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Alberta Weed Survey

Herbicide-Resistant Weeds 2007

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Weed Survey Series

Canada

Alberta Weed Survey of Herbicide-Resistant Weeds in 2007

by

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77-1	Weed survey of cultivated land in Saskatchewan (1977)
78-1	Report on the 1977 weed survey and questionnaire in Saskatchewan
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79-1	Manitoba weed survey questionnaire data (1978)
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PREFACE

A major five-year weed survey project (April 1, 2007-March 31, 2012) entitled “Trends in herbicide-resistant weed occurrence across the prairies” was inititated in 2007. The project involves a survey of resistant weeds in 1,000 randomly-selected fields: 300 in Alberta in 2007, 300 in Manitoba in 2008, and 400 in Saskatchewan in 2009. Unfortunately, we were not able to conduct the field management questionnaire component as planned, because permission was not granted from Viterra, which purchased the assets of Agricore United; the former company had provided us access to their field database, which was used to select survey fields in the three prairie provinces.

Previously published reports in the Weed Survey Series on occurrence of herbicide-resistant weeds were: (1) 04-1: Alberta weed survey of herbicide-resistant weeds in 2001; (2) 04-2: Manitoba weed survey of herbicide-resistant weeds in 2002; (3) 06-1: Saskatchewan weed survey of herbicide-resistant weeds in 2003; and (4) 06-2: Prairie weed survey of herbicide-resistant wild oat from 2001 to 2003. These surveys established a baseline from which to compare the occurrence of herbicide resistance in the future.

This report documents the nature, distribution and abundance of herbicide-resistant weeds in Alberta in 2007. As indicated above, 300 fields were surveyed across the province. The sites in this survey were selected randomly, weighted only according to crop type and ecodistrict similar to methodology used in the general weed survey. All weed species with viable seed were sampled, and resistance testing was the most extensive to date.

Succeeding reports will detail weed resistance in Manitoba in 2008 and Saskatchewan in 2009. A fourth report will integrate the results from the three reports to facilitate a comparison of weed resistance across the major prairie ecoregions and provide “the big picture” of weed resistance in the prairies.

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Monsanto Canada Inc.
Nufarm Agriculture Inc.
Syngenta Crop Protection Canada, Inc.

We gratefully acknowledge the collaboration and assistance of Denise Maurice and Keith Mills, and all the Agricore United staff who collected spring kochia or Russian thistle seedlings. We also acknowledge the assistance of Dr. Bob Blackshaw and crew for logistical support for the spring survey. We thank David Giffen, AAFC Saskatoon, for producing the maps.

Special thanks are extended to the 1,000 producers who participated in this survey.

Hugh J. Beckie, Chris Lozinski, and Scott Shirriff

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A weed resistance survey of 300 randomly-selected fields was conducted across the major ecoregions of Alberta in 2007. All residual weed species with viable seeds were mapped and sampled before harvest. Selected fields were cropped to cereals, oilseeds, or pulses (field pea). Samples of 35 weed species were subsequently screened in the greenhouse with herbicides belonging to various groups. In addition, an early spring survey was conducted to document resistance in kochia and Russian thistle.

Of 179 fields where wild oat samples were collected, 39% had Group 1-resistant wild oat and 12% had Group 2-resistant wild oat. Therefore, Group 1 resistance in wild oat has increased sharply since 2001 (11% of fields), but Group 2 resistance has remained at the same field frequency. Most of the fields with either resistant biotype originated in the Aspen Parkland ecoregion, attributed to historically high frequency of use of products from these groups. Most Group 1-resistant wild oat populations exhibited broad cross-resistance to herbicides from the three chemical classes – fop, dim, den. Group 2-resistant populations also exhibited broad cross-resistance across three classes. Group 8-resistant wild oat was found in 15% of fields. Group 1 resistance was documented in two green foxtail populations; resistance in this weed was not found in the 2001 survey. Group 2 resistance was documented in 40% of 30 fields with chickweed (17% in 2001), all 11 fields with spiny annual sow-thistle (67% in 2001), 17% of 30 fields with cleavers (not reported in 2001), and one field with wild buckwheat, the first global report. Thus, resistance is steadily increasing in chickweed and spiny annual sow-thistle, and most recently, cleavers. Of 95 fields where kochia was sampled, 85% had Group 2-resistant populations, whereas only 1 of 14 fields had a Russian thistle population that was Group 2-resistant. However, all broadleaf weed populations were susceptible to Group 4 herbicides. Group 2 resistance in broadleaf weeds will pose an increasingly weed control challenge for pulse crop producers. All weed populations were susceptible to glyphosate and glufosinate.

When the frequency of fields with weed resistance in this random survey of 300 fields is extrapolated to the total annual-cropped land in Alberta (7,885,000 ha in 2007), it is estimated that 2.1 million ha (27%) is infested with herbicide-resistant weeds, in a total field area of 3.1 million ha (40%). In comparison, the weed resistance survey in 2001 indicated that 0.3 million ha was infested with herbicide-resistant weeds, in a total field area of 1.5 million ha.

Past Weed Resistance Surveys in Alberta

Field surveys of specific resistant-weed biotypes have been conducted in Alberta since 1990. They focused on wild oat (*Avena fatua* L.) resistance to triallate/difenzoquat (Group 8), Group 1, or Group 2 herbicides. In 1990, wild oat seed was collected from 34 fields with a history of repeated triallate use and tested for Group 8 resistance. Forty-four percent of those fields had Group 8-resistant wild oat (O'Donovan et al. 1994b). In 1996, 38 fields where a Group 1 herbicide had been applied that year were surveyed for Group 1-resistant wild oat (O'Donovan et al. 1998). Nine of those fields (25%) had Group 1-resistant wild oat. Most of the populations originated in the southern (Grassland) region of Alberta, which was attributed to greater Group 1 herbicide use (O'Donovan et al. 1998).

In addition to resistance in wild oat, resistance was documented in two broadleaf weeds in Alberta from the late 1980s to mid-1990s. Group 2 resistance in multiple populations of chickweed [*Stellaria media* (L.) Vill.] had been documented since 1988 in the Parkland region of Alberta (Morrison and Devine 1994; O'Donovan et al. 1994a). Two Group 2-resistant populations of spiny annual sow-thistle [*Sonchus asper* (L.) Hill] were described from this area in 1996 (Rashid et al. 2003).

In Wheatland County, Alberta located in the Fescue Grassland ecoregion (defined as an area similar in climate, soils, natural vegetation, and land use (see Figure 1; Agriculture and Agri-Food Canada 2003), 95 fields were surveyed for herbicide-resistant wild oat from 1997 to 1999 (Beckie et al. 1999, 2004a). These fields had been treated repeatedly with the same herbicide

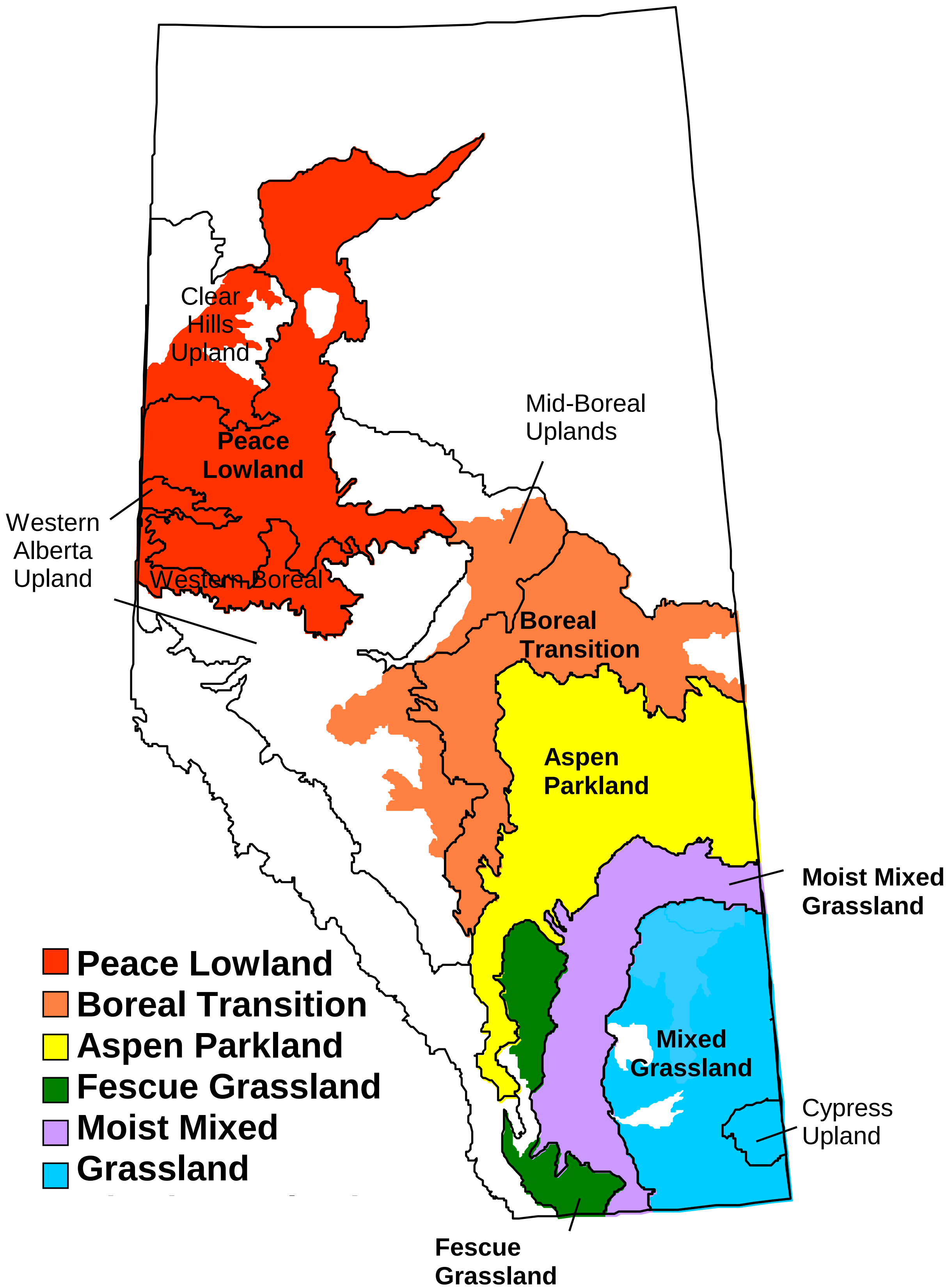


Figure 1. Ecoregions of Alberta (map derived from Agriculture and Agri-Food Canada (2003))

mode of action for wild oat control. Nearly 20% of fields had wild oat with Group 1 resistance, 10% with Group 2 resistance, and 6% with Group 8 resistance.

