Saskatchewan	5,375	(13,281)	2,990	(44)	7.9	1,268	(45,591)	297,249
Idaho	200	(493)	5,210	(77)	36.7	381.8	(14,028)	89,497
Minnesota	571	(1,411)	3,750	(56)	47.0	1,006	(36,950)	235,740
Montana	1,027	(2,537)	2,070	(31)	28.6	608.1	(22,344)	142,555
North Dakota	2,403	(5,938)	2,870	(43)	31.2	2,148	(78,915)	503,479
Ontario	47	(116)	3,570	(53)	13.9	23.3	(857)	5,470
South Dakota	491	(1,213)	2,850	(42)	26.8	374.6	(13,765)	87,822
Washington	220	(545)	3,250	(48)	19.4	139	(5,111)	32,608

[a]Harvested acres, average yield, and yearly average commodity price were obtained from USDA-NASS (2017b), Statistics Canada (2017), and OMAFRA (2017).
[b]Standard error for each state or province was <4.0 where it was possible to calculate.

other small grains in other states or provinces do not exist. Greater emphasis on yield loss due to weeds in these crops is needed in the future.

Winter wheat yield loss estimates ranged from 3.0% to 34.4% across United States and 2.9% for the province of Ontario (Table 2). Spring wheat yield loss estimates ranged from 7.9% to 47.0% across states and provinces (Table 3). Estimates for both winter and spring wheat indicate a fairly wide range of potential yield loss with a greater potential for yield loss in spring versus winter wheat. Despite this range, these data mostly align with previous WSSA Weed Loss Committee reports of 3% to 60% (Bridges 1992) and 5% to 20% yield loss (Chandler et al. 1984), and with previous Canadian estimates of 5% to 15% (Swanton et al. 1993).

Data for our analysis were obtained from herbicide evaluation studies, which may have been conducted in areas with greater weed pressure than production fields due to the objective of determining control efficacy rather than yield loss in the absence of weed control. Potentially, artificially high weed densities may cause an overestimation of wheat yield loss than actually occurs. However, previous research examining yield loss in relation to weed density corroborates our findings. Yield losses due to grassy weeds can be quite high, as much as 92% from cheatgrass (*Bromus tectorum;* Rydrych and Muzik 1968) and 84% from jointed goatgrass (*Aegilops cylindrica* Host; Ogg and Seefeldt 1999). But yield loss from grassy weeds is also variable, with estimates of 0% to 51% for *Lolium perenne* L. ssp. *multiflorum* (Appleby et al. 1976), 6% to 92% for *B. tectorum* (Rydrych and Muzik 1968; Rydrych 1974), and 30% to 84% for *A. cylindrica* (Ogg and Seefeldt 1999). Broadleaf weed species in wheat are much more diverse and include Russian thistle (*Salsola tragus* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], mayweed chamomile (*Anthemis cotula* L.), prickly lettuce (*Lactuca serriola* L.), henbit (*Lamium amplexicaule* L.), common chickweed [*Stellaria media* (L.) Vill.], mustard spp. (*Brassica* spp. L.), and volunteer canola (*Brassica napus* L.). Similarly, for broadleaf weed species, yield loss ranges from 0.3% to 48% from *L. amplexicaule* or *S. media* competition (Conley and Bradley 2005; Farahbakhsh et al. 1987; Northam et al. 1993) and 28% to 51% from blue mustard [*Chorispora tenella* (Pall.) DC.; Swan 1971].

Yield loss in winter and spring wheat in the Pacific Northwest varied by agroecological class, with the greatest yield loss occurring in areas with the lowest rainfall (the wheat-fallow agroecological class in winter wheat at 30.4% (Table 4; Figure 3). Conversely, yield loss in spring wheat, at 21.7%, was greatest in areas of more abundant precipitation where annual crop rotations are practiced. Overall crop productivity is lowest in the wheat-fallow agroecological class, and spring wheat is viewed as a weed management rotation with little economic return in that agroecological class (Schillinger and Young 2004). Under future climate change scenarios, the winter wheat-fallow agroecological class is anticipated to grow in area (Karimi et al. 2017; Storkey et al. 2021), potentially increasing the yield loss potential for the region. Yield loss in spring wheat in the wheat-fallow agroecological class was lowest in the region, but it is also the least productive rotation unless practiced

Table 4. Potential annual spring and winter wheat yield and monetary loss due to weeds for the three agroecological classes comprising the dryland wheat producing area in the inland Pacific Northwest (combined across northern Idaho, Oregon, and Washington) for the period of 2007 to 2015.[a]

