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MANAGEMENT AND CONTROL OF CANADA THISTLE (*Cirsium arvense*)[1,2]

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INTRODUCTION

The life history and biology of Canada thistle [*Cirsium arvense* (L.) Scop. # CIRAR[4]] has been summarized (48, 126, 128, 130, 131, 138, 177). The objective of this review is to update the previous summary on control of Canada thistle (20), critique the refereed literature, and suggest research needs. Although I present a North American agronomist's perspective on the management of Canada thistle, relevant publications from abroad are reviewed as well. A summary of the art and science of managing Canada thistle cannot be current if it is limited to the refereed literature; therefore information from selected research bulletins, registration labels, and nonrefereed sources will be included where appropriate. Research on the biological control of Canada thistle (18, 112, 162, 163, 176, 197, 215, 229, 243, 252) is not covered because it has been unsuccessful.

Canada thistle is a perennial weed with an extensive, spreading root system (16, 116, 128, 137, 204). Adventitious root buds arise from its roots to form new adventitious shoots (110, 111, 116). This is the major method of vegetative propagation for Canada thistle after seedling establishment. Seed production and new seedling emergence are not considered to contribute significantly to the weediness of Canada thistle.

The terminology used to describe the root system of Canada thistle must be defined because confusing multiple terms have been used in the literature (137). Lawrence (150) defined a rhizome as "a creeping stem, not a root, growing beneath the surface, consisting of a series of nodes, and internodes with roots commonly produced from the nodes and producing buds in the leaf axils". Rhizomes are sometimes called rootstocks (137). Canada thistle does not form rhizomes or rootstocks despite this assertion in some reviews (21, 131).

Thickened, propagative Canada thistle roots with root buds grow horizontally and vertically. While these thickened roots are lateral roots, they are not the self-limited, fibrous lateral roots found on most annuals (95). This distinction could be made by using root diameter classes (231). A root bud is a "shoot-forming bud originating on a root" (231). Root buds form adventitiously on Canada thistle roots (110, 111). An adventitious bud is defined as "a bud arising outside of normal morphogenetic sequence, and lacking connection with the shoot or root poles. (It) may give rise to an adventitious shoot." (231).

The multiple terminology for adventitious shoots of Canada thistle arising after adventitious root buds emerge through the soil surface is quite confusing and includes "daughter shoot", "secondary shoot", "regrowth shoot", "root shoot (sic)", "rosette", "root sucker", or "root sprout". The term "root shoot" should be abandoned because it is contradictory, ambiguous, and confusing. The term 'adventitious shoot' will be used in this review for shoots arising from adventitious root buds.

Canada thistle shoots can arise from lateral buds on the underground portion of the stem of parent shoots following mowing or when stem segments are buried (159). Such shoots correspond to lateral branches when they arise above ground. The proportion of shoots arising as adventitious shoots from adventitious root buds or arising from buried stems in the field has not been reported. It is likely that adventitious shoots far outnumber shoots arising from buried stems except, perhaps, following mowing of Canada thistle on undistrbuted soil.

Adventitious shoots have sometimes been called "rosettes" which the American Heritage Dictionary defines as "a circular cluster of leaves or other plant parts". However, the stem of adventitious shoots can emerge and elongate without having a rosette growth habit.

THE EXTENT AND NATURE OF THE PROBLEM

Surveys of Canada Thistle Distribution. Historical, perceptual, and scientific surveys of the worldwide distribution of Canada thistle are limited. Holm and co-workers (131, 132) tabulated the countries in which this weed is present and the perception of experts regarding its seriousness as a weed (Table 1). Although the center of origin of the weed is unknown, it is endemic in Europe, western Asia, and northern Africa (131, 132, 177). Moore (177) suggested that it probably is native to southeastern Europe and the eastern Mediterranean. It also is present in the temperate zones of South America, Africa, New Zealand, and Australia in the Southern Hemisphere (131). Its historical spread into New Zealand and Australia has been reviewed (169), as well as its distribution in Australia in the 1970s (15).

[4]Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Revised 1989. Available from WSSA, 309 W. Clark St., Champaign, IL 61820.

Table 1. World distribution of Canada thistle grouped according to its seriousness in agriculture-based surveys of experts (132).

Serious weed	Principal weed	Common weed	Present as a weed	Non-weedy
Finland	Belgium	Australia	Chile	Afghanistan
Lebanon	Bulgaria	China	Czechoslovakia	Alaska
Portugal	Canada	Japan	France	Rhodesia
Turkey	England	Spain	Iceland	
United States	Germany		Korea	
	Greece		Mexico	
	India		Netherlands	
	Iran		Norway	
	Italy		Sudan	
	New Zealand		Switzerland	
	Pakistan			
	Poland			
	Romania			
	South Africa			
	Soviet Union			
	Tunisia			
	Yugoslavia			

Canada thistle's range covers an estimated 9,770,000 km^2 in North America extending 2090 km north to south and 4700 km east to west (177). The northern extent (Figure 1) of Canada thistle is 59°N in Canada and its southern limit is 40°N in the United States (Figure 2) (78). The most severe infestations in the United States occur in the northern half of the country (128).

Canada thistle is adapted to temperate regions, those with moderate summer temperatures and moderate rainfall (450 to 900 mm/yr) (126, 131). The chief factors limiting its spread across continents have not been determined unambiguously. North American researchers recognized early that Canada thistle was adapted to a wide range of soils and produced deeper roots in clay or muck soils (3.8 m deep) compared to sand, gravel (1 m deep), or limestone (1.8 m deep) soils (60). Also, Canada thistle must have some, as yet unquantified, tolerance to soil salinity, because it was found in 40% of nonmarsh, dryland saline sites surveyed in Al-

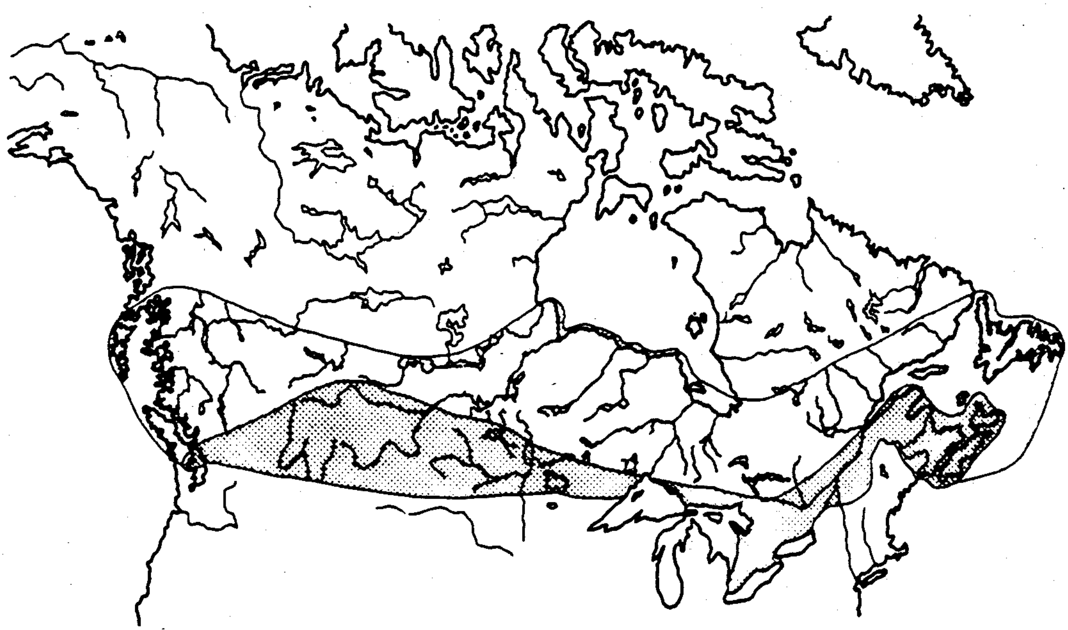

Figure 1. The distribution of Canada thistle in Canada. The darker shading indicates areas of greater abundance (177).

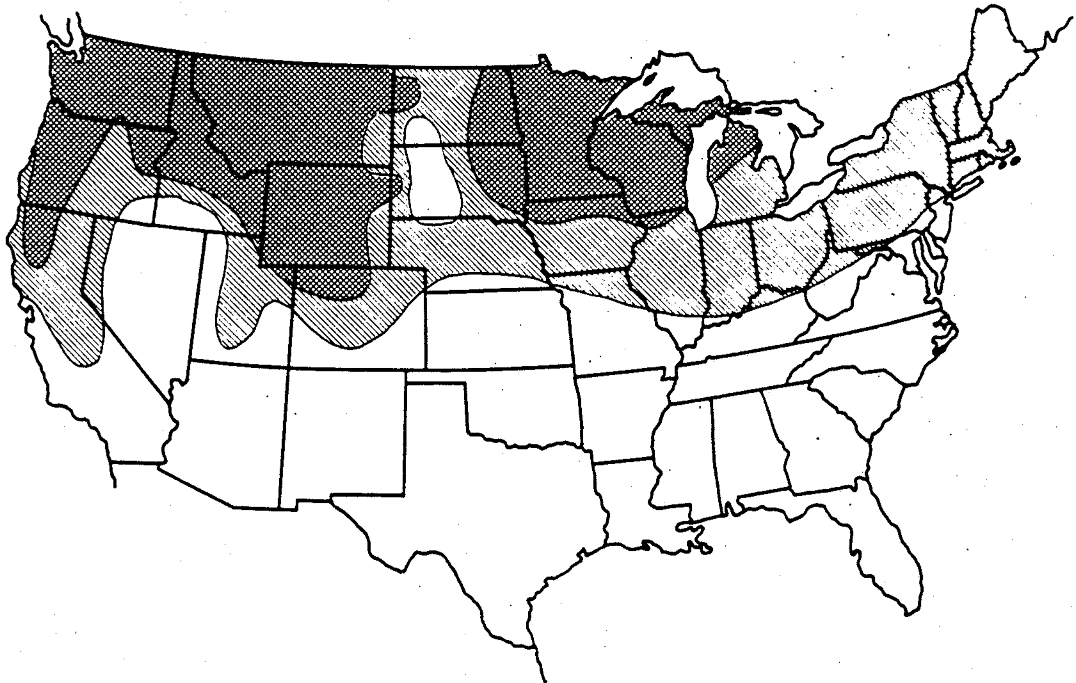

Figure 2. The distribution of Canada thistle in the United States. The darker shading indicates areas of greater abundance (128).

berta, Canada (38). Despite a lack of published quantitative information relating Canada thistle distribution to soil type, others (99) felt that this factor did not limit this weed's geographic distribution. However, high summer temperatures may limit its southern spread in North America (130). When Canada thistle was introduced into Alabama, Louisiana, and Florida, it failed to establish (19), but the reasons for this failure were not defined.

Canada thistle was introduced into French Canada from Europe (19) before being spread into Vermont and New York (228). Detmers (60) concluded that it must have been introduced prior to 1795 because a Vermont law was enacted that year to halt its spread. By 1844, Ohio law limited sale of Canada thistle-contaminated seed and required landowners to mow infested land and adjacent roadsides (60). Judging by its current distribution in North America, state and federal legislation has been somewhat ineffective in limiting the spread of the weed (256).

Current perceptual surveys of experts (Table 2) substantiate earlier estimates of Canada thistle distribution in the United States (Figure 2). In 1987, it was not reported as a problem in Arizona, New Mexico, or California (174). However, it infested many major crops in Colorado, Wyoming, Utah, Montana, Oregon, Idaho, and Washington. Perceptual surveys of farmers in Wisconsin in 1983 also established that Canada thistle was considered a serious weed among 17 to 36% of the surveyed farmers (67).

While perceptual surveys of experts (174) or farmers (67, 83, 92) are valuable in mapping the spread and perceived seriousness of weeds, scientific surveys provide more quantitative, objective information, such as Canada thistle frequency and density, for estimating losses in crop production due to Canada thistle. In 1966, Alex (3, 4) presented detailed information on the density class distribution of this weed in the provinces of Alberta, Saskatchewan, and Manitoba. Thomas (237, 238, 239) has conducted the most thorough series of scientific surveys in Canada (Table 3). Scientific surveys conducted in the late 1970's in North Dakota (65), South Dakota (23), and Minnesota (29) are based on a modification of Thomas' system of weed surveying (Table 4) (237). Because most of these data were gathered after measures were taken to control Canada thistle shoot growth, they may underestimate potential densities present in the absence of control measures.

Canada thistle was one of the five most abundant weeds in a 1986 Manitoba survey of 77 pedigreed alfalfa (*Medicago sativa* L.) seed fields

Table 2. Distribution of Canada thistle in the western United States in major crops based on surveys of experts (174).

Crop	State[a]								
	AR	CA	CO	MT	NM	OR	UT	WA/ID	WY
Alfalfa									
Common	No	No	Yes	Yes	No	Yes	No	Yes	Yes
Troublesome	No	No	Yes	No	No	Yes	No	Yes	Yes
Corn									
Common	NA	No	No	Yes	No	NA	No	Yes	No
Troublesome	NA	No	No	Yes	No	NA	No	Yes	No
Dry beans									
Common	NA	No	No	Yes	NA	NA	Yes	Yes	No
Troublesome	NA	No	No	Yes	NA	NA	Yes	Yes	No
Forest & rangeland									
Common	No	No	NA	No	No	No	No	NA	Yes
Troublesome	NA	NA	NA	Yes	NA	No	NA	NA	NA
Fruits									
Common	No	No	No	Yes	No	Yes	Yes	Yes	NA
Troublesome	No	No	No	Yes	No	No	Yes	Yes	NA
Ornamentals									
Common	No	No	NA	NA	No	Yes	NA	Yes	NA
	No	No	NA	NA	No	Yes	NA	Yes	NA
Pasture & hay									
Common	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Troublesome	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Small grain									
Common	No	No	Yes	Yes	No	Yes	No	Yes	Yes
Troublesome	No	No	Yes	Yes	No	Yes	No	Yes	Yes
Sugarbeets									
Common	NA	No	No	Yes	NA	No	NA	Yes	No
Troublesome	NA	No	No	Yes	NA	No	NA	Yes	No
Turf and landscape									
Common	No	No	No	Yes	No	NA	No	No	NA
Troublesome	No	No	No	Yes	No	NA	No	No	NA
Vegetables									
Common	No	No	NA	NA	No	Yes	No	Yes	NA
Troublesome	No	No	NA	NA	No	Yes	No	Yes	NA

[a]NA = not applicable.