Resistance testing of samples submitted by producers (or industry on behalf of producers) has complemented field surveys in herbicide resistance monitoring in western Canada. Joint testing is conducted by the Crop Protection Lab (CPL) of Saskatchewan Ministry of Agriculture and Agriculture and Agri-Food Canada, Saskatoon. Results from the 1996 to 2006 crop years were recently published (Beckie et al. 2007, 2008). In Alberta, 289 submission samples of wild oat were confirmed as Group 1-resistant: aryloxyphenoxypropionate (fop) only (185 samples), cyclohexanedione (dim) only (2 samples) and fop+dim (124 samples); many resistant wild oat samples originated from the Aspen Parkland ecoregion, although a significant number were from the Grassland region. There were 15 Group 2-resistant wild oat samples from Alberta, and 22 Group 1+2-resistant wild oat samples. Most Group 2- or Group 1+2-resistant samples originated from the Parkland region where Group 2 use is historically the highest (Leeson et al. 2007). The occurrence of intergroup-resistant wild oat has serious consequences for alternative herbicide options in cereal crops (Beckie et al. 2001). Only seven wild oat samples from Alberta during this 11-year period were confirmed as Group 8-resistant.

In samples from Alberta, there was only one case of Group 1-resistant green foxtail [*Setaria viridis* (L.) Beauv.] in the Grassland region in 2006. Ten cases of Group 2-resistant kochia [*Kochia scoparia* (L.) Schrad.] were mainly from the Grassland region. Other Group 2-resistant broadleaf weeds included two populations of wild mustard (*Sinapis arvensis* L.) near Edmonton; two populations of stinkweed (*Thlaspi arvense* L.) in central and northern Alberta, one population of cleavers (*Galium aparine* L.) near Red Deer, three populations of chickweed near Edmonton and Innisfail, and one population of hemp-nettle (*Galeopsis tetrahit* L.) near Carstairs.

In 2007, there was an additional population of resistant wild mustard near Fort Saskatchewan, 42 additional cases of Group 1-resistant wild oat, 19 cases of Group 2-resistant wild oat, and 13 cases of Group 1+2-resistant wild oat (unpublished data).

A survey of weeds resistant to herbicides in 236 randomly-selected fields was conducted across the major ecoregions of Alberta in 2001 (Beckie et al. 2004b, 2008). This baseline survey determined the incidence of herbicide resistance, and serves as a reference for the 2007 survey described herein. All residual weed species with viable seeds were mapped and sampled before harvest. Selected fields were cropped to cereals, oilseeds, or pulses (field pea). Samples of 20 weed species were subsequently screened in the greenhouse with high-risk herbicides belonging to Groups 1 and 2. Producers provided information on herbicide group rotation and resistance awareness and impact via a questionnaire.

Nearly 20% of surveyed fields had a herbicide-resistant weed biotype. Of 190 fields where wild oat samples were collected, 11% had Group 1-resistant wild oat (9% of all fields surveyed) and 13% had Group 2-resistant wild oat (10% of all fields surveyed). Half of the fields with either resistant biotype originated in the Aspen Parkland ecoregion, which was attributed to historically high frequency of use of products from these groups. Most Group 1-resistant wild oat populations exhibited resistance to both fop and dim herbicides. Group 2-resistant populations exhibited broad cross resistance across three classes of Group 2 herbicides. Of 16 broadleaf weed species, Group 2 resistance was detected only in chickweed (17% of fields in the Aspen Parkland ecoregion) and spiny annual sow-thistle (67% of fields in the Moist Mixed Grassland, Fescue Grassland, or Aspen Parkland ecoregions).

Although 82% of producers practiced herbicide group rotation in 2001, the high frequency of use of Group 1 or 2 products (45 and 40% of fields sprayed in 2001, respectively) suggests that rotations practiced by a significant number of these producers are less than effective in delaying resistance to these herbicides. Use of these herbicides for grass weed control in cereal crops is expected to increase with the loss of older chemistries or decline in preemergence application.

Only 5% of producers with resistant biotypes previously suspected or were aware of their occurrence. This low level of awareness was consistent with findings from previous surveys, and may be attributed, in part, to the relatively small infestation area of resistant biotypes in most fields. In 2001, only 12% of producers believed that resistance had a significant impact on their farm. In the next five years, about 20% of producers expected herbicide resistance to pose a moderate or high impact on their farm.

Objectives

In 2007, 300 fields were randomly selected for a weed resistance survey. In the weed resistance survey reported herein, all residual weed species with viable seed were mapped and sampled. Samples were subsequently screened in the greenhouse with various herbicides from different groups.

Sites

A total of 300 fields were surveyed for herbicide-resistant weeds (Map 1). Each field was farmed by a different producer. Similar to the general weed survey (Leeson et al. 2002), a stratified-randomized design was used to select fields (Thomas 1985). The proportional allocation of fields among the major crops grown in each ecodistrict (geographic area within an ecoregion similar in landform, relief, surficial material, climate, soils, natural vegetation, and land use; Agriculture and Agri-Food Canada 2003) was based on data from Statistics Canada (2006). Fields were randomly selected from the Agricore United database. Each sampling unit comprised a 64-ha area. The field allocation by crop in the extension regions of Alberta is shown in Table 1. A majority of the fields (71%) were cropped to cereals. This proportion was lower than that of the 2001 weed resistance survey (85%). Wheat occupied 49% of the 213 survey fields cropped to cereals, barley 43%, and oat 8% – a proportion similar to that of the 2001 survey. Oilseeds

Table 1. Field allocation by crop in the extension regions of Alberta

Crop	Southern	Central	North	Peace	*All areas*
	No. of fields				
Wheat	39	24	33	8	*104*
Barley	27	23	30	11	*91*
Oat	0	5	8	5	*18*
Canola	10	10	33	22	*75*
Flax	2	0	0	0	2
Mustard	2	0	0	0	2
Field pea	2	4	2	0	*8*
Total	*82*	*66*	*106*	*46*	***300***

Table 2. Field allocation by crop in the major ecoregions of Alberta

Crop	Mixed Grassland	Moist Mixed Grassland	Fescue Grassland	Aspen Parkland	Boreal Transition	Peace Lowland	*All areas*
	No. of fields						
Wheat	24	21	5	40	6	8	*104*
Barley	6	19	10	36	8	12	*91*
Oat	1	3	0	7	3	4	*18*
Canola	4	6	4	28	12	21	*75*
Flax	2	0	0	0	0	0	2
Mustard	0	1	1	0	0	0	2
Field pea	0	4	0	4	0	0	*8*
Total	*37*	*54*	*20*	*115*	*29*	*45*	***300***

(mainly canola with two mustard and two flax fields) comprised 26% of fields (canola proportion twice that of the 2001 survey), and field pea 3% (same proportion as that of the 2001 survey). The proportion of fields cropped to cereals ranged from 80% in the Southern region to 52% in the Peace region.

Of the 111 fields (37% of total) in the Grassland region (Mixed Grassland, Moist Mixed Grassland and Fescue Grassland ecoregions), cereals comprised 80% and broadleaf crops 20% (Table 2). In the 2001 survey, cereals had comprised 93% of fields in the Grassland region. Of the 189 fields in the Parkland region (all other ecoregions), cereals comprised two-thirds and broadleafs (primarily canola) one-third of crops grown. In contrast, cereals and broadleafs had comprised 80 and 20%, respectively, of fields in the region in the 2001 survey.

Field Survey

Fields were surveyed using the inverted 'W' pattern (Thomas 1985) in August or September immediately before crop harvest. About 1,000 viable seeds of a weed species were collected, when available, from mature plants occurring in a patch (each patch sampled separately) and placed in an unsealed paper bag (Beckie et al. 2000). If the weed population was widely disseminated across the field with no visible patchiness (i.e., single plants), at least 100 plants were sampled to obtain an estimate of the level of resistance in the weed population. The approximate infestation area of a weed species in a field was recorded. Samples were dried and stored at room temperature before conducting the resistance tests. The number of weed samples tested is shown in Table 3.

Half of the 35 weed species tested for resistance were ranked in the top 20 on the basis of relative abundance in fields surveyed in 2001 (Leeson et al. 2002). Some species whose seeds had been collected were not tested because of limited seed, no known response to herbicides used in screening, or non-viable seed.

Table 3. Weed species tested for resistance

Weed species	Samples tested	Fields	Rank[a]
Grass:	No.	No.	
Barnyard grass, *Echinochloa crusgalli* (L.) P. Beauv.	1	1	15
Downey brome, *Bromus tectorum* L.	1	1	53
Foxtail barley, *Hordeum jubatum* L.	8	8	31
Green foxtail, *Setaria viridis* (L.) Beauv.	16	16	9
Quack grass, *Elytrigia repens* (L.) Desv. ex B. D. Jacks	2	2	14
Wild oat, *Avena fatua* L.	202	179	2
Broadleaf:			
Canada fleabane, *Conyza canadensis* (L.) Cronquist	3	3	-
Canada thistle, *Cirsium arvense* (L.) scop.	2	2	4
Chickweed, *Stellaria media* (L.) Vill.	30	30	3
Cleavers, *Galium aparine* L.	31	30	6
Common groundsel, *Senecio vulgaris* L.	2	2	23
Common pepper-grass, *Lepidium densiflorum* Schrad	1	1	66
Corn spurry, *Spergula arvensis* L.	3	3	26
Cow cockle, *Vaccaria hispanica* (Mill.) Rauschert	6	6	46
Dandelion, *Taraxacum officinale* Weber in F.H. Wigg.	3	3	10
Flixweed, *Descurainia sophia* (L.) Webb ex Prantl	7	7	29
Hemp-nettle, *Galeopsis tetrahit* L.	12	12	8
Knotweed, *Polygonum* spp.	1	1	35
Kochia, *Kochia scoparia* (L.) Schrad.	10	10	20
Lamb's-quarters, *Chenopodium album* L.	26	25	7
Narrow-leaved hawk's-beard, *Crepis tectorum* L.	2	2	17
Night-flowering catchfly, *Silene noctiflora* L.	6	6	47
Perennial sow-thistle, *Sonchus arvensis* L.	7	7	18
Prickly lettuce, *Lactuca serriola* L.	6	6	114
Redroot pigweed, *Amaranthus retroflexus* L.	13	13	22
Russian pigweed, *Axyris amaranthoides* L.	2	2	84
Shepherd's-purse, *Capsella bursa-pastoris* (L.) Medik.	7	7	13
Annual smartweed species, *Polygonum* spp.	7	7	11
Spiny annual sow-thistle, *Sonchus asper* (L.) Hill	11	11	41
Stinkweed, *Thlaspi arvense* L.	46	45	5
Stork's-bill, *Erodium cicutarium* (L.) L'Hér.ex Aiton	3	3	28
Toad flax, *Linaria vulgaris* Hill.	1	1	-
Tumble pigweed, *Amaranthus albus* L.	2	2	-
Wild buckwheat, *Polygonum convolvulus* L.	45	43	1
Wild mustard, *Sinapis arvensis* L.	1	1	37

[a]Relative abundance rank of species in 1,153 fields surveyed in 2001 (Leeson et al. 2002); rank of annual smartweed species is that of pale smartweed.