Crop and agroecological class[b]	Area harvested		Average yield		Yield loss	Potential loss in production		Potential loss in value
	ha × 1,000	(ac × 1,000)	kg ha^{-1}	(bu ac^{-1})	%	kg × 10^6	(bu × 1,000)	US$ × 1,000
Winter wheat	1,028	(2,479)	4,580	(68)	15.7	736.1	(26,360)	149,727
Annual Crop	244	(587)	6,030	(90)	10.5	155.0	(5,551)	31,430
Transition	312	(753)	4,030	(60)	16.6	209.2	(7,490)	42,543
Wheat-Fallow	473	(1,137)	2,900	(43)	30.4	416.8	(14,924)	84,770
Spring wheat	249	(599)	3,850	(57)	20.2	193.8	(6,939)	39,412
Annual Crop	99	(239)	4,280	(64)	21.7	92.1	(3,297)	18,728
Transition	121	(292)	3,310	(49)	18.0	72.2	(2,587)	14,693
Wheat-Fallow	29	(71)	1,950	(29)	3.4	2.0	(71)	400

[a]Harvested acres, average yield, and yearly average commodity price were obtained from USDA-NASS.
[b]Agroecological classes for the inland Pacific Northwest include annual cropped, transition, and wheat-fallow, based on the actual annual land use/cover derived from the Cropland data layer 2008–2015 (Kaur et al. 2017; USDA-NASS 2017b).

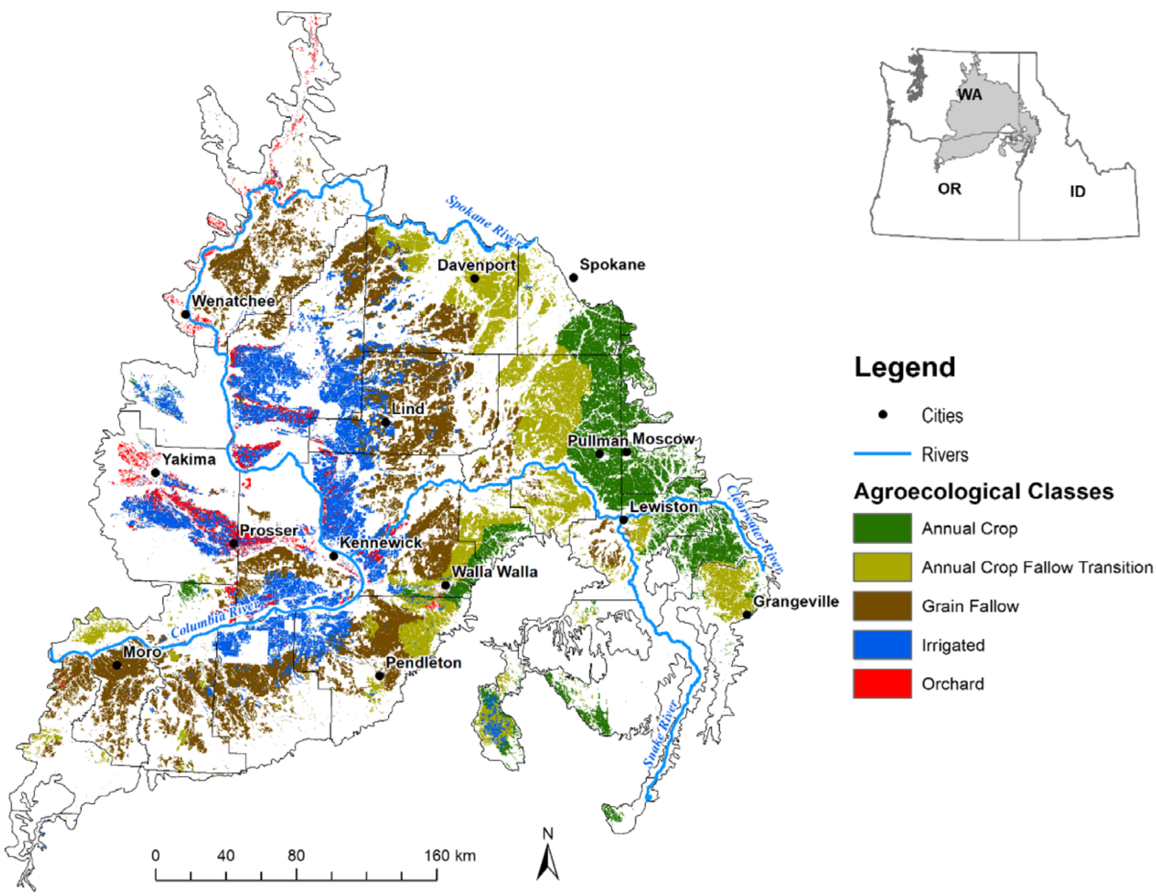

Figure 3. Agroecological classes in the inland Pacific Northwest wheat producing areas are caused by a rainfall gradient, where rainfall increases from west to east across the region. Yield loss estimates are associated with Zone 2, Annual Crop, Zone 3 Annual Crop - Fallow Transition, and zone 5, Grain Fallow.

annually (Juergens et al. 2004; Young et al. 2015). Potential yield loss due to weeds in the Pacific Northwest approached US$190 million.