Table 3. Percentage of infested acreage and density of Canada thistle in U. S. cereals and oilseed crops based on scientific surveys.

State	Crop	Percent infested acreage	Shoot density		References
			Average	Maximum	
		(%)	(no./m²)		
Minnesota	Wheat	36	2	9	127
	Barley	49	3	19	
	Oats	40	3	13	
So. Dakota	Wheat	7	5	24	23
	Flax	17	7	25	
	Oats	20	6	42	
	Barley	16	6	24	
No. Dakota	Wheat	11 to 17	4 to 2	16 to 23	65
	Barley	15 to 32	30 to 22		
	Oats	7 to 15	3 to 4	5 to 21	
	Flax	15 to 26	2 to 1	5	
	Sunflower	29	2	14	

(102). Its frequency was 78% and its density was 1.6 ± 1.9 plants/m^2 (mean ± SD), with a maximum density of 9.7 plants/m^2. It is noteworthy that Canada thistle densities reported in control studies are frequently high (about 40 to 60 plants/m^2) relative to densities reported in surveys of commercial fields in both the United States and Canada (Tables 3 and 4).

Yield Loss Assessment. Yield loss assessment (YLA) due to weeds quantitatively describes relative decreases in crop production as a func-

Table 4. Percentage of infested acreage and shoot density of Canada thistle in various Canadian crops (237, 238, 239).

Province	Crop	Percentage of infested acreage	Shoot density Average	Shoot density Maximum
		(%)	(no./m²)	
British Columbia	Wheat	4	1	4
(Peace River only)	Barley	5	1	3
	Oat	1	2	2
	Canola	2	2	6
	Forage	1	5	10
Alberta	Wheat	7	1	3
(Fort Vermilion only)	Barley	0	0	0
	Canola	4	1	1.6
Saskatchewan	Wheat	14	2	21
	Barley	35	2	10
	Oats	25	1	4
	Flax	48	2	10
	Canola	30	1	4
	Sunflower	14	1	1
	Mustard	25	2	8
	Lentil	11	1	7
	Dry pea	73	3	17
	Winter wheat	21	2	10
Manitoba	Wheat	48	3	21
	Barley	43	2	11
	Oat	28	2	7
	Flax	53	4	22
	Canola	51	1	3
	Sunflower	31	2	10
	Corn	21	4	62
	Alfalfa	78	2	24
Ontario	Corn	18	1	4
(Essex & Kent only)	Soybean	26	1	6
	Tomato	21	1	1
	Cereal	9	1	4
Prince Edward Island	Wheat	13	0.2	0.4
	Barley	16	2	7
	Oats	16	2	9
	Mixed grain	18	2	11
New Brunswick	Wheat	7	0.4	0.4
(5 counties only)	Barley	15	0.6	2
	Oats	22	0.9	2

tion of increasing weed density or biomass and is usually expressed on a "per area" basis. Recently, YLA methodology has been reviewed and updated for diseases and insects (236). YLA of weeds has been descriptive, not mechanistic, and has value in economic analyses of the impact of weeds on crop production. Extension agents use YLA to justify the importance of weed control. Much YLA research has been confused with competition research, which deals with the physiological, ecological, and biochemical mechanisms responsible for plant interactions.

The relative extent to which increasing Canada thistle densities reduce the yield of winter and spring wheat (*Triticum aestivum* L.) (123, 126, 198) (Figure 3 and Table 5), barley (*Hordeum vulgare* L.) (123, 190) (Figure 4 and Table 5), oats (*Avena sativa* L.) (123) (Table 5), rapeseed (*Brassica napus* L.) (189) (Figure 5), and alfalfa (214) has been determined in tilled cropping systems. YLA information has not been published on other major field crops, such as corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.], or in reduced tillage systems.

One probably cannot extrapolate YLA data gathered in one locale to other geographic regions because the results depend on local climate, crop management practices, and the nature of the Canada thistle infestations that were studied. All published YLA data were gathered on tilled land. However, tillage can modify the time of Canada thistle shoot emergence from root buds relative to crop emergence, and thus tillage may influence relative yield losses due to Canada thistle.

Established natural stands of Canada thistle emerged from roots in spring at the same time

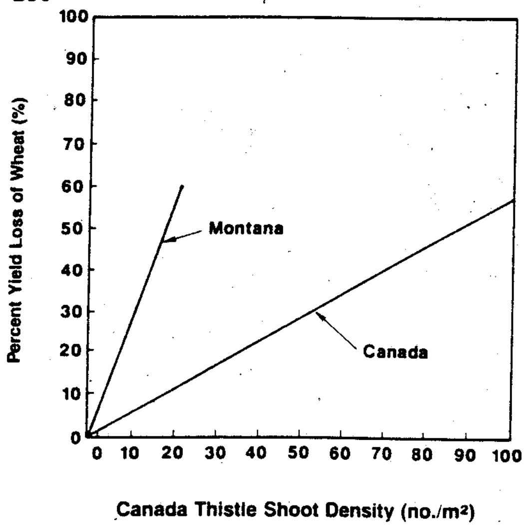

Figure 3. The percent yield loss of standard height spring wheat as affected by Canada thistle density in Canada (198) and Montana (average of 3 yr) (122, 128).

in no-till or fall chisel-plowed plots in North Dakota but before stands in fall moldboard-plowed plots. Established natural infestations of Canada thistle were used in all published YLA studies (126, 189, 190), except those of Schrieber (214) on alfalfa in which spaced Canada thistle transplants were employed. Most research on yield losses caused by annual weeds employed weed seed planted at the same time as the crop to ensure similar or synchronous emergence; weed stands were later thinned to desired densities. The emergence phenology of Canada thistle shoots from roots relative to crop emergence cannot be controlled and depends on both tillage and climate. Adventitious shoot emergence also extends over a protracted period in the spring relative to crop emergence. While the relative emergence phenology of Canada thistle and the crop is likely to modify YLA, critical periods for Canada thistle have not been defined for any crop. No "time of shoot removal" or "time of emergence" studies for Canada thistle have been published.

In YLA studies conducted to date, shoot density was chosen to measure the effect of Canada thistle on crop yield. It is probably more valid to use the term "shoot density" than "plant density" because one established plant (genet) may produce several new adventitious shoots (ramets) from adventitious root buds. Whereas shoot density may be convenient to measure, other growth parameters such as shoot biomass (fresh or dry weight) may be more highly related to relative crop yield losses. However, O'Sullivan et al. (190) found that total Canada thistle shoot density was more closely correlated with barley yield than were shoot dry weight, flowering shoot density, or the density of shoots greater than 0.5 m tall.

Canada thistle densities seldom exceed 60 plants/m^2 on farmland in North America (Tables 3 and 4). In wheat (126), barley (190), and rapeseed (189), yield loss appeared to be best modeled as a linear function of Canada thistle density at shoot densities above 10 shoots/m^2 (Figures 3, 4, and 5). However, more detailed information on YLA below this density may be needed by farmers deciding on the economic return of different control practices to be used at low Canada thistle densities. Other published

Table 5. Relative yield loss in wheat, barley, and oacts due to Canada thistle (122).

Crop	Canada thistle shoot density	Relative yield Trial 1	Relative yield Trial 2
	—(no./m^2)—	—(%)[a]—	
Winter wheat	0	100	100
	2 to 5	86	88
	13 to 20	72	68
	30 to 37	55	61
Spring wheat	0	100	100
	2 to 5	87	92
	13 to 20	73	70
	30 to 37	57	47
Barley	0	100	100
	2 to 5	81	78
	13 to 20	70	50
	30 to 37	37	30
Oats	0	100	-
	2 to 5	88	-
	13 to 20	62	-
	30 to 37	55	-

[a]Yield was expressed as a percentage of the weed-free yield.

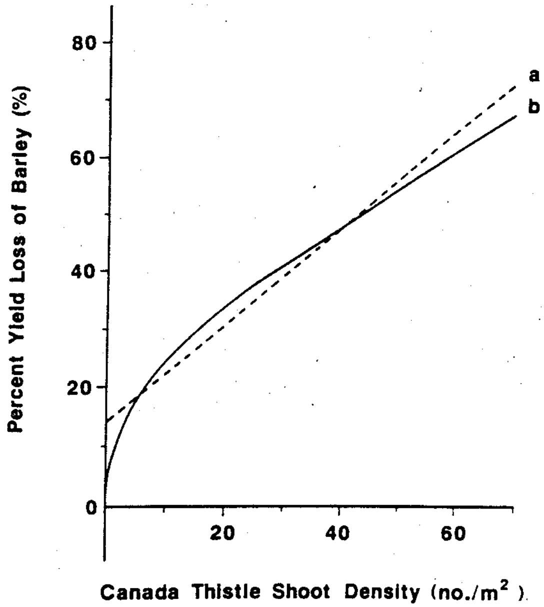

Figure 4. The percent yield loss of barley due to Canada thistle density in Canada. Curve a corresponds to $\hat{Y} = 14.03 + 0.85\,X$ and curve b corresponds to $\hat{Y} = 0.42 + 7.6\,\sqrt{X}$, where $\hat{Y}$ = estimated percent yield loss and X = Canada thistle shoot density (no./m^2). These curves represent untransformed and square root transformed expressions of the same data (190).

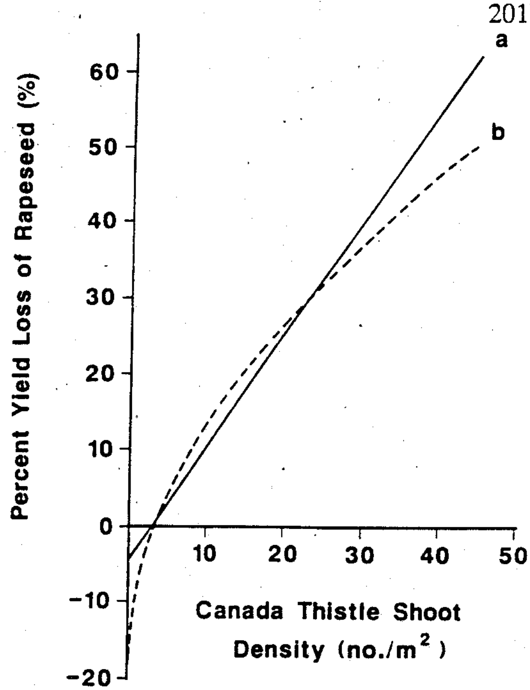

Figure 5. The percent yield loss of rapeseed due to Canada thistle density in Canada. Curve a corresponds to $\hat{Y} = -3.83 + 1.48\,X$ and curve b corresponds to $\hat{Y} = -18.63 + 10.42\,\sqrt{X}$, where $\hat{Y}$ = estimated percent yield loss and X = Canada thistle shoot density (no./m^2). These curves represent untransformed and square root transformed expressions of the same data (189).

data (126, 189, 190) suggest that yield losses are not linearly related to weed density below 10 Canada thistle shoots/m^2 (Figures 4 and 5).

Recently Cousens et al. (54) critiqued earlier YLA models relating relative crop yield loss to weed density and suggested alternative models based on a rectangular hyperbola model incorporating both weed density and the relative time of weed and crop emergence. The equation

$$Y_L = \frac{bD}{e^{cT} + bD/a}$$

may have utility in future studies of crop and Canada thistle YLA. In this model, Y_L is percent yield loss, D is weed density, T is relative time of emergence of weed and crop, and a, b, and c are nonlinear regression coefficients.

The effect of Canada thistle density on spring and winter wheat yields (122, 126, 198) should be reevaluated using modern statistical analysis. The statistical approach used for Canada thistle YLA in barley (190) and rapeseed (189) has some utility. Not only were the literature descriptions of the agronomic practices used in early studies of the YLA of wheat incomplete, but cropping practices have changed drastically since the 1950s. Tillage has been reduced and semidwarf spring wheat varieties have replaced standard height cultivars in many regions of the Northern Great Plains. Both trends may increase wheat yield losses due to Canada thistle because they favor Canada thistle growth.

YLA of Canada thistle growing in other field crops is needed. Likewise, the relative susceptibility of different annual crops to Canada thistle interference should be determined. For example, preliminary data suggest that barley is more susceptible to Canada thistle than is either winter or spring wheat (122). Surprisingly, winter and spring wheat responded similarly to Canada thistle, despite vast differences in their life cycles. Where new crop varieties, such as semidwarf spring wheat, differ greatly in growth habit from previously used cultivars, the YLA of Canada thistle also should be reexamined. More research is needed on the YLA of Canada thistle in reduced- or no-till cropping systems, since decreased tillage favors increases in this perennial weed (242). The relative competitiveness of different crops with different subspecies or ecotypes of Canada thistle deserves research attention, as well.

Quantitative data on the geographic distribution, density, and crop yield losses caused by Canada thistle is a prerequisite for estimating potential losses in crop production due to this weed. However, full economic analysis of the impact of Canada thistle on specific crops and the relative costs and benefits of controlling it have not been published, with the exception of pastures in New Zealand (113). Yield loss estimates have ignored other production costs due to Canada thistle, including reduced harvesting efficiency, increased grain drying costs, decreased grain storability without spoilage, and losses in crop quality. The latter is a factor for some horticultural crops. For example, pea (*Pisum sativum* L.) quality is decreased by Canada thistle because the weed's thorny seedheads cannot be separated easily from harvested peas (36). In pastures, Canada thistle not only reduces forage production, but it impedes grazing (113).

Table 6. Common names of *Cirsium arvense* (L.) Scop. (131).

Country	Name
Australia	Canada thistle Creeping thistle
Chile	Cardo
Denmark	Ager-tidsel Mark-tidsel
England	Field thistle
Finland	Pelto-ohdake
France	Chardon des champs Cirse des champs Sarrette des champs
Germany	Ackerdistel Acker-Kratzdistel Feldkratzdistel
India	Thistle
Italy	Scardaccione Stoppione
Japan	Ezonokitsuneazami
Netherlands	Akkervederdistel
New Zealand	California thistle
Norway	Akertistel
South Africa	Kanadese dissel
Spain	Cardo
Sweden	Akertistel
Thunisia	Cirse des champs
United States	Canada thistle
Yugoslavia	Palamida

SYSTEMS OF WEED MANAGEMENT

This portion of the review will highlight only those aspects of the Canada thistle life cycle that are important for understanding the success or failure of control measures.