Resistance Tests

Resistance tests were initiated 4 months after seeds were collected to reduce the level of innate dormancy. All tests were conducted using pot assays in the greenhouse. Weed species were sprayed at growth stages (usually two to four leaves) for optimum herbicide efficacy. Weed samples were screened for resistance to various herbicides from different groups (Table 4).

Grass weed species were tested for resistance to a maximum of seven Group 1 herbicides: three aryloxyphenoxypropionate (fop) herbicides, three cyclohexanedione (dim) herbicides, and pinoxaden, a phenylpyrazolin (den) herbicide. The three fop herbicides were fenoxaprop (without safener) at 150 g/ha (wild oat) or 40 g/ha (green foxtail and other annual grasses), clodinafop at 35 g/ha, and quizalofop at 35 g/ha (70 g/ha for perennial grasses); the three dim herbicides were sethoxydim at 110 g/ha (wild oat), 50 g/ha (green foxtail), 145 g/ha (other annual grasses), or 500 g/ha (perennial grasses), tralkoxydim at 25 g/ha, and clethodim at 15 g/ha. Pinoxaden was applied at 15 g/ha. All recommended adjuvants were included in the herbicide spray solutions.

Grass or broadleaf weed species were screened for resistance using a maximum of seven Group 2 herbicides. Grass species were treated with three Group 2 herbicides: imazamethabenz, imazamox, and flucarbazone. Imazamethabenz was applied at 500 g/ha, imazamox at 35 g/ha, and flucarbazone at 15 g/ha. Broadleaf weed species were treated with a maximum of five Group 2 herbicides: two imidazolinones (imazethapyr, imazamox), two sulfonylureas (metsulfuron, thifensulfuron:tribenuron mixture), and florasulam, a triazolopyrimidine herbicide. Imazethapyr was applied at 50 g/ha, imazamox at 35 g/ha, metsulfuron at 4.5 g/ha, thifensulfuron:tribenuron at 15 g/ha, and florasulam at 10 g/ha.

In addition to Group 1 and 2 herbicides, weed samples were screened with various Group 4 herbicides, triallate and difenzoquat (Group 8), glyphosate (Group 9) and glufosinate (Group

Table 4. Herbicides used in resistance screening[a]

Herbicide	Group	Weed species	Rate (gai/ha)
Fenoxaprop	1 (Fop)	Wild oat, green foxtail, other annual grass	150, 40, 40
Clodinafop	1 (Fop)	Wild oat, green foxtail	35, 35
Quizalofop	1 (Fop)	Wild oat, green foxtail, perennial grass	35, 35, 70
Sethoxydim	1 (Dim)	Wild oat, green foxtail, other annual grass, perennial grass	110, 50, 145 500
Tralkoxydim	1 (Dim)	Wild oat, green foxtail	25, 25
Clethodim	1 (Dim)	Wild oat, green foxtail	15, 15
Pinoxaden	1 (Den)	Wild oat, green foxtail	15, 15
Imazamethabenz	2 (Imi)	Wild oat	500
Imazethapyr	2 (Imi)	Broadleafs	50
Imazamox	2 (Imi)	Grass and broadleafs	35, 35
Metsulfuron	2 (SU)	Broadleafs	4.5
Thifensufuron: tribenuron	2 (SU)	Broadleafs	15
Flucarbazone	2 (SCT)	Wild oat	15
Florasulam	2 (TZP)	Broadleafs	5
2,4-D or MCPA	4 (Auxin)	Broadleafs	350, 350
Dicamba	4 (BA)	Broadleafs	140
Fluroxypyr	4 (CA)	Broadleafs	80
Triallate	8	Wild oat	1,180
Difenzoquat	8	Wild oat	700
Glyphosate	9	Grass and broadleafs	450 (annuals); 900 (perennials)
Glufosinate	10	Grass and broadleafs	500

[a]For each herbicide, only weed species listed on the label as being controlled were screened. *Abbreviations:* BA: benzoic acid; CA: carboxylic acid; Dim: cyclohexanedione; Den: phenylpyrazolin; Fop: aryloxyphenoxypropionate; Imi: imidazolinone; SCT: sulfonylaminocarbonyltriazolinone; SU: sulfonylurea; TZP: triazolopyrimidine.

10). Herbicides were applied using a moving-nozzle cabinet sprayer equipped with a flat-fan spray tip (TeeJet 8002VS) calibrated to deliver 200 L/ha of spray solution at 275 kPa in a single pass over the foliage.

Thirty-six plants were grown in flats measuring 52 by 26 by 5 cm that were filled with a commercial potting mixture amended with a slow-release fertilizer. Plants were visually assessed as herbicide-resistant or herbicide-susceptible at 21 to 28 d after treatment. A minimum of 100 seedlings per sample were screened in each resistance test. Treatments (and untreated controls) were replicated three times and the tests were repeated. Known herbicide-resistant and herbicide-susceptible biotypes, when available, were included in all tests (Beckie et al. 2000).

Spring Seedling Field Survey: Kochia and Russian Thistle

In collaboration with Agricore United staff, an early spring (April/May) field survey of herbicide-resistant kochia and Russian thistle (*Salsola tragus* L.) was conducted. In many crops, these two weeds are still green near harvest with non-viable seed set. Therefore, the true occurrence of resistance in these weeds has been underestimated in the past. Kochia seedlings were collected from 95 fields and Russian thistle seedlings from 14 fields, mainly from Southern Alberta (Grassland region). Two kochia fields, however, were located in the Aspen Parkland region. Similar to the resistance survey conducted in late summer, fields were randomly selected; however, fields were qualified from the Agricore United dataset as having one or both of these weeds present, which was noted during crop scouting in previous year(s). Seedlings were transplanted from the field, grown to maturity in the greenhouse, seeds were harvested, and progeny (F_1) seedlings sprayed with thifensulfuron:tribenuron at 15 gai/ha or dicamba at 140 gai/ha. Twenty seedlings from each field populaton were randomly selected for F_1 screening (12 individuals per seedling). Screening procedures were similar to those described previously.

Grass Weed Resistance

Of the 179 fields where wild oat samples were collected, 70 (39%) had Group 1-resistant wild oat (Table 5, Map 2). Therefore, 23% of all fields surveyed (300) had resistant wild oat. This field frequency of resistance is sharply greater than that documented in the 2001 survey (11%) (Beckie et al. 2004b). Based on this rate of increase in resistance, half of all fields in Alberta with wild oat populations will have a Group 1-resistant biotype by 2010. Almost half of these fields were located in the Aspen Parkland ecoregion, followed by about 20% of sites in the Moist Mixed Grassland and Peace Lowland, 13% in the Mixed Grassland, 6% in the Fescue Grassland, and only 1% in the Boreal Transition ecoregion. These percentages are generally similar to those noted for the 2001 survey. Resistance occurrence was proportionally greatest in the Aspen Parkland and Peace Lowland ecoregions (44% of fields, respectively, where seeds were collected), similar to that found in the 2001 survey. The relatively small sample size in the Boreal Transition ecoregion may underestimate the true frequency of resistance. Based on samples

Table 5. Fields with resistance by ecoregion

	Group 1-resistant wild oat			Group 2-resistant wild oat		
Ecoregion	Resistant	Tested[a]	Surveyed[a]	Resistant	Tested	Surveyed
	No.	%		No.	%	
Mixed Grassland	9	39	24	2	9	5
Moist Mixed Grassland	12	32	22	2	5	4
Fescue Grassland	4	36	20	3	27	15
Aspen Parkland	32	44	28	10	14	9
Boreal Transition	1	12	3	2	25	7
Peace Lowland	12	44	27	2	7	4
Alberta	*70*	*39*	*23*	*21*	*12*	*7*

[a]Tested -fields where seeds were collected; surveyed – all fields surveyed.

Table 6. Wild oat herbicide use in western Canada in the past five years[a]

	Wheat	Barley	Pulses
	% of fields		
Group 1	87	75	33
Group 2	12	20	67
Other	1	4	0

[a]Based on herbicide histories of fields where weed samples were collected and submitted for herbicide resistance testing.

submitted for testing between 1996 and 2006, most cases of Group 1 resistance originated in the Aspen Parkland region where Group 1 use has historically been high (Beckie et al. 2007, 2008).

The reason for the significant increase in field frequency of Group 1 resistance is related to the reliance on these herbicides for control of wild oat and other grasses in cereal crops. Based on herbicide records of fields from which weed seed samples were submitted by farmers or industry for resistance testing (Beckie et al. 2007, 2008), Group 1 herbicides were applied to 87% of wheat fields and 75% of barley fields during the past 5 years (Table 6). Data from industry indicate two-thirds to three-quarters of wheat or barley fields were sprayed with a group 1 herbicide in 2009 (pers. comm.). These two crops accounted for two-thirds of all crops surveyed (Table 1). Resistance to these herbicides can develop after fewer than 10 applications in a field.

The cross-resistance pattern of the wild oat populations did not show a marked difference in resistance frequency to the seven Group 1 herbicides (data not shown). Whereas resistance frequency of fields was generally greater to fop than dim herbicides (especially clethodim) in the 2001 survey, that trend was not apparent in this survey although clethodim resistance frequency was the lowest (69% of Group 1-resistant populations vs. 90% for fenoxaprop). Resistance frequency to pinoxaden, the sole ‘den’ Group 1 herbicide, was between these two values.

Group 2 resistance was confirmed in 21 wild oat populations (12% of fields where seeds were collected or 7% of all fields surveyed (Table 5, Map 3). This frequency of resistance was similar to that in 2001 (Beckie et al. 2004b). Similar to 2001, the majority of fields with resistance were located in the Parkland region where Group 2 herbicide use is greatest. Similar to Group 1 resistance, half of the fields with Group 2-resistant wild oat were located in the Aspen Parkland ecoregion. Most cases of Group 2 resistance in wild oat, based on samples submitted by producers between 1996 and 2006, also originated in the Aspen Parkland ecoregion (Beckie et al. 2007, 2008). Broad cross-resistance was evident among populations to the Group 2 herbicides, imazamethabenz, imazamox, and flucarbazone, similar to that observed in the 2001 survey (data not shown). The divergent paths of Group 1 vs 2 resistance evolution in this weed over the past 6 years is probably related to herbicide group-use intensity, as shown above (Table 6).