By weighted average based on production, weeds cause a potential 23.5% yield loss in winter wheat across the United States and Canada and 19.5% yield loss in U.S. and Canadian spring wheat when using BMPs but no herbicidal weed control (Table 5). These estimates are slightly higher than those by Chandler et al. (1984) who reported a 13% average yield loss in wheat due to weeds in the United States and 5% to 15% in Canada. These estimates are also higher than worldwide historical estimates of 9.8% (Cramer 1967) and 12.3% (Oerke et al. 1994). However, these estimates do align with reported by Oerke (2006) of a potential yield loss of 18% to 29%. Greater yield loss due to weeds in our analysis compared with previous estimates corroborates findings of the Broadbalk experiment in England, where yield loss is greater now than before herbicides were introduced (Storkey et al. 2021). The trend of increasing losses is attributed to a warming climate and shorter wheat cultivars (Storkey et al. 2021).

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Table 5. Wheat yield and monetary loss due to weeds for the United States and Canada.

	Average yield loss[a]	Potential loss in production		Potential loss in value[b]
	%	kg × 10^6	(bu × 1,000)	US$
Winter wheat				
U.S.	25.4	10,511	(386,220)	2,193,730,855
Canada	2.9	93	(3,408)	19,357,921
Total	23.5	10,500	(385,820)	2,191,455,233
Spring wheat				
U.S.	33.2	4,843	(177,947)	1,135,304,825
Canada	8.0	1,566	(57,556)	367,210,218
Total	19.5	6,673	(245,190)	1,392,677,532

[a]Estimate is a weighted average by production of states or provinces relative to total production.
[b]Value is based on the average price of winter wheat (US$5.68 bu^{-1}) and spring wheat (US$6.38 bu^{-1}) from 2007 to 2017 (USDA-NASS 2017b).

Potential yield loss is in contrast to realized or actual yield loss. Actual wheat yield loss due to weeds is 7.7%, ranging from 3% to 13% (Oerke 2006), which is much less than our potential yield loss estimate. This difference is understandable since farmers will not completely ignore weeds. However, if a weed population is resistant to the herbicide applied, farmers may largely fail to control weeds, likely realizing yield losses aligned with our estimates.

Crop losses due to weeds are of critical concern in wheat-producing areas. In very low external input/low yielding wheat production systems, where wheat yields are often less than 2,000 kg ha^{-1} yr^{-1}, herbicide resistance threatens to regress reductions in tillage (a process outlined by Shaw et al. 2012). Wheat growers managing such systems in North America cannot afford alternative herbicides that are often costlier, do not have any economically viable rotational crop, and thus are forced to use mechanical weed control to manage weeds (Schillinger and Young 2004).

Based on these yield loss estimates, the potential winter wheat loss due to weeds is 10.5 billion kg with a potential loss in value of US$2.19 billion for the United States and Canada (Table 5). Potential spring wheat loss due to weeds is 6.67 billion kg with a potential loss in value of US$1.39 billion for the United States and Canada. These data strongly indicate the continued need for investment in weed science research.

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References

Appleby AP, Olson PD, Colbert DR (1976) Winter wheat yield reduction from interference by Italian ryegrass. Agron J 68:463–466

Burke IC (2018) Use of 2,4-D and other phenoxy herbicides in small grains in the United States. Industry Task Force II on 2,4-D Research Data Economic Benefits Study. https://24d.info/wp-content/uploads/2020/08/6_Small_Grains.pdf. Accessed: March 4, 2021.

Bridges DC (1992) Crop losses due to weeds in the United States. Champaign, IL: Weed Science Society America. 403 p

Chandler JM, Hamill AS, Thomas AG (1984) Crop losses due to weeds in Canada and the United States. Champaign, IL: Weed Science Society of America

Conley SP, Bradley KW (2005) Wheat (*Triticum aestivum*) yield response to henbit (*Lamium amplexicaule*) interference and simulated winterkill. Weed Technol 19:902–906

Cramer HH (1967) Plant Protection and World Crop Production. Leverkusen: Farbenfabriken Bayer AG (Pflanzenschutz-Nachrichten Bayer; vol. 20). 524 p

[FAO] Food and Agriculture Organization of the United Nations (2017) FAOSTAT. http://www.fao.org/faostat/en/#data. Accessed: February 18, 2021

Farahbakhsh A, Murphy KJ, Madden AD (1987) The effect of weed interference on the growth and yield of wheat. Proc Br Crop Prof Conf 3:955–961