Fyske (99) asserted that Canada thistle in Europe was associated with field crop nurseries, orchards, and vineyards, but not with turf or grasslands. Earlier in the century, Canada thistle was associated with cereals because there was no in-crop tillage or effective herbicides. However, as effective herbicides were introduced in cereals, Canada thistle increased in row crops because in-crop tillage did not completely control it. With the advent of reduced tillage farming, Canada thistle has once again become a concern.

Subspecies Variation in Relation to Control. The taxonomy and plant description of Canada thistle have been reviewed (128, 131, 177), as has the history of Canada thistle taxonomy (60, 177). Holm et al. (131) also tabulated the common names given to Canada thistle in various languages (Table 6). In English it is most commonly called Canada thistle, creeping thistle, or California thistle (169). The name "cursed thistle" (228) is no longer used, although it has a charm all its own.

The terms 'ecotype', 'subspecies', 'variety', and'selection' have been used to describe morphological, physiological, or ecological variation in Canada thistle below the species level, often without establishing the correct use of these terms. Morphologically distinct 'varieties' (sic) of Canada thistle were recognized as early as 1939 (255). Moore and Frankton (178) described four subspecies of Canada thistle based on plant morphology (Table 7). Variation in Canada thistle growth habit has been described, but not related to subspecies (Table 8). Lawrence (150) defined subspecies as "a subdivision of a species having its own distribution but not sufficiently distinct (morphologically or genetically) to deserve elevation to the rank of species." He noted that a 'variety' is a unit subordinate to the subspecies when the latter category is used. Otherwise it is subordinate to the species. As Lawrence (150) noted, both terms are subject to varying definitions by different authors. Whereas 'subspecies' and 'variety' are used by plant taxonomists, the term 'ecotype' ('biotype') is used by plant ecologists and requires experimental verification. Odum (180) defined an 'ecotype' as a locally adapted population of a species with a wide geographic range. Ecotypes are frequently defined by reciprocal transplants in different locations from different parts of a species' range or by transplanting to a common environment. An ecotype is not a taxonomic term but may be used in parallel with 'subspecies' or geographic 'variety'. The term

Table 7. Key to four subspecies of Canada thistle [*Cirsium arvense* (L.) Scop.] (178; reproduced from Agriculture Canada Monograph No. 10 with permission of the Minister, Supply and Services, Canada).

Leaves gray with hairs appressed to the leaf surface on underside.
.... C. var. *vestitum*

var. *vestitum* Wimm. & Grab., Fl. Siles, III, 82. 1829 (*C. incanum* S.G. Gmel. Fisch. ex MB.). Stem and flower peduncles tomentose; leaves gray tomentose below, usually entire or shallowly pinnatifid, flat; spines weak.

Leaves smooth or only covered with light, cobweb-like hairs on underside. Leaves then, flat, with few marginal spines which are fine and short.

Leaves are all entire or the upper leaves are entire and the lower stem leaves shallowly and regularly indented or undulating.
.... C. var. *integrifolium*

var. *integrifolium* Wimm. & Grab., Fl. Siles. III, 82. 1829. (*C. setosum* (Willd.) MB.). Leaves thin and flat, usually oblong or elliptic in outline; all leaves entire or the upper, smaller leaves entire and the lower leaves shallowly and symmetrically pinnatifid, or undulating; spines few and fine, to 3 mm long.

Leaves shallowly to deeply indented. Identations often asymmetrical.
.... C. var. *arvense*

var. *arvense* (var. *mite* Wimm. & Grab., Fl. Siles. III, 82. 1829). Upper leaves elliptic to oblong, subentire or entire; lower stem leaves elliptic to oblanceolate, shallowly pinnatifid to deeply and often irregulary segmented and often with few remote lobes of unequal length; marginal spines few, fine, to 3 mm long.

Leaves are thick, somewhat leathery. The surface is wavy and the marginal spines are numerous, stout and long.
.... C. var. *horridum*

var. *horridum* Wimm. & Grab., Fl. Siles. III, 82. 1829 (typical *C. arvense*, sensu Fernald 1950). Leaves of rather tough texture, stiff, the surface wavy, not flat, deeply and symmetrically lobed, lobes pointed; marginal spines numerous, stiff and stout, yellow, longer than in the other varieties.

Table 8. Variable morphological and physiological traits described for ecotypes of Canada thistle.

Trait	Reference
Average seed weight (0.067 to 0.152 g/100 seed)	(125)
Innate dormancy of freshly harvested seed (0 to 92% germination at harvest)	(125)
Shoot emergence phenology from established roots	(125)
Leaf shape	(125)
Plant height (69 to 138 cm)	(125)
Flowering phenology and response to photoperiod and temperature	(136)
Root-forming ability	(125, 136)
Root bud-forming ability	(136)
Root or shoot response to photoperiod and temperature	(136)

Table 9. Shoot regrowth of 10 Canada thistle ecotypes over 4 yr following repeated sweep cultivation[a] for the first 2 yr during summer fallow in Montana (1960 and 1961) (127; adapted with the permission of the Weed Science Society of America).

	Canada thistle survival[b,c]			
Ecotype	Year 1	Year 2	Year 3	Year 4
	(%)			
LW	136	32 a	0	0
G1	197	15 b	0	0.7
G4	153	12 bc	0	0
A1	119	10 bc	0	0
G2	163	8 bc	0	0
G3	167	5 bc	0	2.0
YM	117	3 bc	0	0
FM	111	3 bc	0	0
PW	115	1 c	0	0
F1	150	0.4 c	0	0

[a]Cultivations with duckfoot sweeps 7.5 to 10 cm deep in 1960 on June 1 and 22, July 13, August 3 and 24, and September 7, and in 1961 on June 1 and 22, and July 13.

[b]Canada thistle survival based on original number of shoots counted June 1, 1959 and the number of shoots prior to the first cultivation each year from 1960 (Year 1) to 1963 (Year 4).

[c]Means with the same letters were not different at $P = 0.05$ according to Duncan's multiple range test.

'selection' may be more accurate if it is used in the sense of "a carefully chosen or representative collection."

These definitions are not merely of academic interest. Subpopulations of Canada thistle respond differently to control practices, such as tillage (Table 9) or herbicides (Table 10). It is not known whether various subspecies of Canada thistle respond differently to control measures. When 10 ecotypes differing in response to *Puccinia obtegens* for biological control were classified according to subspecies, disease susceptibility was unrelated to subspecies (245). Closer attention to defining subpopulations as subspecies or ecotypes may help explain frequently reported inconsistency in control.

Different ecotypes of Canada thistle vary in their morphology and life history traits (Table 8). In fact, differences in root-forming (125, 136) or adventitious root bud-forming ability (136) may help explain observed differences in ecotype response to cultivation for control at least after 1 yr of tillage (127) (Table 9). Two-yr-old artificially established stands of 10 Canada thistle ecotypes responded differently to a duckfoot cultivator with sweeps operated 7.5 to

Table 10. Canada thistle ecotype response to postemergence herbicides.

Herbicide	Rate	Difference found	Subspecies/ecotype	Measured parameters	Greenhouse or field	References
	(kg/ha)					
Amitrole	4.5	Yes	10 ecotypes	Shoot survival	Field	(127)
	10 to 40 mg/plant	Yes	Mite and horridum	Visual rating Shoot weight	Greenhouse	(206)
	2.2 to 4.5	Yes	4 ecotypes	—	—	(221)
2,4-D	1.7	Yes	10 ecotypes	No. adventitious shoots per area	Field	(129)
	1.7	Yes	10 ecotypes	Shoot survival	Field	(127)
	1.1	Yes	3 ecotypes	Visual rating shoot and root weight	Greenhouse	(153)
	—	Yes	Mite and horridum	No. adventitious shoots per area	Field	(207)
	0.8 to 1.7	Yes	4 ecotypes	—	Greenhouse	(221)
	1.1	Yes	3 ecotypes Mite and horridum	Root weight	Greenhouse	(136)
2,4-DB	0.8 to 1.7	Yes	4 ecotypes	—	Greenhouse	(221)
Dicamba	0.3 to 0.6	Yes	Mite and horridum	No. adventitious shoots per area	Field	(206, 207)
	1.1	Yes	3 ecotypes Mite and horridum	Root weight	Greenhouse	(136)
	0.1 to 0.3	Yes	4 ecotypes	—	Greenhouse	(221)
Glyphosate	1.1	Yes	Mite and horridum	Visual rating Shoot weight No. adventitious shoots per area	Field Greenhouse	(209) (208)
Picloram	0.3 to 0.6	No	Mite and horridum	No. adventitious shoots per area	Field	(206)
	0.1 to 0.3	Yes	3 ecotypes Mite and horridum	Root weight	Greenhouse	(136)

10 cm deep every 21 days for 2 yr starting in mid-July in Montana.

While such intensive secondary tillage is no longer encouraged in fallow because of concerns about soil erosion, some ecotypes are difficult to control by tillage. No studies of the soil persistence of Canada thistle roots have been published; however, Hodgson's (127) tillage study suggests that the root population has a longevity of 2 to 3 yr.

Herbicide tolerance should not be confused with resistance. LeBaron and Gressel (152) defined natural tolerance of a population as low susceptibility to a control treatment in an unselected population which was never exposed to control, whereas resistance of a population is a reduced response to a control measure after it is used due to natural selection. Over 25 yr ago Dersheid (58) suggested that repeated herbicide treatment is likely to cause a Canada thistle population composed of herbicide-susceptible, -intermediate, and -resistant individuals to change and become composed of only resistant plants. The development of herbicide resistance after repeated applications of herbicides over time has never been documented in the field. Partially herbicide-tolerant ecotypes have been found for amitrole (1*H*-1,2,4-triazol-3-amine) (79, 126, 127, 209, 221), 2,4-D [(2,4-dichlorophenoxy)acetic acid] (127, 129, 136, 153, 221), dicamba (3,6-dichloro-2-methoxybenzoic acid) (136, 206, 207, 221), and glyphosate [*N*-(phosphonomethyl)glycine] (208, 209) (Table 10). In the early 1960s Derscheid (58) recommended that the same herbicides (e.g., phenoxyacetic acids) should not be applied year after year as the sole strategy for Canada thistle control to avoid development of tolerant or resistant populations.

Most field research on ecotype or subspecies response to herbicides were applied at the bud stage (Table 10). Stage of development at treatment, however, can modify the response of different ecotypes in the field (127). For example, percent survival of Canada thistle ecotypes in Montana ranged between 22 and 75% when 2,4-D at 1.7 kg ae/ha was applied at the bud stage and between 38 to 95% when applied at the bloom stage (127).

Because ecotypes respond differentially to one herbicide does not ensure that they will react differentially to other herbicides (153, 206) or to cultivation (127). Young potted ecotypes which differed in susceptibility to 2,4-D responded similarly to picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) at 0.28 kg ae/ha (153) or 0.28 to 0.56 kg ae/ha (206), but this response was modified by temperature in the growth chamber (136). Environment also may modify ecotype or subspecies response to herbicides. Increasing temperature changed the relative response of different ecotypes to 2,4-D and dicamba in the growth chamber (136).

Control Strategies. Ironically, most nonherbicidal methods of managing Canada thistle used today were employed at least 150 yr ago when Stevens (228) summarized farmer practices used for the "extirpation" (eradication) of this weed. Biological control and planting weed-free seed are two exceptions, although early legislation suggests that the spread of Canada thistle seed in commercial crop seed was long recognized as a problem. Stevens (228) cited use of the following practices: 1) deep (moldboard) plowing, 2) frequent (moldboard) plowing, 3) repeated summer fallow cultivation, 4) repeated mowing, 5) burning, 6) heavy planting of competitive forage legumes or grasses, 7) planting of competitive rows crops, 8) "smothering" with thick layers of straw (90 cm deep) or boards to exclude light over Canada thistle patches, 9) application of salt solutions, and 10) combinations of these various practices. Of course, burning, salt application, and "smothering" are no longer used. However, covering Canada thistle with boards, sheet metal, or tar paper reportedly were effective in eradicating the weed, although quantitative data were not presented (225). Canada thistle grows poorly in low light and seedling survival is reduced (27, 60, 126). Spence and Hulbert (225) observed that straw was ineffective in eradicating Canada thistle; roots extended beyond areas where Canada thistle shoots were covered (255). Stevens' (228) early summary makes it clear that no one method was consistently effective in eradicating Canada thistle.

Willard and Lewis (255) indicated on-farm control programs must prevent seed formation and remove or destroy roots. Of course, seedling establishment also must be prevented, as most control systems recommended by Willard and Lewis in the 1930s for destroying the established root system undoubtedly did. Most current cultural methods of control kill the roots by preventing shoot growth and, thus, deplete roots of their nutritional reserves over time (58). As early as 1918, the objective of cultural control was to eradicate Canada thistle by "destroying top growth to starve roots out" (19).

The target stages in the Canada thistle life cycle for the six major methods of control are summarized in Figure 6. Of course, individual control measures applied at only one life cycle stage are never completely effective. Cleaning harvesting equipment before entering new fields and planting weed-free crop seed only prevents or limits Canada thistle from being introduced or spread on fields. Killing Canada thistle shoots or ramets, or preventing seed production or dispersal in areas bordering fields, can limit natural seed dispersal into new fields via wind or water. Tillage, mowing or grazing, herbicides, biological control, and competitive crops differ in their relative efficacy for limiting seed dispersal. They also differ for limiting or preventing seedling establishment from seed, reproductive maturation, and vegetative propagation from adventitious root buds. Only tillage or some herbicides reduce seedling establishment from the seed bank, whereas tillage, herbicides, biological control, and competitive crops limit plant establishment from the root bud bank. Only tillage has been established to reduce the persistence of the roots in the absence of shoot growth (127). No control measures have been reported to influence persistence of the soil seed bank. Seed production and dispersal can be modified by tillage or mowing to some extent. These control measures differ drastically in their relative effectiveness in limiting or preventing component stages of the Canada thistle life cycle.

Many researchers have noted that Canada thistle control is inconsistent or erratic. Alley (7) felt that either proven practices were not used or that the methods did not work in all parts of this weed's geographic range. He also proposed that herbicide-resistant strains had developed, although no proof was offered. Perhaps more attention should be given to the impact of root distribution and density in the soil profile, previous cropping history, previous Canada thistle management or control practices, and environment on the effectiveness of management practices.