Group 1- and 2-resistant wild oat were found in 15 fields (8%): 8 fields in the Aspen Parkland ecoregion, 2 in the Peace Lowland, 2 in the Mixed Grassland, and 1 each in the Boreal Transition, Moist Mixed Grassland, and Fescue Grassland ecoregions (Map 4). In 2001, 6 fields (3%) had Group 1- and 2-resistant wild oat. The most likely reason for selection of this double-resistant biotype was frequent use of Group 1 herbicides resulting in resistance, followed by selection of Group 2 resistance after switching to products with that mode of action. Infestation of this biotype in a field reduces postemergence herbicide options in all crops except canola.

Group 8 (triallate, difenzoquat)-resistant wild oat was found in 26 fields (15%) (Map 5). Testing for this biotype was not conducted in 2001. Resistant populations were equally distributed between Grassland and Parkland ecoregions. These herbicides were applied on <5% of cultivated land in Alberta in early 2000s (Beckie et al. 2004b). Given the low usage of these herbicides, results may reflect resistance selected in the 1980s or 1990s that has persisted in the seed bank. Group 1- and 8-resistant wild oat was found in 8% of fields (Map 6); Group 1-, 2-, and 8-resistant wild oat was found in 5% of fields (Map 7). Inter-group resistant populations were distributed evenly across Grassland and Parkland ecoregions.

Only two fields in the southern region (Moist Mixed Grassland ecoregion) and northern region (Aspen Parkland ecoregion) had Group 1-resistant green foxtail (Map 8), with no fields with Group 2 resistance. Resistance in this weed was not documented in the 2001 survey. Resistance was not found in any other grass weed species.

Broadleaf Weed Resistance

Twelve of 30 fields (40%) had Group 2-resistant chickweed; these fields were located in the Aspen Parkland ecoregion (Map 9). In 2001, four of 24 fields (17%) in the Aspen Parkland ecoregion had Group 2-resistant chickweed. Therefore, Group 2 resistance in this weed is increasing relatively rapidly. The cross-resistance pattern among the twelve populations indicated broad resistance across the three chemical classes, similar to that of wild oat. Group 2-resistant chickweed in central Alberta has been reported since 1988 (Beckie et al. 2001; Morrison and Devine 1994).

All 11 fields with spiny annual sow-thistle had metsulfuron-resistant populations (Map 10). Five fields were located in the Aspen Parkland ecoregion, three fields in the Moist Mixed Grassland, two fields in the Boreal Transition, and one field in the Fescue Grassland ecoregion. In 2001, four of six fields (67%) had Group 2-resistant spiny annual sow-thistle; these fields were located in the Moist Mixed Grassland, Fescue Grassland, or Aspen Parkland ecoregions (Beckie et al. 2004b). Thus, resistant populations have now been found in the Boreal Transition ecoregion. Even with the small sample size, growers with this weed species should assume their populations are Group 2-resistant.

Five of 30 fields (17%) had Group 2 (imazethapyr, florasulam)-resistant cleavers (Map 11). All fields were located in the Aspen Parkland region. Resistance in this weed was not found in the 2001 survey, although resistance in cleavers was first confirmed in 1996 (Heap 2009). In addition, a sample near Red Deer submitted for testing in 2002 was confirmed as Group 2-resistant (Beckie et al. 2007, 2008). Because cleavers is increasing in abundance at the fastest rate among all weeds (Leeson et al. 2005), the occurrence of resistance in almost 20% of tested populations will cause future challenges in controlling this weed, especially in pulse crops.

One field in the Aspen Parkland had Group 2 (thifensulfuron: tribenuron, florasulam)-resistant wild buckwheat (Map 12). This is the first global report of resistance in this weed species (Heap 2009). Because wild buckwheat is the most abundant weed in Alberta, the discovery of resistance in this species is a concern and should be monitored closely.

Resistance to Group 2 herbicides in the other broadleaf weed species was not detected. Group 2-resistant ball mustard, wild mustard, stinkweed, and hemp-nettle in Alberta have been reported previously (Beckie et al. 2001, 2007, 2008; Heap 2009).

The timing of the field survey favors weed species whose maturity is similar to that of the crop; species that mature before the crop and shed seed or that are immature and non-viable near crop harvest are biased against for seed collection. Ideally, seed collection in a field planted to a spring-seeded crop would occur over multiple dates from July to crop harvest.

Province-wide, kochia and Russian thistle are ranked 20th and 24th respectively, although in southern Alberta, Russian thistle is ranked 2nd and kochia 3rd. (Leeson et al. 2002). Group 2 (thifensulfuron: tribenuron)-resistant kochia was found in 85% of the 95 fields surveyed (Map 13). This result is surprising, considering resistance in this weed was first documented in the Prairies only 20 years ago. We have gone from complete susceptibility to almost complete resistance in this time span. Unfortunately, the predominant target-site mutation responsible for resistance in kochia ($Trp_{574}Leu$) confers broad cross-resistance across Group 2 chemistries (Warwick et al. 2008). However, no populations were resistant to dicamba, a Group 4 herbicide. Therefore, there are non-Group 2 herbicide options to control resistant kochia in cereal crops. However, control of this weed will be challenging in pulse crops because of the reliance on Group 2 herbicides for weed control (Table 6).

In contrast to resistance in kochia, only one of the 14 fields had Group 2-resistant Russian thistle (red dot, Map 13). It is unknown why resistance has taken divergent paths in these two species. Both are biologically and ecologically similar – both having the C_4 photosynthetic pathway, both heat-, drought-, and salinity-tolerant, both tumbleweeds, etc. Across the Prairies, kochia is rapidly increasing in abundance and invading northern regions of the grainbelt, while Russian thistle is falling in abundance and retreating from lands once occupied (Beckie and Francis 2009; Friesen et al. 2009).

Test results indicate no resistance among the tested weed species to Group 4, 9 (glyphosate), or 10 (Liberty) herbicides.

Land Area Impacted by Herbicide-Resistant Weeds

When the frequency of fields with weed resistance in this random survey of 300 fields is extrapolated to the total annual-cropped land in Alberta (7,885,000 ha in 2007), it is estimated that 2.1 million ha (27%) is infested with herbicide-resistant weeds, in a total field area of 3.1 million ha (40%) (Table 7). In comparison, the weed resistance survey in 2001 indicated that 0.3 million ha was infested with herbicide-resistant weeds, in a total field area of 1.5 million ha. Therefore, the actual area infested with herbicide-resistant weeds has increased 7-fold, while the total field area affected has doubled over this intervening 6-year period.

Table 7. Estimated annual-cropped land area in Alberta impacted by herbicide-resistant (HR) weeds in 2007

Biotype	Infestation area (ac/ha)	Field area (ac/ha)
Gp 1-HR wild oat	2,031,991 / 822,668	3,570,591 / 1,445,583
Gp 2-HR wild oat	389,519 / 157,700	389,519 / 157,700
Gp 1+2-HR wild oat	779,444 / 315,564	973,798 / 394,250
Gp 8-HR wild oat	359,494 / 145,544	779,038 / 315,400
Gp 1-HR green foxtail	64,920 / 26,283	129,840 / 52,567
Gp 2-HR broadleafs	1,668,846 / 675,645	1,882,675 / 762,217
Total	**5,294,214 / 2,143,405**	**7,725,461 / 3,127,717**

Implications and Benefits to Alberta's Agri-Food Sector

Monitoring for weed resistance in an integral component of product stewardship and serves as an warning system for farmers to adopt integrated practices to delay or manage resistance and for industry to develop herbicide solutions to emerging weed problems. Communicating results of the survey to farmers creates awareness of herbicide resistance at the local level. In turn, farmers save money and reduce herbicide use by not applying ineffective herbicides on resistant weed populations. A prime example of that is the finding from this study that most kochia populations are Group 2-resistant. Combined with the prevalence of Group 2 resistance in some other broadleaf weeds, pulse crop producers in particular need alternative weed control options. Based on herbicide records of farmers who submitted weed samples for resistance testing from 1996 to 2008, about 20% had performed an additional herbicide application in the same growing season to control the weed escapes. In many instances, the population was still not controlled. Thus, the agronomic, environmental, and economic sustainability of Alberta's crop production in the medium- and long-term can only be enhanced by bringing greater awareness of herbicide resistance at the local level – field, farm, district, community. Local awareness will hopefully catalyze the adoption of proactive resistance management practices.

Agriculture and Agri-Food Canada. 2003. A national ecological framework for Canada: GIS data. [Online] Available: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html [25 November 2008].

Beckie, H. J., C. Brenzil, and G. Holzgang. 2007. Herbicide resistance testing: 1996-2006 results of samples submitted to the Crop Protection Lab, SAF. Saskatoon, SK: Agriculture and Agri-Food Canada. 22 p.

Beckie, H. J. and A. Francis. 2009. The biology of Canadian weeds. 65. *Salsola tragus* L. (updated). Can. J. Plant Sci. 89:775-789.

Beckie, H. J., L. M. Hall, S. Meers, J. J. Laslo, and F. C. Stevenson. 2004a. Management practices influencing herbicide resistance in wild oat (*Avena fatua*). Weed Technol. 18:853-859.

Beckie, H. J., L. M. Hall, and F. J. Tardif. 2001. Herbicide resistance in Canada - where are we today? Pages 1-36 *In* R. E. Blackshaw and L. M. Hall, eds. Integrated Weed Management: Explore the Potential. Sainte-Anne-de-Bellevue, QC: Expert Committee on Weeds.

Beckie, H. J., I. M. Heap, R. J. Smeda, and L. M. Hall. 2000. Screening for herbicide resistance in weeds. Weed Technol. 14:428-445.

Beckie, H. J., J. Y. Leeson, and A. G. Thomas. 2004b. Alberta weed survey of herbicide-resistant weeds in 2001. Weed Survey Series Publ. 04-1. Saskatoon, SK: Agriculture and Agri-Food Canada. 66 p.

Beckie, H. J., J. Y. Leeson, A. G. Thomas, C. A. Brenzil, L. M. Hall, G. Holzgang, C. Lozinski, and S. Shirriff. 2008. Weed resistance monitoring in the Canadian Prairies. Weed Technol. 22:530-543.