Harker KN (2001) Survey of yield losses due to weeds in central Alberta. Can J Plant Sci 81:339–342

Heap I. The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed: October 26, 2021

Juergens LA, Young LA, Schillinger WF, Hinman HR (2004) Economics of alternative no-till spring crop rotations in Washington's wheat-fallow region. Agron J 96:154–158

Karimi T, Stöckle CO, Higgins SS, Nelson RL, Huggins D (2017) Projected dryland cropping system shifts in the Pacific Northwest in response to climate change. Front Ecol Evol 5:20

Kaur H, Huggins DR, Rupp RA, Abatzoglou JT, Stöckle CO, Reganold JP (2017) Agro-ecological class stability decreases in response to climate change projections for the Pacific Northwest, USA. Front Ecol Evol 5:51

Northam FE, Stahlman PW, Abd El-Hamid M (1993) Broadleaf weed control in winter wheat. West Soc Weed Sci Res Prog Rep III:173–175

Ogg A, Seefeldt S (1999) Characterizing traits that enhance the competitiveness of winter wheat (*Triticum aestivum*) against jointed goatgrass (*Aegilops cylindrica*). Weed Sci 47:74–80

[OMAFRA] Ontario Ministry of Agriculture, Food, and Rural Affairs (2017) Field Crops. http://www.omafra.gov.on.ca/english/stats/crops/index.html. Accessed: February 18, 2021

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43

Oerke EC, Dehne HW, Schönbeck F, Weber A (1994) Crop production and crop protection – Estimated losses in major food and cash crops. Amsterdam: Elsevier Science. 808 p

Paarlberg R (2014) A dubious success: the NGO campaign against GMOs. GM Crops Food 5:223–228

Rydrych D (1974) Competition between winter wheat and downy brome. Weed Sci 22:211–214

Rydrych DJ, Muzik TJ (1968) Downy brome competition and control in dryland wheat. Agron J 60:279–280

Schillinger WF, Young DL (2004) Cropping systems research in the world's driest rainfed wheat region. Agron J 96:1182–1187

Schillinger WF (2005) Tillage method and sowing rate relations for dryland spring wheat, barley, and oat. Crop Sci 45:2636–2643

Shaw DR, Culpepper S, Owen M, Price A, Wilson R (2012) Issue Paper: Herbicide-resistant weeds threaten soil conservation gains: finding a balance

for soil and farm sustainability. Ames, IA: Council for Agricultural Science and Technology. 49 p
Soltani F, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2016) Potential corn yield losses from weeds in North America. Weed Technol 30:979–984
Soltani F, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148–154
Soltani N, Dille JA, Robinson DE, Sprague CL, Morishita DW, Lawrence NC, Kniss AR, Jha P, Felix J, Nurse RE, Sikkema PH (2018a) Potential yield loss in sugar beet due to weed interference in the United States and Canada. Weed Technol 32:749–753
Soltani N, Dille JA, Gulden R, Sprague C, Zollinger R, Morishita DW, Lawrence NC, Sbatella GM, Kniss AR, Jha P, Sikkema PH (2018b) Potential yield loss in dry bean crops due to weeds in the United States and Canada. Weed Technol 32:342–346
Statistics Canada (2017) Data. https://www.statcan.gc.ca/eng/start. Accessed: February 18, 2021.
Storkey J, Mead A, Addy J, MacDonald AJ (2021) Agricultural intensification and climate change have increased the threat from weeds. Glob Change Biol DOI: 10.1111/gcb.15585
Swan DG (1971) Competition of blue mustard with winter wheat. Weed Sci 1:340–342
Swanton CJ, Harker KN, Anderson RL (1993) Crop losses due to weeds in Canada. Weed Technol 7:537–542
[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Survey (2017a) Agricultural Chemical Use Program. Wheat. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2017_Cotton_Soybeans_Wheat_Highlight/ChemUseHighlights_Wheat_2017.pdf. Accessed: February 25, 2021
[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Survey (2017b) https://www.nass.usda.gov/. Accessed: February 18, 2021
Walker PT (1983) Crop losses: the need to quantify the effects of pests, diseases and weeds on agricultural production. Agric Ecosyst Environ 9:119–158
Walker PT (1987) Losses in yield due to pests in tropical crops and their value in policy decision-making. Insect Sci Appl 8:665–671
Walsh MJ, Powles SB (2014) Management of herbicide resistance in wheat cropping systems: learning from the Australian experience. Pest Manag Sci 70:1324–8
Young FL, Alldredge JR, Pan WL, Hennings C (2015) Comparisons of annual no-till spring cereal cropping systems in the Pacific Northwest. Crop Forage Turfgrass Manage 1:1–7