It is a truism that factors beyond human control can limit control measures. In the 1910s, cultural control measures often were reported to fail on wet land; also, control was easier after a drought than in wet years (19). Designing research experiments to study or prove such assertions with natural weed stands is challenging at best.

In 1952 Lee (155) observed that "no single

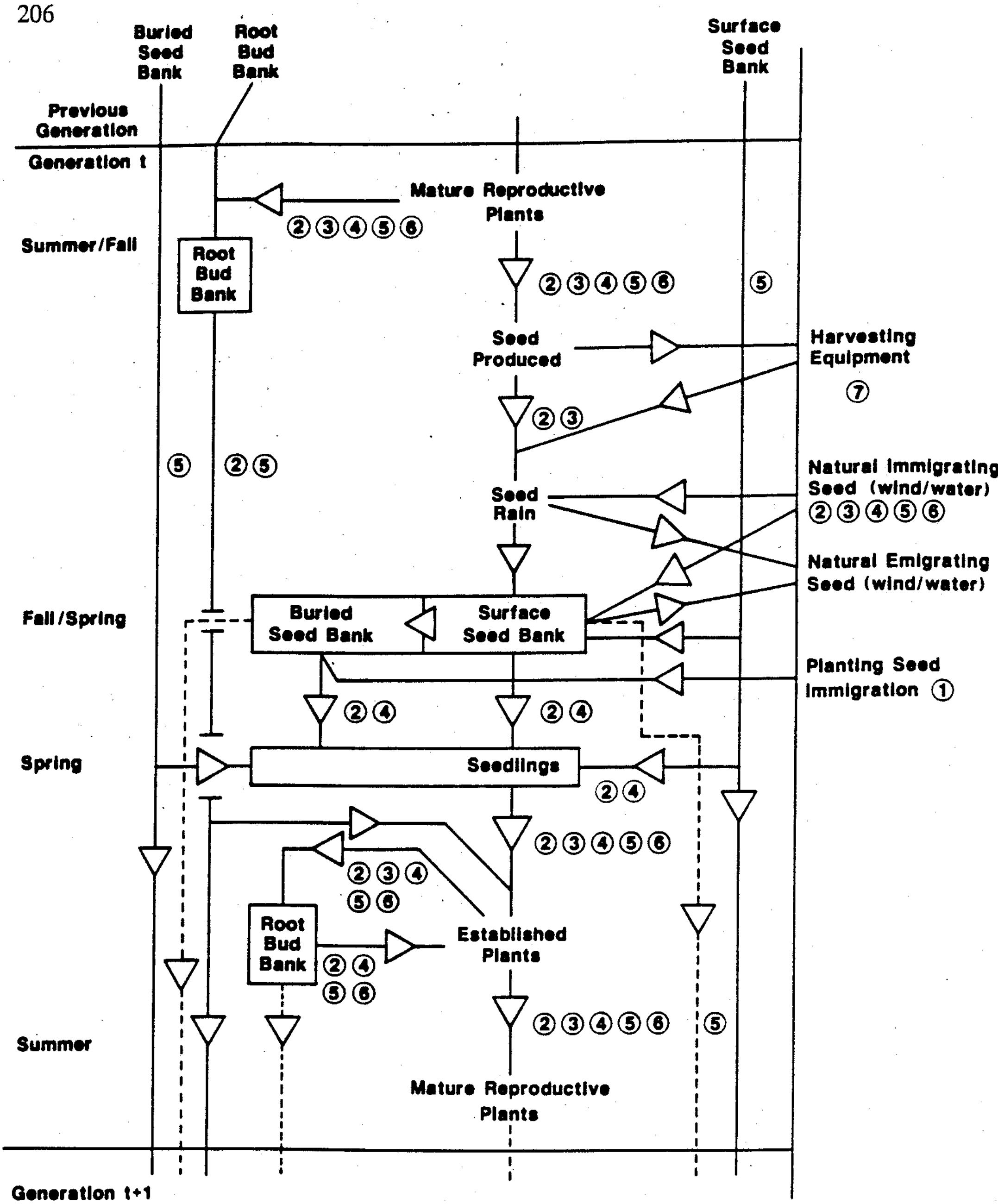

Figure 6. Flow chart outline of the life cycle stages of Canada thistle over two generations. The life cycle stages that can be manipulated by man are indicated by *1* planting weed-free crop seed, *2* tillage, *3* mowing or grazing, *4* herbicide application, *5* biological control, *6* planting competitive crops, and *7* cleaning combines [modified after Sagar & Mortimer (205; adapted by permission of Academic Press, Inc.)].

treatment, regardless of practice, can be relied upon to produce complete kill" of Canada thistle. This viewpoint persists to the present. In 1982, Strand (230) proposed that integrated control programs require 5 to 10 yr of effort and observed, "Canada thistle control is not a 'one-shot' treatment. A series of well calculated and timely operations is essential for successful results."

Crop Competition. Early in the century, competitive "smother" crops were advocated as one way of managing Canada thistle (19). Early agriculturalists observed that this weed did not tolerate shade. Alfalfa and sweetclover (*Melilotus* sp.) were recognized as useful because of their rapid early canopy closure in spring (60, 204, 225). Alfalfa is advantageous because it does not require annual reseeding as does sweetclover (204). Established alfalfa emerges before Canada thistle and can be mowed early and frequently; mowing significantly stresses the weed (60). In the 1920s, Detmer (60) suggested the following sequence for Canada thistle control: 1) a "smother" forage crop for 2 to 3 yr; 2) moldboard plowing in fall, followed by 3) a row crop that can be cultivated. Hodgson (124) observed that 3 yr of alfalfa reduced Canada thistle densities to 1% of control stands. He verified that alfalfa emerges before Canada thistle and recovers more rapidly than the weed. Mowed alfalfa decreased Canada thistle stands better than unmowed alfalfa. In most research, it is difficult to distinguish whether interference (or competition) from the forage crop itself or the management practices used to produce it (e.g., mowing) are responsible for Canada thistle control.

Heavy stands of forage grasses have been recommended for Canada thistle control. In Sweden, wide row spacing (20 to 50 cm) of forages permitted Canada thistle to produce more dry matter after 2 yr than did narrow spacing (< 20 cm) (108). Results were average for solid stands of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* Huds.), orchardgrass (*Dactylis glomerata* L.), perennial ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.), and alfalfa in this study.

Detmer (60) found that timothy, orchardgrass, and redtop (*Agrostis alba* L.) were less effective than alfalfa or sweetclover in suppressing Canada thistle shoot growth. He suggested that they were ineffective because the grass stands were sparser and were cut later than was alfalfa. The timing of mowing may be important for managing Canada thistle. Thrasher et al. (240) also observed that various forage grasses were relatively ineffective in suppressing Canada thistle (Table 11). The relative competitiveness of different Canada thistle ecotypes or subspecies with crops has not been reported.

Table 11. The influence of interference by forage grass species on Canada thistle density in the same Idaho pastures over 3 yr (1958 to 1960) (240; adapted with the permission of the Weed Science Society of America).

Species	Canada thistle density			
	Year 1	Year 2	Year 3	3-yr mean
	(no./m²)			
Kentucky bluegrass	9.3	5.7	2.5	5.7
Russian wildrye	5.7	3.2	1.7	3.6
Reed canarygrass	4.7	3.2	1.8	3.2
Orchardgrass	3.2	3.6	2.5	3.2
Smooth bromegrass	3.2	3.6	1.4	2.9
Tall fescue	2.9	2.5	1.4	2.2

Grazing and Mowing. The competitiveness and effectiveness of different forage species for reducing Canada thistle stands is modified by forage management, such as the timing and frequency of mowing. Less is known about the effectiveness of grazing than mowing for Canada thistle control, although sheep and goats were recommended for control in pastures early in the century (19). Trumble and Kok (243) summarized several components of good pasture management for Canada thistle control (Figure 7). Rotational grazing or nongrazed pasture reduced Canada thistle spread, whereas continuous grazing allowed rapid weed spread (243). In Australia, heavy pasture grazing by sheep reduced the rate of Canada thistle spread, as measured by changes in patch diameter (16).

Repeated mowing can severely reduce Canada thistle stands in forages, such as alfalfa or legume and grass mixtures (Table 12) (17, 59, 113, 124, 126, 168, 214, 253). In most studies it took only 3 yr of forage production plus mowing to severely reduce Canada thistle stands, but data on reinfestation rates or the later persistence of control were not presented. Unfortunately, the initial Canada thistle density and changes in density were not documented in these studies, only percentage stand reductions or percentage visible control. Apparently, infrequent mowing was ineffective for Canada thistle control (17).

Differences in initial Canada thistle density could influence how quickly stands were reduced. In Indiana, three shoot densities of artificially established Canada thistle growing in alfalfa were reduced to nearly zero after 3 yr of mowing (Figure 8) (214). These weed stands were sparse (5 to 22 plants/m²) and mowing followed 4 days of grazing by sheep each of the 3 yr. McKay et al. (168) felt that alfalfa reduced Canada thistle stands substantially because it emerges before Canada thistle in spring and forms a competitive cover. It also recovered more rapidly from mowing than did Canada thistle.

In the 1930s Willard and Lewis (255) asserted that repeated mowing merely checked Canada thistle growth but did not destroy this weed. However, they failed to specify the mowing height, starting date, and frequency and

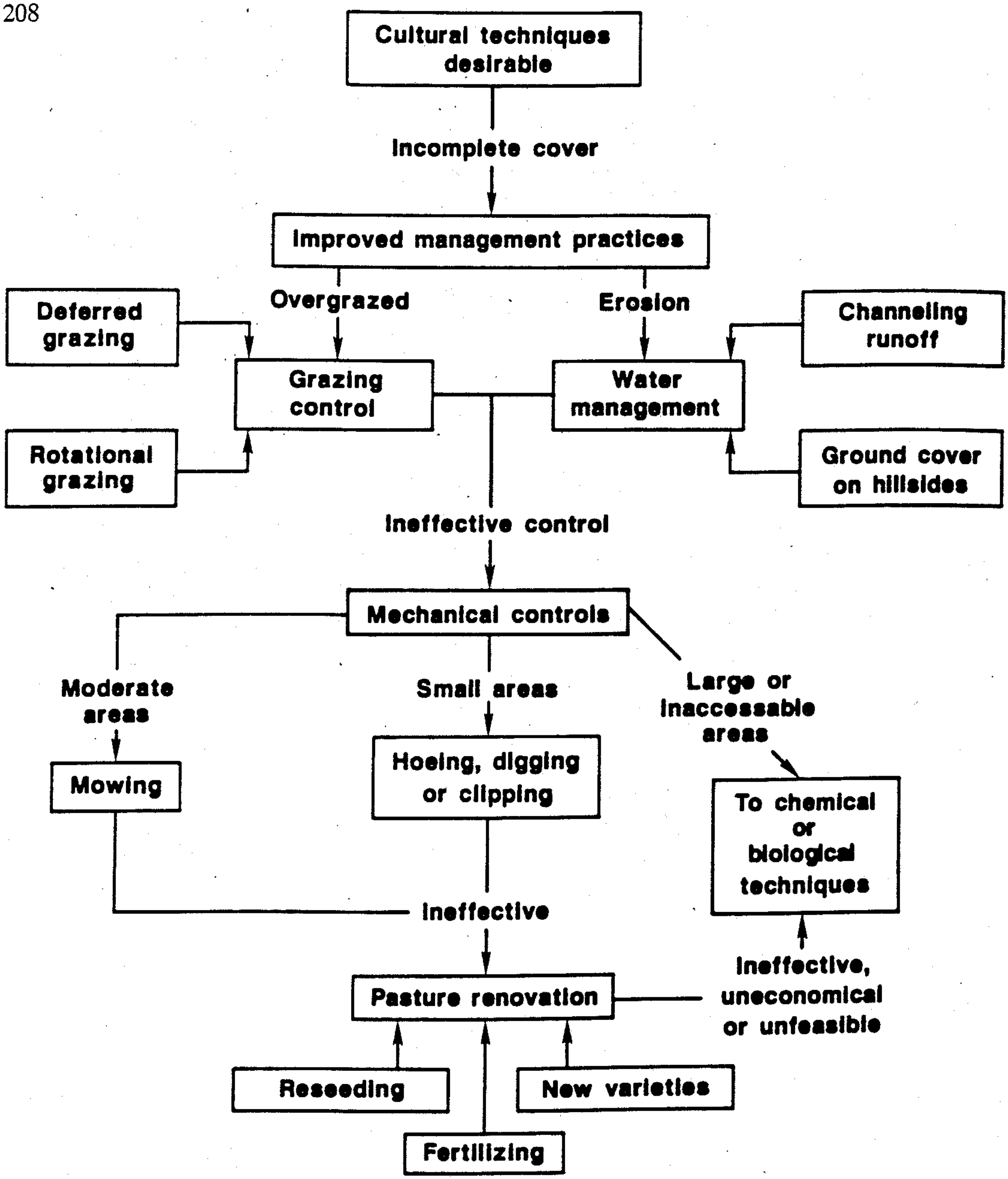

Figure 7. A flow chart outline of the decision-making process for Canada thistle suppression by cultural and mechanical techniques in pasture (243; adapted by permission of Blackwell Scientific Publications, Ltd.).

duration of mowing in this research. Incomplete reporting of field research procedures and operations is a fairly common flaw of early Canada thistle control studies. Willard and Lewis (255) recommended that mowing should start on June 1 when the plants were in bloom and should be repeated at 4- to 6-week intervals. Foote et al. (94) also felt that mowing along roadsides only weakened Canada thistle, and control was unacceptable unless mowing was frequent.

The timing of initial mowing and mowing frequency in relation to forage stand establishment can modify how quickly control is achieved (59). Derscheid et al. (59) cultivated an infested area four times at 3-week intervals before seeding either alfalfa, bromegrass (*Bromus* sp.), or a forage mixture in mid-August. Apparently,

Table 12. Effect of mowing on Canada thistle shoot control in alfalfa or mixed pasture over time (adapted with the permission of the Weed Science Society of America).