Beckie, H. J., A. G. Thomas, A. Légère, D. J. Kelner, R. C. Van Acker, and S. Meers. 1999. Nature, occurrence, and cost of herbicide-resistant wild oat (*Avena fatua*) in small-grain production areas. Weed Technol. 13:612-625.

Friesen, L. F., H. J. Beckie, S. I. Warwick, and R. C. Van Acker. 2009. The biology of Canadian weeds. 138. *Kochia scoparia* (L.) Schrad. Can. J. Plant Sci. 89:141-167.

Heap, I. M. 2009. International Survey of Herbicide-Resistant Weeds. [Online]: http://www.weedscience.com.

Leeson, J. Y., A. G. Thomas, H. J. Beckie, L. M. Hall, C. Brenzil, R. C. Van Acker, K. R. Brown, and T. Andrews. 2007. Group 2 herbicide use in the prairie provinces. Proc. 2004 National Meeting. Sainte-Anne-de-Bellevue, QC: Canadian Weed Science Society. [Online]: http://www.cwss-scm.ca.

Leeson, J. Y., A. G. Thomas, and L. M. Hall. 2002. Alberta weed survey of cereal, oilseed and pulse crops in 2001. Weed Survey Series Publ. 02-1. Saskatoon, SK: Agriculture and Agri-Food Canada. 263 p.

Leeson, J. Y., A. G. Thomas, L. M. Hall, C. A. Brenzil, T. Andrews, K. R. Brown, and R. C. Van Acker. 2005. Prairie weed surveys of cereal, oilseed and pulse crops from the 1970s to the 2000s. Weed Survey Series Publ. 05-1. Saskatoon, SK: Agriculture and Agri-Food Canada.

Morrison, I. N. and M. D. Devine. 1994. Herbicide resistance in the Canadian prairie provinces: five years after the fact. Phytoprotection 75 (Suppl.):5-16.

O’Donovan, J. T., K. N. Harker, R. E. Blackshaw, A. Rashid, M. P. Sharma, A. Khan, D. Maurice, and S. Kibite. 1998. Investigation of herbicide resistant wild oat populations in Alberta. Final Report Project No. 920037. Vegreville, AB: Alberta Research Council. 134 p.

O’Donovan, J. T., G. M. Jeffers, D. Maurice, and M. P. Sharma. 1994a. Investigation of a chlorsulfuron-resistant chickweed [*Stellaria media* (L.) Vill.] population. Can. J. Plant Sci. 74:693-697.

O'Donovan, J. T., M. P. Sharma, K. N. Harker, D. Maurice, M. N. Baig, and R. E. Blackshaw. 1994b. Wild oat (*Avena fatua*) populations resistant to triallate are also resistant to difenzoquat. Weed Sci. 42:195-199.

Rashid, A., J. C. Newman, J. T. O’Donovan, D. Robinson, D. Maurice, D. Poisson, and L. M. Hall. 2003. Sulfonylurea herbicide resistance in *Sonchus asper* biotypes in Alberta, Canada. Weed Res. 43:214-220.

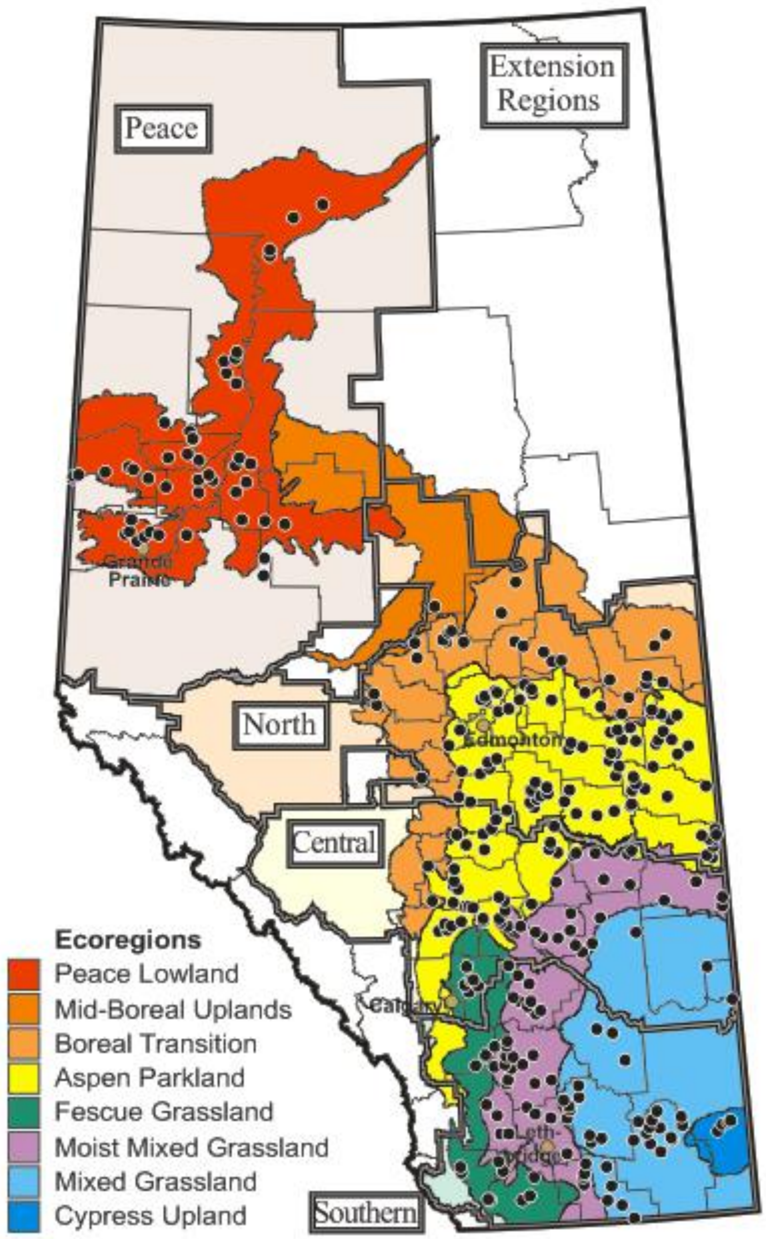
Statistics Canada. 2006. November estimate of production of principal field crops, Canada, 2006. Field Crop Reporting Series Vol. 85, No. 8. Catalogue No. 22-002-XIB, Ottawa, ON. 31 p.

Thomas, A. G. 1985. Weed survey system used in Saskatchewan for cereal and oilseed crops. Weed Sci. 33:34-43.

Warwick, S. I., R. Xu, C. Sauder, and H. J. Beckie. 2008. Acetolactate synthase target-site mutations and single nucleotide polymorphism genotyping in ALS-resistant kochia (*Kochia scoparia*). Weed Sci. 56:797-806.

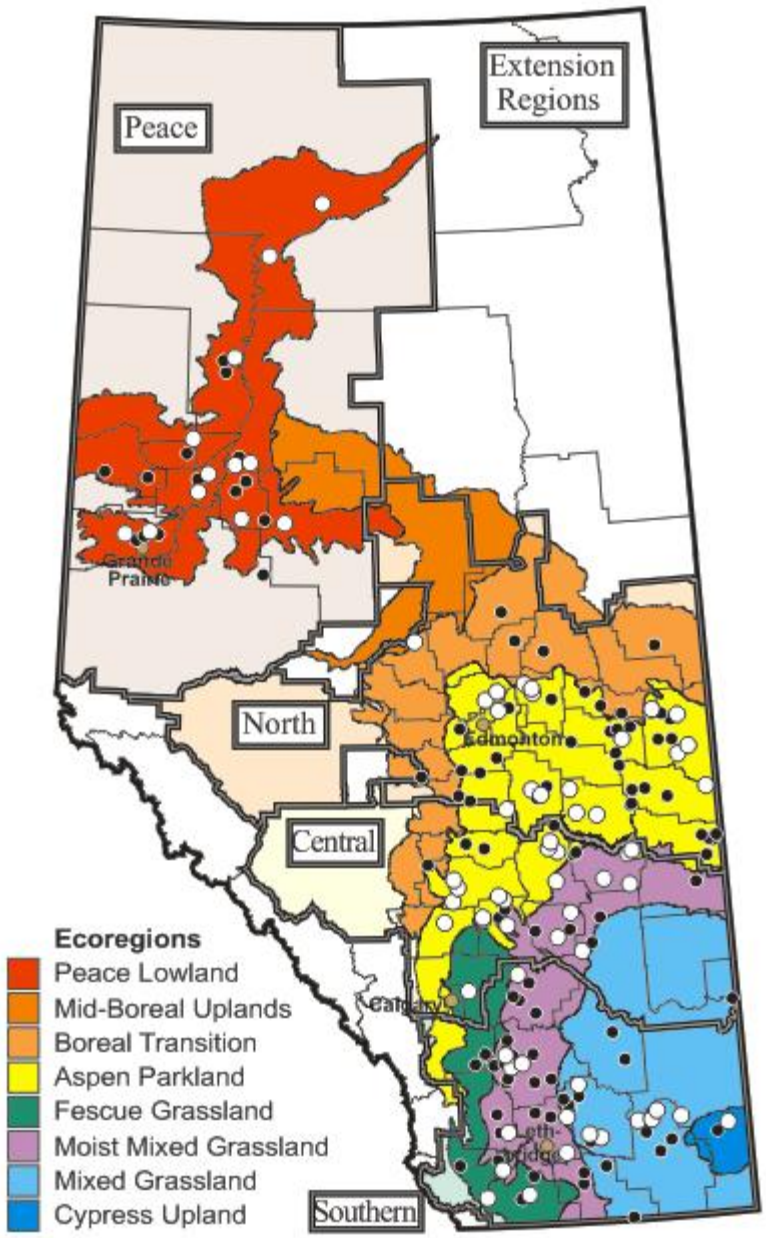
MAPS

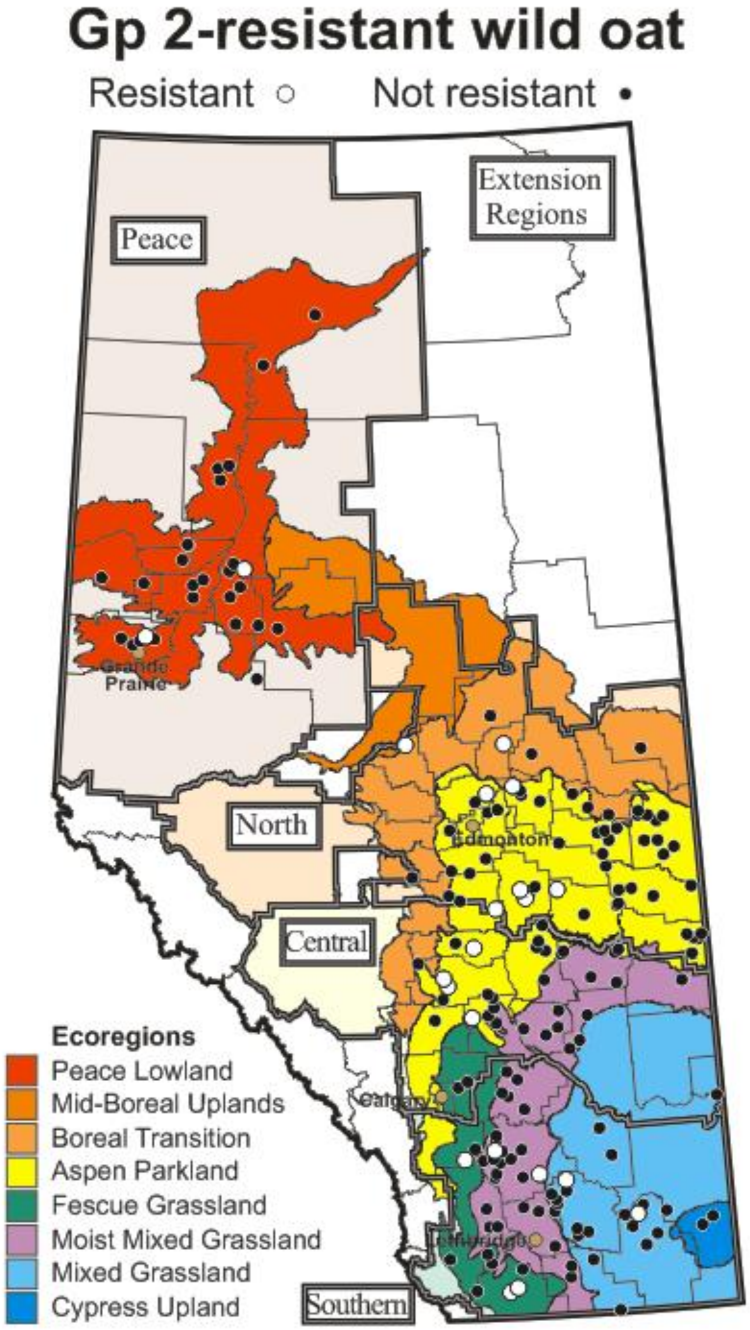
Surveyed fields



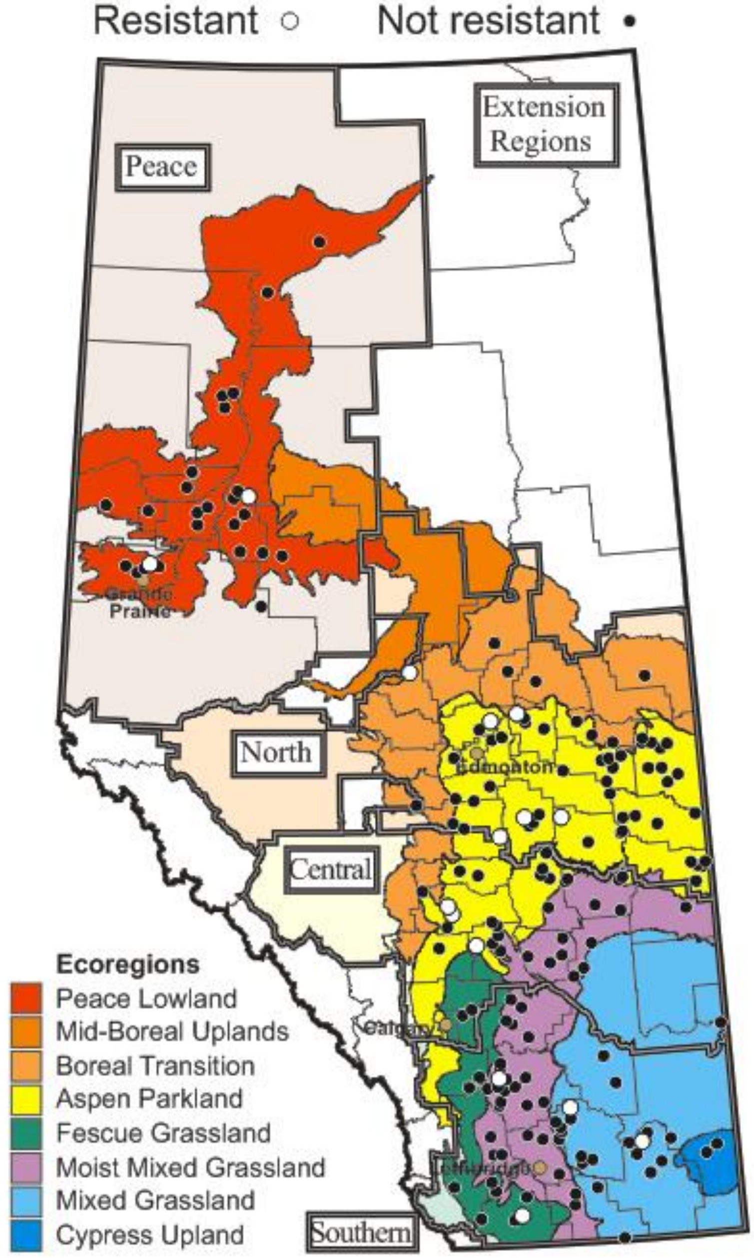
Gp 1-resistant wild oat

Resistant ○ Not resistant •



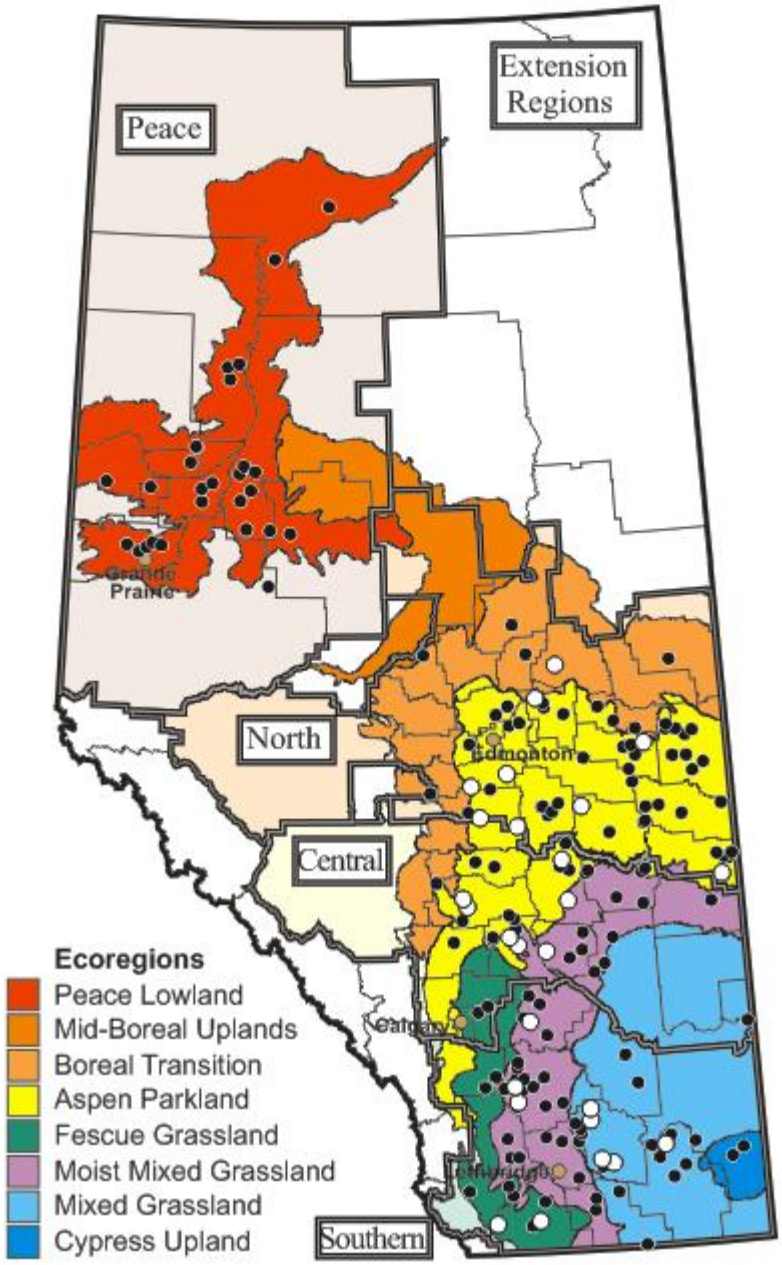

Gp 2-resistant wild oat
Resistant ○ Not resistant •
Extension Regions
Peace
North
Central
Southern
Grande Prairie
Edmonton
Calgary
Lethbridge
Ecoregions
Peace Lowland
Mid-Boreal Uplands
Boreal Transition
Aspen Parkland
Fescue Grassland
Moist Mixed Grassland
Mixed Grassland
Cypress Upland