Forage	Mowing frequency	State	Year	Canada thistle Control	Canada thistle Survival	Reference
				(%)	(%)	
Alfalfa	2X/year	MT	1	—	100	(126)
			2	—	60	
			3	—	11	
			4	—	9	
			5	—	1	
Alfalfa	2X/year	MT	1	—	100	(124)
			2	—	14	
			3	—	5	
			4	—	5	
			5	—	1	
Alfalfa[a]	—	SD	1	88	—	(59)
			2	98	—	
			3	100	—	
Alfalfa[b]	—	SD	1	62	—	
			2	89	—	
			3	100	—	
Alfalfa + grass (Trial 1)	2X/year	MT	2	—	121	(126)
			3	—	11	
			4	—	11	
			5	—	0.5	
Alfalfa + grass (Trial 2)			2	—	46	
			3	—	17	
			4	—	16	
			5	—	5	
Alfalfa + grass (Trial 1)	—	ID	1	36	—	(168)
			2	90	—	
			3	93	—	
			4	99	—	
Alfalfa + grass (Trial 2)	—	ID	1	50	—	
			2	90	—	
			3	99	—	
Alfalfa + grass (Trial 3)	—	ID	1	90	—	
			2	95	—	
			3	99	—	
			4	99	—	
Alfalfa + bromegrass[a] (Trial 1)	—	SD	1	88	—	(59)
			2	100	—	
			3	100	—	
Alfalfa + bromegrass[b] (Trial 2)	—	SD	1	71	—	
			2	92	—	
			3	100	—	
Bromegrass[a] (Trial 1)	—	SD	1	88	—	
			2	93	—	
			3	100	—	
Bromegrass[b] (Trial 2)	—	SD	1	68	—	(59)
			2	93	—	
			3	100	—	

[a] Mowed only in 2nd and 3rd yr.
[b] Mowed all 3 yr.

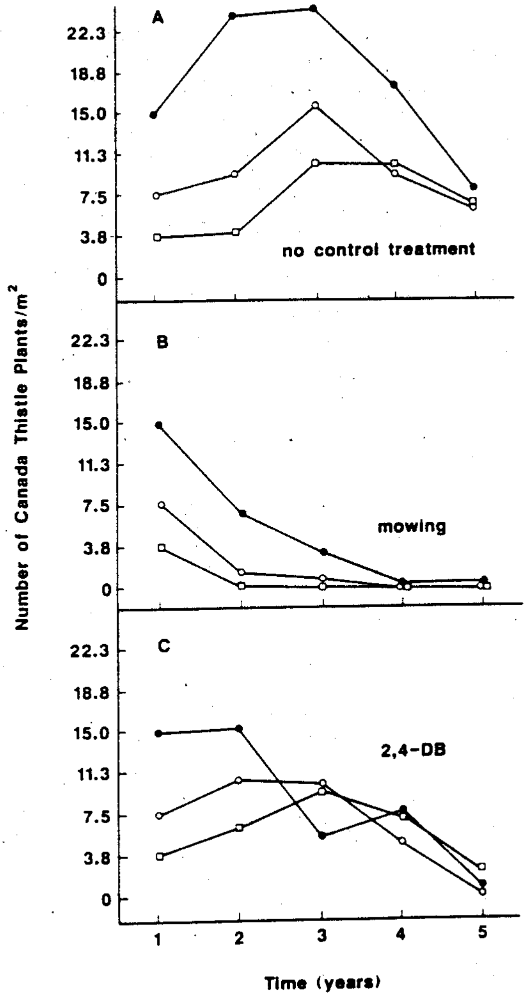

Figure 8. Changes in Canada thistle shoot density over 5 yr (1961 to 1965) in alfalfa in Indiana as influenced by (A) no control, (B) mowing after each grazing period, and (C) 2,4-DB at 1.12 kg ae/ha applied at the bud stage. At year 1 artificially started Canada thistle stands were initially 3.8 plants/m² (=□), 7.5 plants/m² (=○), and 15 plants/m² (=●). Densities were determined in the fall of each year (214; reprinted with the permission of the Weed Science Society of America).

forage stand competition with Canada thistle was reduced if newly established forage stands were mowed too early. Forages suppressed Canada thistle better when initial mowing was delayed until the second year (Table 12). Nevertheless, control in the second and third years of the study were uninfluenced by the prior mowing regime during the first year. In Ohio pastures, three repeated mowings starting in June (June 1, July 1, and August 1) were more effective than three repeated mowing starting in July (July 1, August 1, and September 1) for controlling Canada thistle (253). Although changes in Canada thistle stand were not documented, Welton et al. (253) asserted that frequent early mowing (June 1, July 1, August 1, and September 1; or June 1, July 1, and August 1; or July 1, August 1, and September 1) nearly eliminated Canada thistle after 3 yr. Such frequent mowing would limit forage production.

The physiological or biochemical mechanism by which mowing controls Canada thistle is unknown. Perhaps root biomass reserves are gradually exhausted by the stress if mowing is frequent. In Ohio, frequent mowing delayed and reduced percentage dry weight and carbohydrate accumulation in roots late in the growing season (253).

Tillage. Improper tillage can spread Canada thistle across fields (255). Newly infested areas in cultivated fields often occur in a direct line with old patches of Canada thistle, suggesting that roots were dragged by tillage implements.

While only tillage is considered in this section, it must be recognized that tillage should be integrated into cropping systems that are accepted by farmers. Several early tillage systems were designed to gradually starve Canada thistle roots and prevent new shoot emergence, further limiting assimilate accumulation in roots (19, 126). However, the actual physiological and biochemical mechanism for root biomass reductions by tillage are unknown.

Tillage can be divided into primary tillage (e.g., moldboard or chisel plowing) and secondary tillage (e.g., field cultivation or harrowing). Primary tillage is often done once prior to repeated secondary tillage for Canada thistle control. Secondary tillage may be done in row crops, but it controls Canada thistle more effectively in fallow, especially in arid western states where summer fallow is used for soil moisture conservation. Repeated fallow cultivation over 2 to 3 yr eliminated this weed (Table 9), as did hand hoeing (Table 13). An adequate description of tillage for weed control should include the following factors: 1) type of tillage implements or combinations of implements, 2) tillage depth, 3) time that tillage was initiated, 4) frequency of tillage operations, 5) duration of tillage, and 6) integration into cropping systems. The American Society of Agricultural Engineers recently standardized descriptions of tillage implements (106). Most published research falls short of this ideal.

Comparisons of the relative effectiveness of different tillage implements for Canada thistle control is limited (241). In one study, alternate weekly moldboard plowing or alternate weekly

Table 13. Control of Canada thistle by repeated hand hoeing in corn for 1, 2, and 3 years (46; adapted by permission of the Weed Science Society of America).

Treatment	Years of hoeing	Canada thistle control[a]		
		1971	1972	1973
	(no.)		(%)[b]	
Hoed	1	100 a	40 m	35 jk
	2	100 a	100 ab	84 a-g
	3	100 a	100 a	100 a
Not hoed	0	0 h	0 n	0 k

[a] Control observations were made in September each year.
[b] Means in the same column followed by the same letter were not different at P = 0.05 by Duncan's multiple range test.

field cultivation for one growing season (9 to 10 times) controlled Canada thistle equally well in the subsequent growing season (241) (Table 14). Field cultivators with duckfoot sweeps (55, 59, 127, 225) and sugarbeet cultivators equipped with duckfoot sweeps (241) have been researched more than disks (55, 59) for secondary tillage because they undercut Canada thistle shoots. However, one-way disking 10 cm deep, tandem disking 10 cm deep, and field cultivation with duckfoot sweeps every 2 weeks were equally effective in preventing Canada thistle shoot regrowth in the following growing season in South Dakota (59).

Timing of initial secondary tillage may be important for Canada thistle control. Delaying tillage until bloom in mid-August drastically decreased control in the following year relative to tillage initiated earlier when the weed produced 2.5 cm of shoot growth (Table 14; 241). Consequently, later researchers recommended that tillage should start prior to Canada thistle bloom (225). Detmers (60) recommended that summer fallow tillage should start in Montana as soon as shoots emerge, as did Hodgson (126). The significance of the time of initial cultivation to long-term control requires systematic reappraisal.

The frequency of summer fallow cultivation for Canada thistle control has been researched. Before 1937, "black fallow" was recommended for Canada thistle control in the Pacific Northwest (216). Nevertheless, an inflexible schedule of cultivation at fixed intervals probably has no place in Canada thistle control because of the potential for soil erosion. The objective should be to prevent shoot growth; summer fallow tillage should be timed so that Canada thistle shoots are no more than 7.5 cm tall (19). Six to eight cultivations per growing season each at this stage adequately controlled Canada thistle regrowth. Tillage did not need

Table 14. Comparative effectiveness of various types of summer fallow tillage in one growing season (1931) on Canada thistle shoot control early in the following growing season (1932) in Idaho (adapted from ref. 241 by permission of the American Society of Agronomy, Inc.).

Treatment	Date first tilled (1931)	Stage of growth when first tilled	Tillage treatments	Canada thistle control (May 9, 1932)
			(no./yr)	(%)[a]
Weekly cultivation[b]	May 5	Vegetative[c]	19	100
Alternate weekly cultivation[b]	May 5	Vegetative[c]	10	100
Alternate weekly plowing[d]	May 5	Vegetative[c]	9	100
Delayed plow, weekly cultivation[b,d]	Aug. 10	Bloom	7	0
Control	—	—	—	—

[a]Control observed on May 9, 1932.
[b]Sugarbeet cultivator equipped with 12 30-cm duckfoot sweeps was used.
[c]2.5 cm tall.
[d]Moldboard plowing.

to be as frequent toward the end of the growing season as at the start because later emergence was slower.

In Idaho, Tingey (241) reported that sweep field cultivation every other week was as effective as weekly cultivation in reducing Canada thistle infestations. If continued for 2 yr, no shoots emerged in the third growing season. In contrast, Rogers (204) suggested cultivation for 2 yr as new shoots emerged (as many as 20 times per year) in Colorado. In 2 yr of field research, tillage every 21 days was most effective (216) (Table 15). There was no advantage to more frequent tillage. Of course, if Canada thistle shoots had not emerged at the prescribed interval, the land was not tilled.

In South Dakota, Derscheid et al. (59) found that field cultivation with duckfoot sweeps at 2-, 3-, or 4-week intervals (eight, six, and five operations per growing season, respectively) were equally effective in preventing regrowth in the second growing season. In Montana, Hodgson (124, 126, 127) verified that duckfoot cultivation 7.5 to 10 cm deep every 21 days in summer fallow or when shoots emerged for 2 yr prevented shoot regrowth in the third growing season (Table 9). Six or seven cultivations in one growing season provided up to 98% control one growing season later. In Idaho, McKay et al. (168) also found that clean cultivation three times at 21 day intervals with irrigation between cultivations gave the greatest control in the shortest time.

Table 15. The effect of frequency of cultivation on eradication of Canada thistle in summer fallow in Idaho (216).

Trial	Cultivation interval	Cultivations needed for eradication[a]	Time to eradication
	(days)	(no.)	(days)
1	7	18	122
	14	9	122
	21	6	115
	28	4	122
2	14	11	367
	21	7	136
	28	6	156
	35	9	469
	42	8	469

[a]When Canada thistle was 12.5 cm tall, plots were moldboard plowed 15 cm deep followed by cultivation with a duckfoot field cultivator 10 to 12.5 cm deep.

As effective as frequent cultivation during summer fallow may be, it is costly and can interfere or conflict with other farm operations (246). It also exposes the soil to wind and water erosion. Several researchers suggested various ways in which secondary tillage can be integrated into other cropping practices. Cox (55) recommended interrow sweep cultivation in corn at weekly intervals for heavy Canada thistle infestations followed by moldboard plowing in fall. Since then, others have recommended deep fall moldboard plowing to turn Canada thistle roots up in combination with either summer fallow or in-crop tillage for row crops (225). Primary tillage 2 to 3 weeks after fall herbicide treatment improved herbicide performance (37).

Alley (7) observed that Canada thistle control with tillage was more erratic in Wyoming than in higher rainfall regions. He noted that shoot regrowth following tillage was limited, perhaps explaining the discrepancy in control. Also, in 1846, Stevens (228) noted that fewer tillage operations were needed for Canada thistle control in dry years, presumably because fewer Canada thistle shoots emerged. One yr after a drought, Canada thistle root biomass to a depth of 50 cm was severely reduced in spring wheat following fall chisel-plowing in North Dakota (45).

Different ecotypes also respond differently to tillage (127) (Table 9). Some ecotypes are better able to withstand frequent disturbance than others.

Soil Fertility. The extent to which management of soil fertility influences Canada thistle control is complex and depends on crop species, rotation, and irrigation management. The influence of wheat and pasture fertility management on Canada thistle control have been studied most intensively.

Fertilizer was applied to enhance crop competitiveness with Canada thistle. In Idaho, nitrogen at 90 kg/ha broadcast-applied yearly to the surface of the same irrigated spring wheat plots did not provide long-term control of Canada thistle (Table 16) (168). But, when nitrogen-treated spring wheat was sprayed with an amine salt of 2,4-D at 2.2 to 3.4 kg ae/ha, in-crop Canada thistle control was much better than with 2,4-D alone; control was 98 versus 80%, respectively, after 4 yr. Registered rates of 2,4-D in spring wheat are 0.56 kg ae/ha or less in the United States. Hume (134) reported that the influence of fertilization on Canada thistle density in dryland spring wheat depended on rotation in 21 yr of cereal rotation research in Saskachewan, Canada (Table 17). Canada thistle densities in continuous spring wheat were much greater in unfertilized plots than in fertilized plots [90 kg/ha of N:P:K (23:23:0)], yet differences were less marked for either wheat-fallow or wheat-wheat-fallow rotations. But, in Montana, surface broadcast nitrogen (N) reapplied yearly at 60 kg/ha to dryland spring wheat plots actually increased Canada thistle density over time (124, 126) (Table 18). Broadcast nitrogen at planting also failed to enhance Canada thistle control with 2,4-D at 0.84 kg ae/ha applied postemergence.

In dryland Nebraska pastures, nitrogen as ammonium nitrate at 45 kg/ha also increased Canada thistle density and biomass over time (203) (Table 19). Apparently, Canada thistle was able to exploit fertilization better than could forage grasses. In contrast, nitrogen rate was a conributing factor in whether Canada thistle increased or decreased in irrigated grass pasture in Idaho (240), averaged across six grass species [bluegrass (*Poa* sp.), bromegrass (*Bromus* sp.), Reed canarygrass (*Phalaris arundinacea* L.), orchardgrass, tall fescue (*Festuca arundi-*

Table 16. Residual control of Canada thistle shoots with 2,4-D and nitrogen (90 kg/ha) in irrigated spring wheat over 5 yr (1953 to 1957) in Idaho. 2,4-D amine at 2.2 kg ae/ha was applied in the first year and 3.4 kg ae/ha thereafter in-crop when vegetative Canada thistle was less than 30 cm tall (168).

Treatment	Canada thistle control			
	Year 1	Year 2	Year 3	Year 4
	(%)[a]			
Spring wheat	0	0	0	0
Spring wheat + nitrogen	16	32	10	16
Spring wheat + 2,4-D	25	31	67	80
Spring wheat + nitrogen + 2,4-D	50	89	96	98
Spring wheat + nitrogen + 2,4-D in spring and fall[b]	75	84	93	96
Cultivation 1 year, spring wheat + nitrogen + 2,4-D thereafter	96	99	99	99

[a]Shoot regrowth density was counted in June, and therefore data show the effect of the previous year's treatment.
[b]Fall treatment was made in mid-September.

Table 17. Canada thistle shoot density as affected by nitrogen plus phosphorous fertilization[a, b] and a spring wheat plus fallow rotation over 21 yr in Saskatchewan (134).

Treatment	Canada thistle density	
	1979	1980
	(no./m²)	
Fertilized		
Continuous spring wheat[a]	5.3	5.1
Fallow to wheat[b]	4.2	0.9
Fallow to wheat to wheat[a]	0.5	5.5
Unfertilized		
Continuous spring wheat	21.5	18.9
Fallow to wheat	6.0	1.0
Fallow to wheat to wheat	4.2	10.1

[a] 90 kg/ha of 23-23-0 N-P-K applied per crop.
[b] 56 kg/ha of 11-48-0 N-P-K applied per crop.

Table 18. Residual control of Canada thistle shoots in dryland spring wheat with in-crop 2,4-D and nitrogen (56 kg/ha) over 4 yr (1952 to 1955) in Montana. 2,4-D propylene glycol butyl ether ester at 0.8 kg ae/ha was applied at the early bud stage of Canada thistle (124; adapted with the permission of the Weed Science Society of America).

Treatment	Canada thistle control		
	Year 1	Year 2	Year 3
	(%)[a]		
Spring wheat	119	147	157
Spring wheat + nitrogen	156	310	312
Spring wheat + 2,4-D	14	3	1
Spring wheat + nitrogen + 2,4-D	9	3	1
2,4-D alone	29	49	39

[a]Control as a percent of the original stand.

Table 19. Effect of nitrogen fertilizer (45 kg N/ha as ammonium nitrate) on Canada thistle and musk thistle shoot density and total thistle herbage biomass in Nebraska pastures over 2 yr (1978 to 1979) (203; adapted by permission of the Weed Science Society of America).

Treatment	Shoot density of thistle species[a, b]		Posttreatment density of combined thistles[a, c]			Combined thistle herbage biomass[a, c]		
	Canada thistle	Musk thistle	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
	(no./m²)					(kg/ha)		
Check	11 cd	10 ab	57 b	68 a	34 b	1470 b	3370 b	2560 b
Ammonium nitrate	28 ab	14 ab	82 a	72 a	50 a	3450 a	4390 a	3520 a

[a]Means in a column followed by the same letter do not differ at $P = 0.05$ by Duncan's multiple range test.
[b]Pretreatment thistle shoot density was determined on May 25, 1978.
[c]Posttreatment density was determined concurrently with herbage biomass determinations during the third week of July in year 0, 1, and 2.

nacea Schreb.), and Russian wildrye (*Elymus junceus* Fisch.)] (Table 20). Increasing nitrogen rate under irrigation tended to reduce Canada thistle density, especially at high nitrogen rates of 450 kg/ha. Without irrigation, density was not reduced consistently by N fertilization. Irrigation and high nitrogen fertilization may have enabled the forages to interfere better with Canada thistle growth. Kentucky bluegrass (*Poa pratensis* L.) fertilized before planting with N-P-K in Quebec had as many Canada thistle shoots as unfertilized plants after 3 yr (115). 2,4-D as the butyl ester at 1.1 kg ae/ha in June and early September severely reduced Canada thistle after 3 yr, regardless of the fertility management.

Table 20. Effect of nitrogen fertilizer and irrigation on the Canada thistle shoot density in six forage grasses[a] in Idaho over 2 yr (1958 to 1960) (240; adapted with the permission of the Weed Science Society of America).

Year	Irrigation[b]	Canada thistle density N fertilization (kg/ha) 0	60	110	220	450
		(no./m²)				
1	None	4.3	5.0	3.2	2.9	5.0
	Low	4.7	4.3	4.3	3.2	1.8
	Medium	7.9	7.5	6.8	2.5	2.9
	High	6.5	6.5	8.2	4.7	2.5
2	None	4.7	4.7	2.5	3.2	4.7
	Low	4.3	3.9	5.4	2.2	1.4
	Medium	6.5	6.8	4.7	2.2	0.7
	High	4.3	3.9	3.9	1.4	1.1
3	None	3.2	2.9	1.8	2.2	4.3
	Low	2.5	1.8	2.2	1.1	1.4
	Medium	1.8	1.8	1.4	1.4	0.7
	High	1.4	2.2	1.4	0.7	1.1

[a]Kentucky bluegrass, smooth bromegrass, reed canarygrass, tall fescue, orchardgrass and Russian wildrye.
[b]The unirrigated plots had 45.1, 40.8, and 49 cm of rainfall in the first, second, and third years. Low and medium irrigation was applied when 90 and 60%, respectively, of available soil moisture had been depleted. High irrigation maintained the soil moisture at field capacity.

The reasons for the inconsistency in Canada thistle response to fertilizer in these research studies are unclear. Initial soil nitrogen status and distribution could influence the response of Canada thistle to applied nitrogen but was not reported in any study. The form of applied nitrogen (nitrate or ammonium) could have an effect on Canada thistle physiology as well but was only reported in one study (203). Natural water availability also could modify nitrogen availability, as well as plant response. Fallowing improves both soil moisture and increases nitrate availability and, thus, may have reduced the magnitude of Canada thistle response to fertilizer in the two wheat-fallow rotations in Canada compared to the continuous spring wheat (134).

Other factors in crop management, such as tillage, may have modified Canada thistle response to fertilizer. The influence of climate on the relative competitiveness of Canada thistle with crops may be important; in Canada, fertilizer enhanced the competitiveness of the crop relative to Canada thistle (134) but further south in Montana and Nebraska, Canada thistle was better able to exploit applied nitrogen than were pasture species (203) or wheat (124). The relative ability of different Canada thistle subspecies or ecotypes to exploit soil fertility has not been studied.

HERBICIDES FOR CANADA THISTLE CONTROL

Herbicides for Canada thistle control will be reviewed and critiqued in this section, as well as the fate of radiolabeled herbicides in this weed. In no instance has the identity of ^{14}C-herbicide or ^{14}C-metabolites been confirmed by chemical methods, such as mass spectrometry. Almost all 'identification' has relied on R_f zone separations by thin layer chromatography. In no instance have plants treated with ^{14}C-herbicide also been sprayed with unlabeled herbicide at phytotoxic doses. Consequently, the duration of herbicide uptake and translocation in Canada thistle may have been overestimated since some herbicides may inhibit their own translocation. Canada thistle plants with well-developed thickened roots have been used in few studies of the fate of ^{14}C-herbicides; most researchers used 8- to 10-leaf seedlings or cuttings. The size of the root system may influence herbicide movement. There has been little effort to relate laboratory research results to field results on Canada thistle control with herbicides.

Registered Herbicides and Herbicide Combinations. Brief reviews of herbicidal control of Canada thistle have appeared, usually as extension publications (24, 60, 126, 160). Herbicides currently registered for Canada thistle shoot suppression or control in U.S. crops are listed in Table 21. Most research reports dealt with Canada thistle shoot control for only one growing season.

Eradication of this weed was seldom considered as a research goal. Eradication is the removal or killing of the entire plant, including perennial roots (60). In 1943, Pavlychenko (194) wrote, "So far the bulk of experimental work on eradication of perennial weeds by chemicals has been carried on in an empiric way to determine the lethal quantity of the herbicides and the time and form of application for each species of weed under certain growing conditions. Just how these chemicals act to effect the death of the plant, however, has remained obscure."

Despite extensive research on the mechanism or mode of action of herbicides in other species, the reasons why control measures must extend over 2 to 3 yr to be successful on Canada thistle remain obscure (55, 256). It is not known whether herbicides accumulate in and kill adventitious root buds directly or whether they prevent new adventitious shoot and root growth, forcing depletion and eventual death of existing roots by starvation. Of course, the persistence of the Canada thistle root system in the field has not been documented either. In 1970, Chancellor (48) was the first to suggest, ". . .that the use of chemicals that can stimulate dormant buds to grow, followed by more conventional herbicides to kill them, may well prove to be the only satisfactory solution [for Canada thistle control]." Even though nitrogen (110, 166) and soil-applied chlorsulfuron {2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]benzenesulfonamide} (69, 70) stimulated preformed adventitious root buds to grow, these observations have not been exploited for Canada thistle control in the field.

Nonselective Soil Sterilants, Fumigants, and Residual Herbicides. Early research on eradication of Canada thistle was reviewed (Table 22) (126). Unfortunately, the approach taken was to apply high rates of nonselective chemicals without regard for persistent residues which could damage rotational crops or leave the soil barren for several years. Some early herbicides were potent health hazards, as well. Of course, it probably was expected that only small areas or patches would be treated, but no attempt was made to integrate herbicide use with other management approaches. Consequently, this research is now only of historical interest.

Pavlychenko (194) was the first to excavate trenches through herbicide-treated Canada thistle patches to determine the depth of root kill (Figure 9). He observed that while sodium chlorate at 670 to 1010 kg/ha killed roots to a depth of 28 cm, some lateral roots encroached below this depth near the treated borders. Several applications of sodium chlorate were needed for root eradication, and an area 90 to 120 cm beyond the patch border had to be treated to kill roots extending beyond the patch (255). Persistent sodium chlorate residues prevented new root growth into treated regions.

Soil fumigants, such as 1,3-dichloropropene, ethylene bromide, and chloropicrin, have received limited attention for Canada thistle control (191, 192). Their nonselectivity, toxicity, cost, and the requirement for special application equipment has limited soil fumigation to high-value horticultural crops prior to planting. Rate and depth of injection modified Canada thistle control by fumigation. These soil fumigants are not now registered as herbicides, only as fungicides or nematicides, except for 1,3-dichloropropene[5]. But, even though the 1,3-dichloropropene label lists it as a herbicide, the label lacks specific use information on perennial weed control.

Amitrole. A restricted-use mixture of amitrole and ammonium thiocyanate (NH_4SCN)[6] is currently registered in the United States for post-

[5]U.S. trade name is Vorlex.

[6]U.S. trade name is Amitrol-T.

Table 21. Selected U.S. registered herbicides (1989) with at least partial ability to suppress or control Canada thistle shoots.

Crop	Herbicide	Trade name	Type[a]	Formulation concentration	Rate	Type of application[b]	Additives	Canada thistle[c]
				(ai or ae)	(lb ai or ae/A)			
Wheat and barley	Bromoxynil	Buctril	EC	2 lb/gal	0.25 to 0.5	Post	No	—
		Buctril 4E	EC	4 lb/gal	0.25 to 0.5	Post	No	—
	2,4-D	Weedone	EC	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64	WS	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64A						
		Weedar Emulsamine E-3	OS	2.7 lb/gal	0.34 to 0.64	Post	No	–
		Dacamine	EC	3.6 lb/gal	0.45	Post	No	—
	Chlorsulfuron	Glean	DF	75%	0.023	Post	Surfactant	4 to 6" tall
	Clopyralid	Curtail (+ 2,4-D)	EC	0.4 + 2 lb/gal	0.15	Post	No	—
	Dicamba	Banvel	WS	4 lb/gal	0.06 to 0.12	Post	No	—
	MCPA	Weedar MCPA Concentrate	EC	4 lb/gal	0.75 to 1.0	Post	No	–
		Weedar Sodium Concentrate	WS	2 lb/gal	0.75 to 1.0	Post	No	—
		Weedar MCPA ester	EC	4 lb/gal	0.25 to 0.75	Post	No	—
	Metsulfuron	Ally	DF	60%	0.006	Post	Surfactant	Rosette to 6" tall
Oats	Bromoxynil	Buctril	EC	2 lb/gal	0.5 to 0.5	Post	No	—
		Buctril 4E	EC	4 lb/gal	0.25 to 0.5	Post	No	—
	Chlorsulfuron	Glean	DF	75%	0.023	Post	Surfactant	4 to 6" tall
	2,4-D	Weedone	EC	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64	WS	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64A						
		Weedar Emulsamine E-3	OS	2.7 lb/gal	0.34 to 0.64	Post	No	—
		Dacamine	EC	3.6 lb/gal	0.45	Post	No	—
	Dicamba	Banvel	WS	4 lb/gal	0.06 to 0.12	Post	No	—
	MCPA	Weedar MCPA Concentrate	EC	4 lb/gal	0.75 to 1.0	Post	No	—
		Weedar Sodium Concentrate	WS	2 lb/gal	0.75 to 1.0	Post	No	—
		Weedar MCPA ester	EC	4 lb/gal	0.25 to 0.75	Post	No	—
Rye	Bromoxynil	Buctril	EC	2 lb/gal	0.25 to 0.5	Post	No	—
		Buctril 4E	EC	4 lb/gal	0.25 to 0.5	Post	No	—
	2,4-D	Weedone	EC	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64	WS	3.8 lb/gal	0.48 to 0.98	Post	No	—
		Weedar 64A						
		Weedar Emulsamine E-3	OS	2.7 lb/gal	0.34 to 0.64	Post	No	—
		Dacamine	EC	3.6 lb/gal	0.45	Post	No	—
	MCPA	Weedar MCPA Concentrate	EC	4 lb/gal	0.75 to 1.0	Post	No	—
		Weedar Sodium Concentrate	WS	2 lb/gal	0.75 to 1.0	Post	No	—
		Weedar MCPA ester	EC	4 lb/gal	0.25 to 0.75	Post	No	—

emergence control of Canada thistle growing in roadsides, fence rows, railroads, hardwood nurseries, and industrial sites. At one time, amitrole and NH_4SCN were tested in corn (193), fallow (148), and pasture (17) for Canada thistle control, but registered uses on agronomic or horticultural crops for food were cancelled in 1971 (47). It may be either applied alone or

Table 21. Continued.