Gp 1- and 2-resistant wild oat

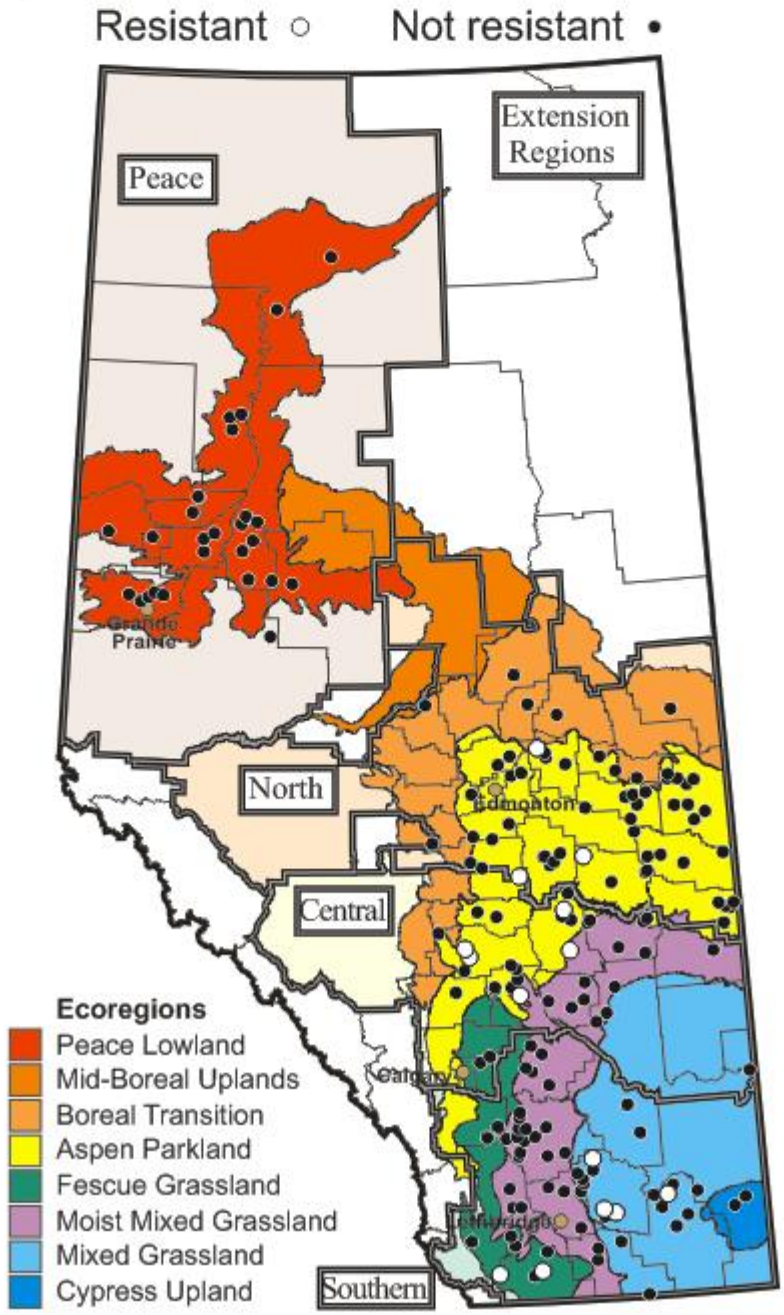


Gp 8-resistant wild oat

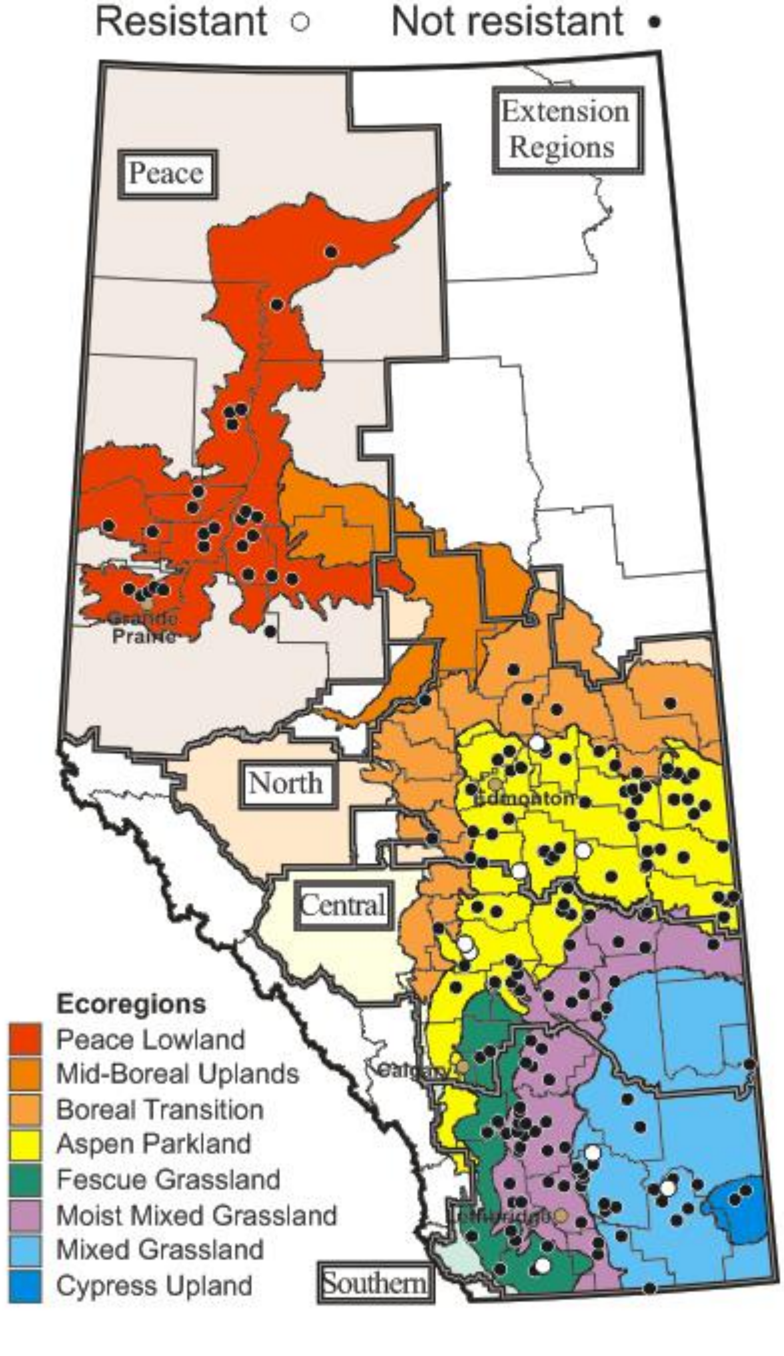
Resistant ○   Not resistant •



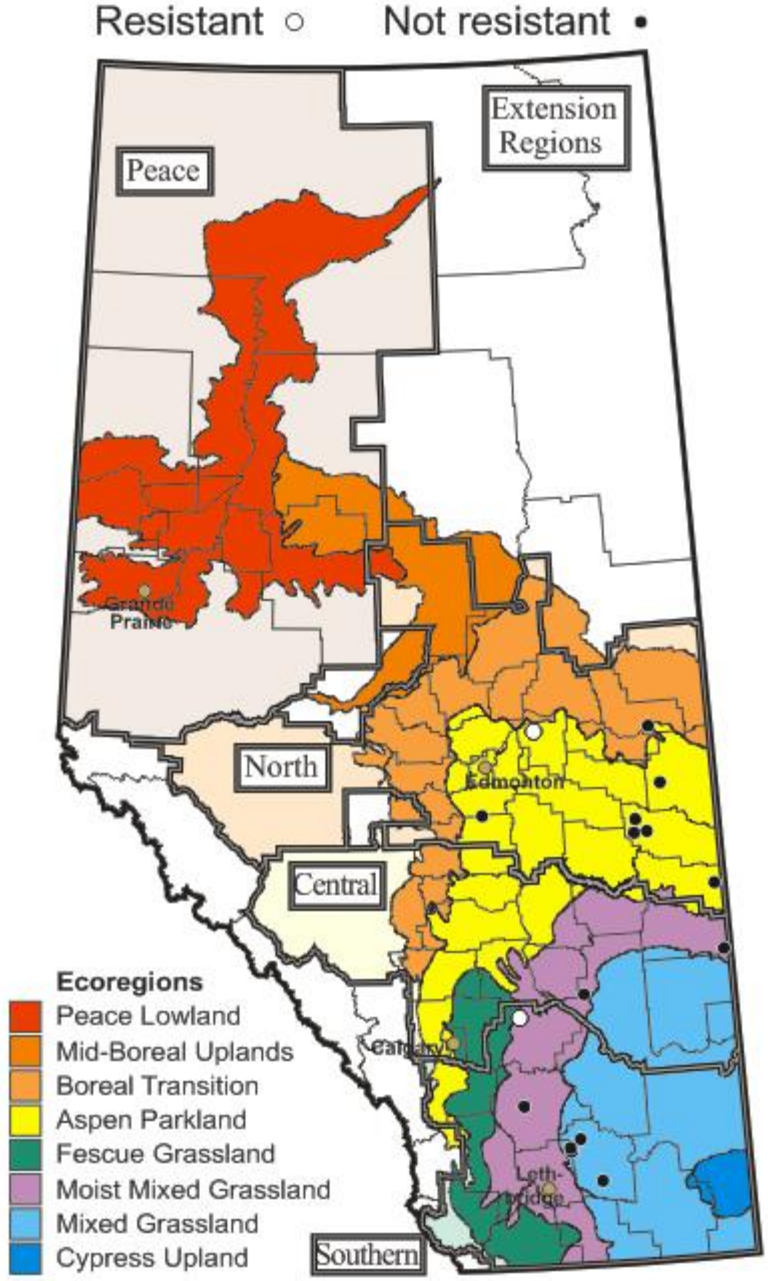
Gp 1- and 8-resistant wild oat



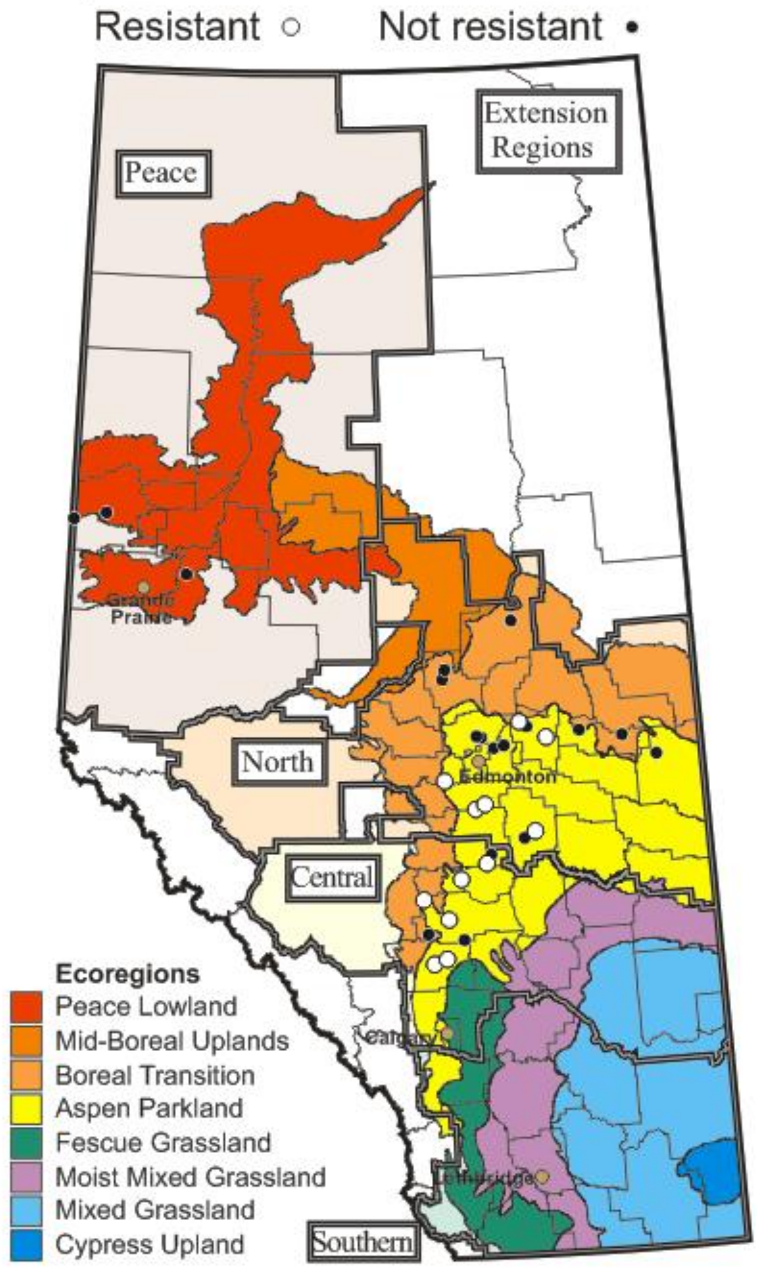
Gp 1- and 2- and 8-resistant wild oat



Gp 1-resistant green foxtail