Crop	Herbicide	Trade name	Type[a]	Formulation concentration	Rate	Type of application[b]	Additives	Canada thistle[c]
Corn	Atrazine	AAtrex 4L	EC	4 lb/gal	2 + 2 (twice)	Post	Oil	10 to 20" + 6"
		AAtrex 80W	WP	80%	2 + 2 (twice)	PPI	—	6" + 10 to 20"
		Aatrex Nine-0	WDG	85.5%	4	Pre/post	Oil	—
		Atrazine 4L	EC	4 lb/gal	4	Post	Oil	
		AAtrex 80W	WP	80%	4	Pre	—	—
	Bentazon	Basagran	WS	4 lb/gal	1 + 1 (twice)	Post	Oil	8" to bud
	Bromoxynil	Buctril	EC	2 lb/gal	0.25 to 0.38	Post	—	—
		Buctril 4E	EC	4 lb/gal	0.25 to 0.38	Post	—	—
	2,4-D	Weedar 64 or 64A	WS	3.8 lb/gal	0.5 to 0.7	Post	—	—
		Weedone	EC	3.8 lb/gal	0.23 to 0.3	Post	—	—
		Weedone LV6	EC	5.7 lb/gal	0.23 to 0.3	Post	—	—
		Weedone 638	EC	2.8 lb/gal	0.23 to 0.3	Post	—	—
		Weedar Emulsamine E-3	OS	2.7 lb/gal	0.25	Post	—	—
		Dacamine	EC	3.6 lb/gal	0.45	Post	—	—
	Dicamba	Banvel	WS	4 lb/gal	0.5	Post	—	—
Sorghum	Atrazine	AAtrex 4L	EC	4 lb/gal	2 + 2 (twice)	Post	Oil	10 to 20" + 6"
		AAtrex 80W	WP	80%	2 + 2 (twice)	PPI	—	6" to 10 to 20"
		AAtex Nine-0	WDG	85.5%	4	Pre/post	Oil	—
		Atrazine 4L	EC	4 lb/gal	4	Post	Oil	
		AAtrex 80W	WP	80%	4	Pre	—	—
	Bentazon	Basagran	WS	4 lb/gal	1 + 1 (twice)	Post	Oil	8" to bud
	Bromoxynil	Buctril	EC	2 lb/gal	0.25 to 0.38	Post	—	—
		Buctril 4E	EC	4 lb/gal	0.25 to 0.38	Post	—	—
	2,4-D	Weedar64/ 64A	WS	3.8 lb/gal	0.5	Post	—	—
		Weedone	EC	3.8 lb/gal	0.3	Post	—	—
		Weedone LV6	EC	5.7 lb/gal	0.3	Post	—	—
		Weedone 638	EC	2.8 lb/gal	0.3	Post	—	—
		Weedar Emulsamine E-3	OS	2.7 lb/gal	0.3 to 0.5	Post	—	—
		Dacamine	EC	3.6 lb/gal	0.45	Post	—	—
	Dicamba	Banvel	WS	4 lb/gal	0.25	Post	—	—
Soybean	Acifluorfen	Tackle Blazer	WS	2 lb/gal	0.5	Post	Oil or surfactant	8" to bud
	Bentazon	Basagran	WS	4 lb/gal	1 + 1 (twice)	Post	Crop oil	8" to bud
Sugarbeet	Clopyralid	Stinger	WS	3 lb/gal	0.3	Post	No	—
Dry bean	Bentazon	Basagran	WS	4 lb/gal	1 + 1 (twice)	Post	Crop oil	8" to bud
Pea	Bentazon	Basagran	WS	4 lb/gal	1 + 1 (twice)	Post	Crop oil	8" to bud
	MCPA	Thistrol	WS	2 lb/gal	1.0	Post	—	4 to 10" tall
Pasture	Bromoxynil	Buctril	EC	3 lb/gal	0.5	Post	—	—
		Buctril 4	EC	4 lb/gal	0.5	Post	—	—
	Chlorsulfuron	Glean	DF	75%	0.023	Post	Surfactant	—
	2,4-D	Dacamine 4D	EC	3.6 lb/gal	0.9	Post	—	—
		Weedar emulamine E-3	OS	2.7 lb/gal	0.38 to 2.7	Post	—	—
		Weedone	EC	3.8 lb/gal	1.9	Post	—	—
		Weedar 64	WS	3.8 lb/gal	0.9 to 1.9	Post	—	—
	Dicamba	Banvel	WS	4 lb/gal	1 to 2	Post	—	—
	Metsulfuron	Escort	DF	60%	0.03 to 0.06	Post	Surfactant	—
	Picloram	Tordon 22K	WS	2 lb/gal	0.5 to 1	Post	—	—

'ıble 21. *Continued.*

Crop	Herbicide	Trade name	Type[a]	Formulation concentration	Rate	Type of application[b]	Additives	Canada thistle[c]
Fallow	Atrazine	AAtrex 4L	EC	4 lb/gal	0.5 to 3	Post	—	—
		AAtrex 80W	WP	80%	0.5 to 3	Post	—	—
		AAtrex Nine-o	DWG	85.5%	0.5 to 3	Post	—	—
	Chlorsulfuron	Glean	DF	75%	0.023	Post	Surfactant	—
	2,4-D	Weedar 64	WS	3.8 lb/gal	1.0 to 3.0	Post	—	—
		Weedone	EC	3.8 lb/gal	0.5 to 1.0	Post	—	—
	Dacamine	EC	3.6 lb/gal	0.9 to 1.8	Post	—	—	
	Dicamba	Banvel	WS	4 lb/gal	1 to 2	Post	—	—
	Glyphosate	Roundup	WS	3 lb/gal	1.5 to 2.3	Post	Surfactant	—
	Metsulfuron	Ally	DF	60%	0.006	Post	Surfactant	—
	Picloram	Tordon 22K	WS	2 lb/gal	0.06 to 0.25	Post	—	—
Noncrop	Amitrole	Amitrol-T	WS	2 lb/gal	2 to 4	Post	—	Bud to bloom
	Atrazine	AAtrex 4L	EC	4 lb/gal	2 + 2 (twice)	Post	Oil	10t o 20" + 6"
		AAtrex 80W	WP	80%	2 + 2 (twice)	PPI	—	6" + 10 to 20"
		AAtrex Nine-0	WDG	85.5%	4	Pre/post	Oil	—
		Atrazine 4L	EC	4 lb/gal	4	Post	Oil	
		AAtrex 80W		80%	4	Pre	—	—
	Bromoxynil	Buctril	EC	2 lb/gal	0.5 to 1	Post	—	—
		Buctril 4E	EC	4 lb/gal	0.5 to 1	Post	—	—
	Chlorsulfuron	Telar	DF	75%	0.06 to 0.18	Post	Surfactant	—
	2,4-D	Weedar 64	WS	3.8 lb/gal	1.9 to 3.8	Post	—	—
		Weedone	EC	3.8 lb/gal	0.5 to 1.0	Post	—	—
		Weedar Emulsamine	OS	2.7 lb/gal	3.2 to 5.4	Post	—	—
		Dacamine 4D	EC	3.6 lb/gal	0.9 to 1.8	Post	—	—
	Dicamba	Banvel	WS	4 lb/gal	1 to 2	Post	—	—
		Trooper	WS	4 lb/gal	2 to 4	Post	—	—
	Dichlobenil	Casoran 4G	G	96%	75 to 200	Inc	—	—
	Glyphosate	Roundup	WS	3 lb/gal	1.5 to 2.3	Post	Surfactant	—
		Rodeo	WS	4 lb/gal	1.5 to 2.3	Post	Surfactant	—
	Hexazinone	Velpar	S	80%	6 to 12	Post	Surfactant	—
		Velpar L	WDG	2 lb/gal	6 to 12	Post	Surfactant	—
	Imazapyr	Arsenal	L	2 lb/gal	1 to 1.5	Post/pre	Surfactant	—
			G	99.5%	1	Pre	—	—
	Metsulfuron	Escort	DF	60%	0.004 to .008	Post	Surfactant	—
	Picloram	Tordon 22K	WS	2 lb/gal	2 to 3	Post	-	—
	Sulfometuron	Oust	DF	75%	0.4 to 0.75	Post	Surfactant	—
	Tebuthiuron	Spike	DF	85%	2	Post/pre	—	—

[a]DF = dry flowable; EC = emulsifiable concentrate; OS = oil soluble; S = solid; WDG = water-dispersable granule; WS = water-soluble; WP = wettable powder.
[b]Pre = preemergence; ppi = preplant incorporated; post = postemergence; inc = incorporated.
[c]Where two stages are presented: 1st stage of growth + 2nd stage of growth.

mixed with persistent herbicides such as simazine (6-chloro-*N,N'* - diethyl-1,3,5-triazine-2,4-diamine)[7].

Rates of amitrole that effectively control Canada thistle are high (2.2 to 9.0 kg ai/ha) and nonselective for most crops (Table 22). When applied to Canada thistle at the bud stage in July, amitrole at 2.2 kg ai/ha plus NH_4SCN did not provide adequate control but at 4.5 kg ai/ha Canada thistle density decreased to only half of what it was 1 yr earlier (148). But, in both South Dakota (58) and Montana (126), amitrole at 4.5 kg/ha plus NH_4SCN applied at the bud stage provided over 90% control 1 yr later. In Australian pastures, amitrole and NH_4SCN as a spot treatment (17) or at 2.2 kg/ha (213) provided poor control of Canada thistle, even when reapplied at the same site 2 yr in succession (213). In Maryland, amitrole at 2.2 to 4.5 kg/ha applied to emerging Canada thistle in late

[7]U.S. trade name is Amizone.

Table 22. Nonselective soil sterilants or residual herbicides for Canada thistle shoot control.

Herbicide	Rate	Duration of control	Reference
	(kg/ha)	(yr)	
Amitrole + NH_2SCN	4.5 to 9.0	2 to 3	(126)
	4.5	1 to 2	(126)
Ammonium sulfate	4.5 to 6.6	1	(59)
Arsenate, Ca & Na	—	—	(60)
Arsenic pentoxide	670 to 1010	—	(194)
Atrazine	22.4 to 44.8	1 to 2+	(126, 128)
Borax	13.4	3+	(59)
Carbon bisulfide	—	—	(139, 224)
Chlorate, Na	—	—	(139, 225, 255)
	—	—	(139)
	5.6	2 to 3	(59)
	1120	1	(126)
	670 to 1010	—	(194, 195)
2,4-D	2.2 to 4.5	1 to 2+	(126, 128)
	2.2 to 22.4	< 1	(126)
Dichlobenil	6.7 to 9.0	1+	(12)
Dicamba	1.1 to 22.4	—	(126, 128)
	1.1 to 22.4	2+	(126, 128)
	0.6 to 4.5	2+	(126, 128)
Diuron	0.8	3	(59)
Erbon	0.6 to 1.1	3	(59)
Fenac	2.8 to 11.2	1	(126, 128)
	4.5	2+	(126, 128)
Isocil	22.4	2+	(126, 128)
Fenuron	0.8	3+	(59)
	22.4 to 33.6	—	(126, 128)
	90	1 to 2	(126)
Linuron	22.4	<1	(126, 128)
MCPA	44.8	2+	(126, 128)
Monuron	—	—	(139)
	0.8	3+	(59)
	90	1 to 2	(126)
Picloram	0.6 to 10	—	(126, 128)
	0.6 to 4.5	2+	(126, 128)
Simazine	18	1 to 2	(126)
2,3,6 TBA	11.2 to 22.4	2+	(126, 128)
	11.2 to 33.6	1 to 2	(126)

May or early June before spring plowing provided only 70% control in corn in either the year of treatment or 1 yr later (193).

Inconsistent Canada thistle control with amitrole may be related to the growth stage when treated (59). Amitrole at 2.2 to 6.7 kg/ha controlled Canada thistle better 1 yr after application when sprayed at the bud stage rather than the spring rosette stage on noncropland in South Dakota. Repeated treatments were needed for long-lasting control in Montana (127).

The foliar penetration, translocation, and metabolism of amitrole in plants has been reviewed (47). Amitrole is readily absorbed by Canada thistle foliage (222). Leaves absorbed 96% of ^{14}C-amitrole after 12 h with little conversion to $^{14}CO_2$. Only 1 to 4% of the radiolabel could be washed from treated leaves. High relative humidity (95 versus 35%) enhanced herbicidal activity, presumably by enhancing foliar uptake (121).

Different Canada thistle ecotypes translocated radiolabel from ^{14}C-amitrole unequally, but root bud kill was unrelated to radiolabel transport (79). Herbicide uptake for 3 to 7 days was needed for root bud kill. Amitrole itself was translocated only in the light (119). But, an unidentified nonglucose conjugate of amitrole apparently was translocated in both the light and dark and was phytotoxic when it was reapplied to Canada thistle foliage.