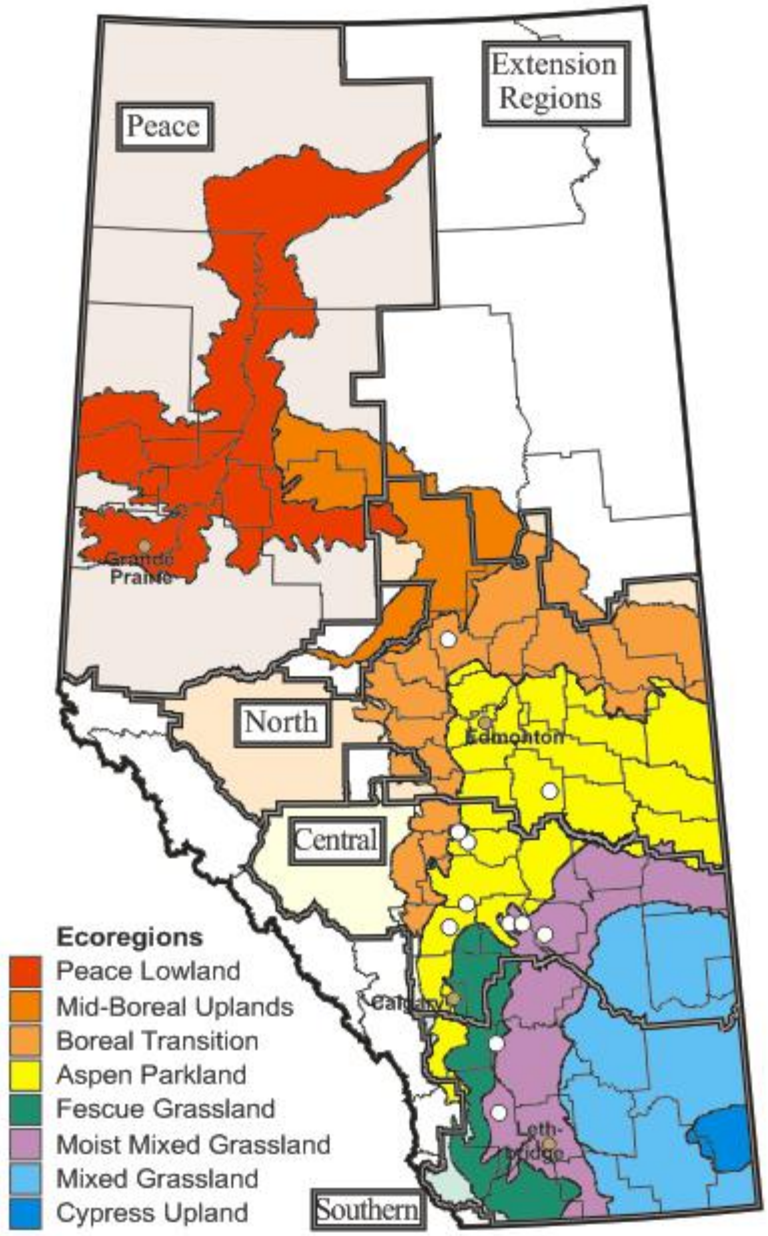


Gp 2-resistant chickweed

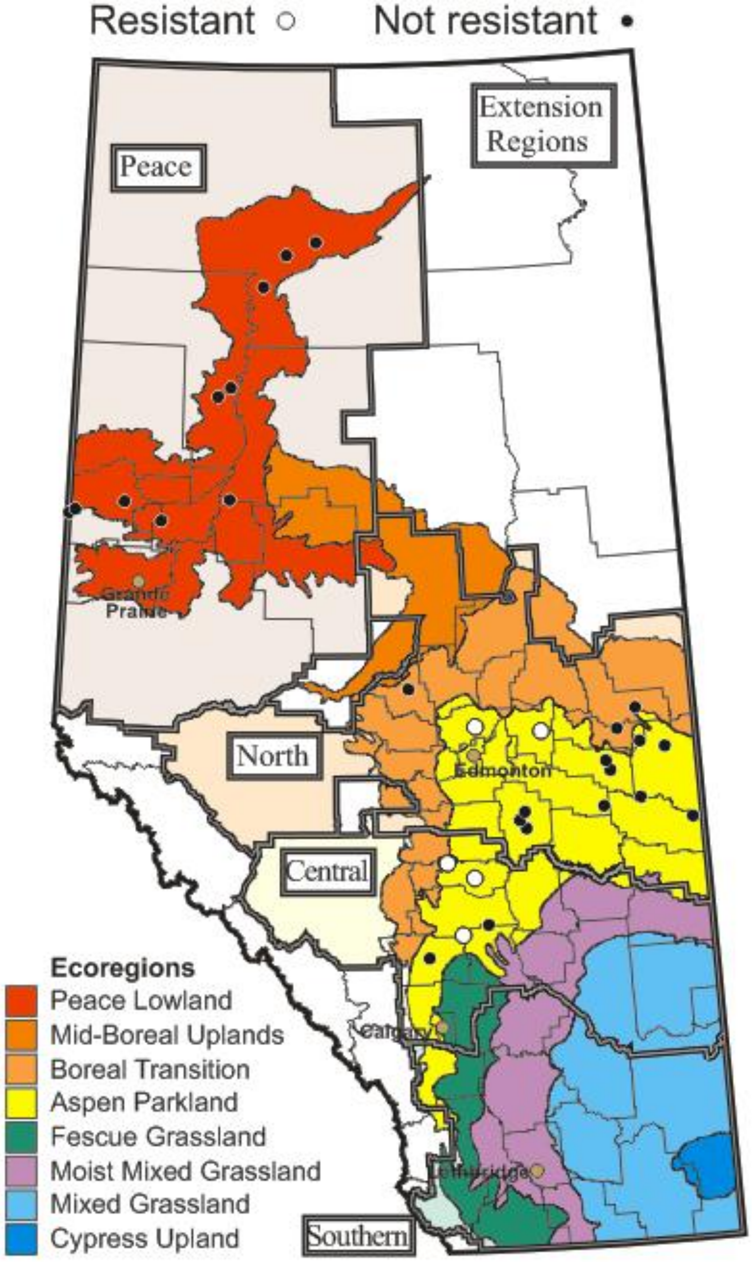


Gp 2-resistant spiny annual sow-thistle

Resistant ○ Not resistant •

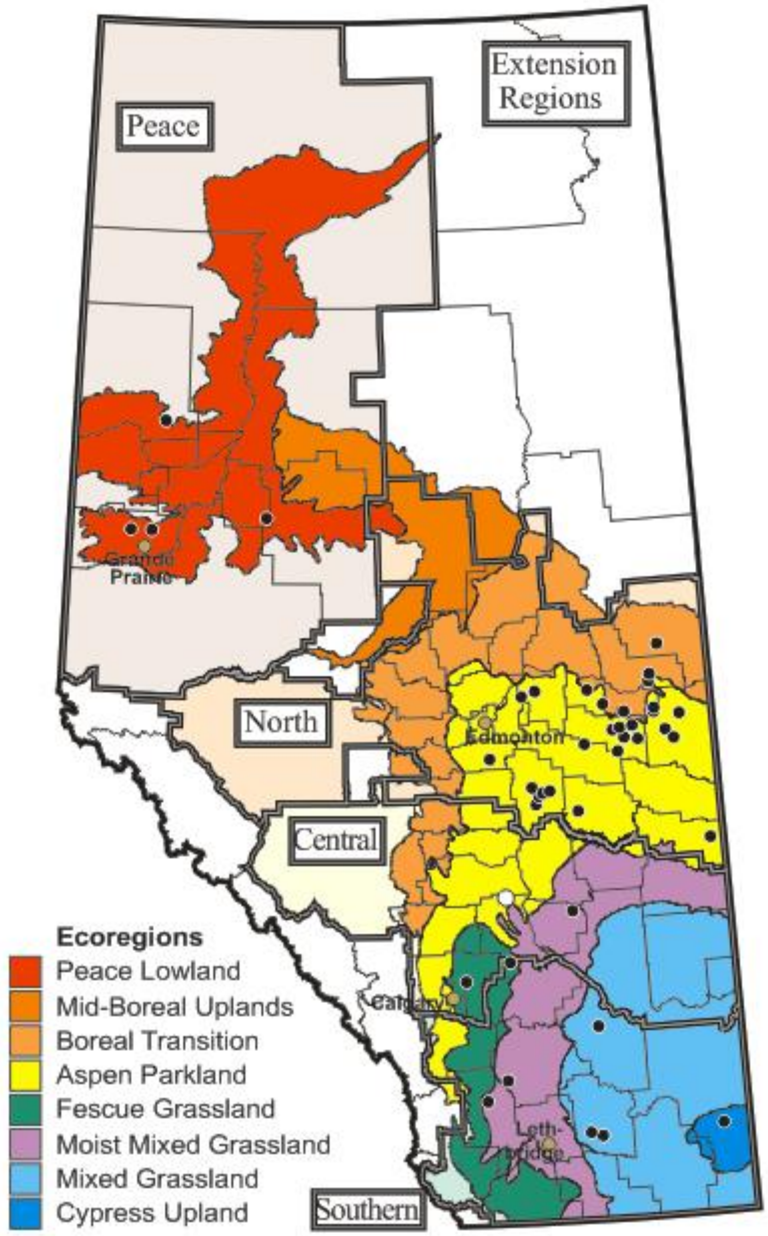


Gp 2-resistant cleavers



Gp 2-resistant wild buckwheat

Resistant ○ Not resistant •



Kochia

Resistant ○ Not resistant •