Intact seedlings and excised leaves of Canada thistle metabolized ^{14}C-amitrole to three uncharacterized metabolites (119, 120). One metabolite was phytotoxic and more damaging to Canada thistle than amitrole itself. However, Carter (47) could not duplicate this early research and considered it to be an artifact. Amitrole was metabolized 10 to 15% more in light than in darkness over 48 h (223). However, leaves in light were warmer than those in darkness and increasing temperature (15.5 to 27.5

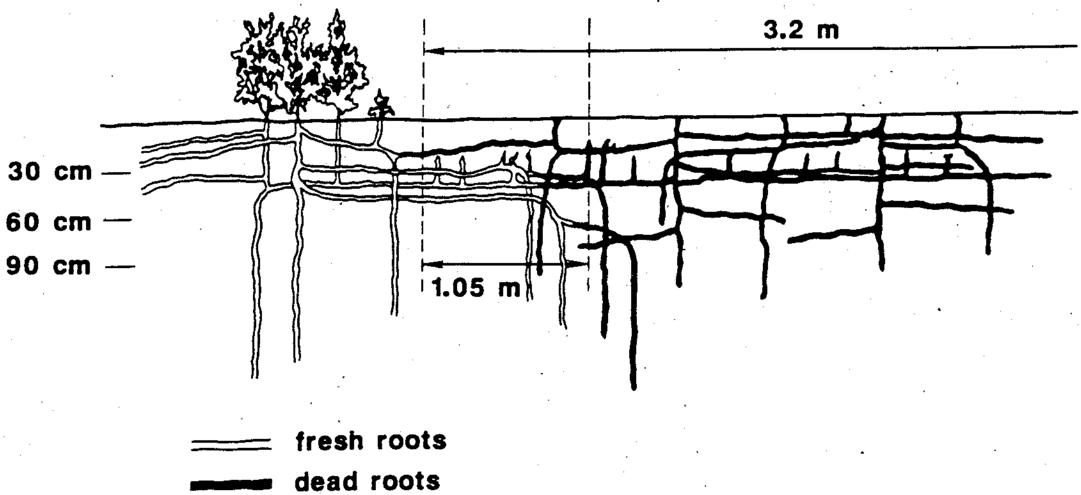

Figure 9. Canada thistle root distribution in the soil profile 12 months after treatment with sodium chlorate at 1000 kg/ha. The treated area was 3.2 m wide. Roots were dead (black) 90 cm deep in the center of the plot, but only 28 cm deep 1.05 m in from the border of the plot. Fresh roots grew 1.05 m into the plots under the sterile, chlorate-treated soil zone near the border and produced new shoots which were killed as they entered the treated soil zone (194).

C) increased amitrole metabolism and phytotoxicity. Because NH_4SCN inhibited amitrole metabolism, it was presumed to enhance foliar phytotoxicity to Canada thistle.

Glyphosate. Glyphosate[8] is a nonselective postemergence-applied herbicide that is currently registered for Canada thistle shoot control at 0.8 to 2.5 kg ae/ha and is applied either at or after the bud stage or in the late summer and fall before a killing frost. There are no published reports concerning minimal doses that prevent seed production.

Researchers have attempted to define which growth stage of Canada thistle should be sprayed with glyphosate for best residual control a year after treatment. Because emergence of Canada thistle's adventitious shoots is protracted in spring, glyphosate applied early preplant does not control all shoots or completely prevent shoot emergence later (138, 139). Adventitious shoots failed to emerge one season after 60-cm tall Canada thistle was sprayed at the flower bud stage in an English orchard (25). Although late fall treatments have not been contrasted with earlier application times, residual control with glyphosate was best when plants were sprayed at the late bud or flowering stages compared to earlier times (25, 50, 138, 249).

The bud stage was suggested to be more susceptible to control measures than other stages in the Canada thistle life cycle as early as 1947 (26) because soluble root carbohydrates were lowest at budding. In Nebraska, control was excellent (≥ 90%) one growing season following treatment with glyphosate at 0.6 kg ae/ha at the flower bud stage in either early August or early September (Figure 10), regardless of whether plants were water stressed or not (149). Glyphosate reduced root length to 36 and 59% of control values in two separate years (Figure 11); reductions were observed throughout the soil profile 90 cm deep. But glyphosate at 2.8 kg ae/ha (with surfactant) provided only 75% shoot control 1 yr after an August application on a noncropland site in another study (63). In Canada, glyphosate applied at 1.0 or 1.5 kg ae/ha to Canada thistle at the bud stage reduced densities 75% 1 year after application (185).

In England, glyphosate at 1.4 to 2.2 kg ae/ha controlled new adventitious shoot growth for at least 1 yr when Canada thistle was sprayed in ripe wheat (30% moisture content) just prior to harvest (57, 181). Grain dry matter content was unaffected when applications were timed properly. Such preharvest applications may allow treatment at the susceptible late bud stage and may permit direct combining in the Northern Great Plains, in lieu of swathing, allowing more timely harvesting. As O'Keefe (181) pointed out, preharvest treatment improves harvesting efficiency and reduces harvested grain moisture, thereby decreasing both drying and cleaning costs.

When Canada thistle roots were unearthed 2 months following preharvest treatment with

[8]U.S. trade name is Roundup.

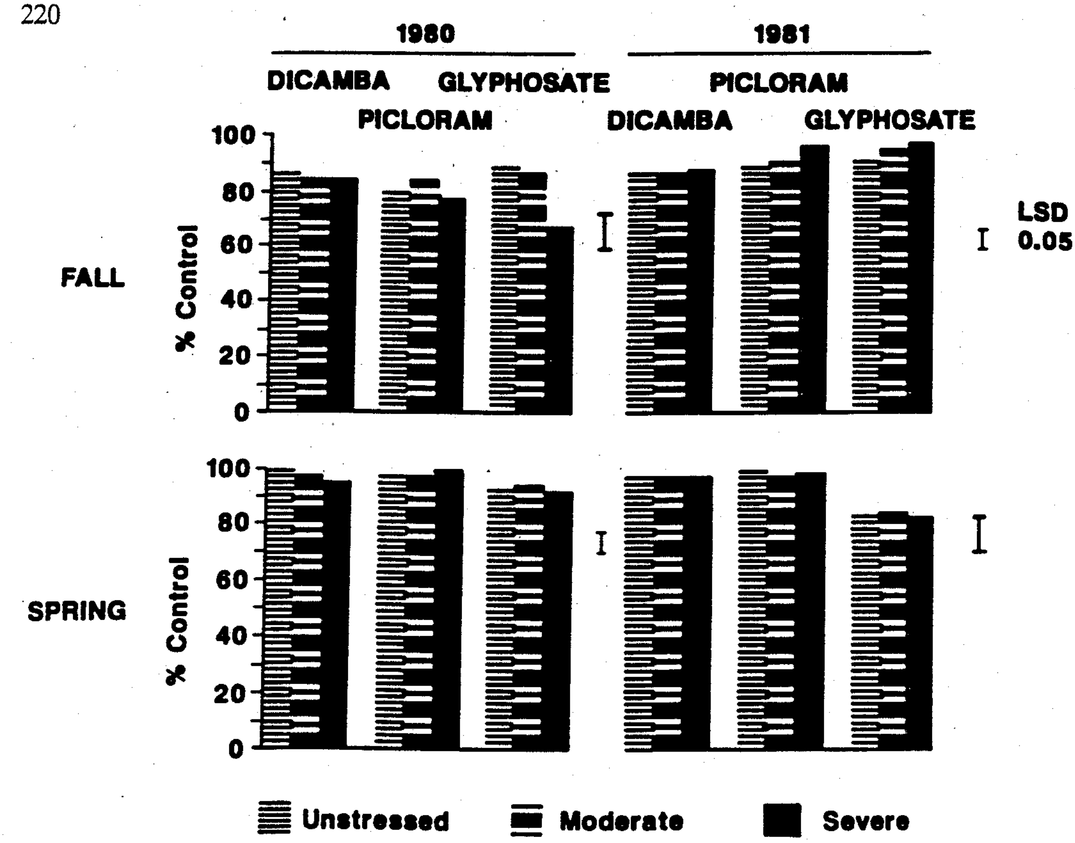

Figure 10. Control of Canada thistle in fallow on September 24, 1980, and June 6, 1981, following herbicide application on August 5, 1980; control of Canada thistle on October 9, 1981, and June, 1982, following herbicide application on September 9, 1981, in Nebraska. Dicamba, glyphosate, and picloram were applied at 1.1, 0.6, and 2.5 kg ae/ha, respectively. LSDs at P = 0.05 are presented for each evaluation. Progressive water stress was induced in different plots by providing various levels of irrigation throughout the growing season. (149; reprinted with the permission of the Weed Science Society of America).

glyphosate at 1.4 kg ae/ha and were segmented, new adventitious shoot emergence was almost totally inhibited (57). Preharvest treatments are not registered now in the United States. In the Northern Great Plains, Canada thistle often cannot be sprayed immediately after cereal swathing in August because there is too little foliage remaining on the basal part of the plant for adequate spray absorption. Cereals also are swathed close to the ground, removing basal leaves.

Enough time must elapse between harvest, mowing or clipping,and later spraying for new adventitious shoots to emerge and grow enough in the fall to intercept the herbicide spray. Two weeks was too short a period for adequate adventitious shoot growth after clipping when glyphosate at 1.7 or 2.5 kg ae/ha was applied to Canada thistle-infested wheat stubble (30). But residual control 1 yr after treatment was equally good (>80%) whether 4 or 9 weeks elapsed between clipping and spraying.

Enough time also must elapse between spraying and later tillage to allow a phytotoxic dose of glyphosate to be translocated from the Canada thistle foliage to the roots. In Canada, rototilling Canada thistle infested soil 4 weeks after late August treatment with glyphosate at 1.1, 2.2, or 4.5 kg ae/ha (without surfactant) improved residual adventitious shoot control in the following growing season (249). In contrast, tillage did not improve later shoot control when glyphosate was applied in summer fallow in Canada (138). The U. S. registration label suggests a minimum interval of 3 days between spraying and tillage to allow basipetal translocation of glyphosate to the roots.

In the greenhouse, when glyphosate at 0.28 kg ae/ha was applied to well-rooted, potted Canada thistle, enough herbicide translocated to the roots between 2 and 3 days after treatment to inhibit subsequent adventitious shoot growth (142). However, 3 days was inadequate for glyphosate to translocate through the interconnected roots from sprayed to untreated shoots

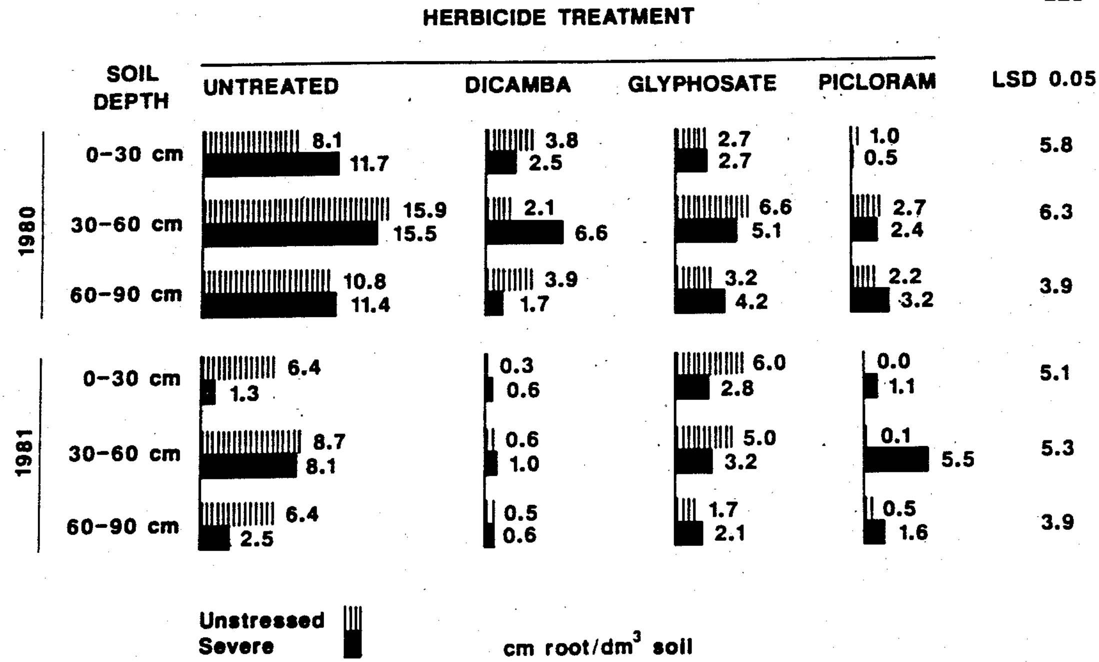

Figure 11. Canada thistle root length (cm/dm^3) observed after excavation at various depths of soil in June, 1981, and June, 1982, following sequential herbicide application in August, 1980, and September, 1981, respectively. Dicamba, glyphosate, and picloram were applied at 1.1, 0.6, and 2.5 kg/ha, respectively, in Nebraska. Water stressed plots were not irrigated whereas unstressed plots were irrigated (149; reprinted by permission of the Weed Science Society of America).

in an untilled field, as measured by death of neighboring, untreated shoots (31).

Fall-applied glyphosate effectively controlled adventitious shoot emergence of Canada thistle for one growing season in some studies (22, 45, 72, 151) but not in others (93). In South Dakota, glyphosate applied at 1.1, 2.2, or 4.5 kg ae/ha in late September on cropland provided better control of later emerging shoots than treatment in mid-June (22). In Idaho, fall-applied glyphosate at 2.2 to 4.5 kg ae/ha prevented adventitous shoot emergence for 9 months in an untilled juniper (*Juniperus communis* L.) nursery (45).

Repeated fall-applied glyphosate was not advantageous for Canada thistle eradication in either Michigan (210) or North Dakota (45). Even glyphosate at 1.7 kg ae/ha applied once in late September provided control for only a limited period; enough new adventitious shoots emerged 2 (45) or 3 yr later (210) to require control. Sandberg et al. (210) suggested that glyphosate induced "dormancy" of root buds which ended 2 to 3 yr after treatment. However, Carlson and Donald (45) showed that glyphosate reduced root biomass and root bud number at a depth of 90 cm in the year following one late-fall treatment. Root biomass was reduced further by two annual late-fall applications of glyphosate but the decrease was not great enough to prevent later reestablishment of the surviving weed from adventitious root buds.

These observations in spring wheat substantiate earlier rated control in corn following 2 yr of late-fall (mid- to late October) glyphosate treatment at 2.2 kg ae/ha (251). However, visually evaluated residual control was not followed for more than one growing season after the last application and no in-crop herbicides were applied other than cyanazine {2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl] amino]2-methylpropanenitrile} at 3.4 kg ai/ha. Reductions in root length also were noted to a depth of 90 cm one growing season after spraying Canada thistle in the flower bud stage with glyphosate at 0.6 kg ae/ha (149). Late fall-applied glyphosate is especially useful for Canada thistle control in spring-sown crops which lack effective registered herbicides for controlling this weed. Dicamba and clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) could be used for this purpose as well, assuming rotational crops tolerate residues of either herbicide.

Glyphosate applied to Canada thistle by rope-wick growing in white clover failed to control shoot emergence 1 yr after application (170). A

1:2 dilution of glyphosate:water (v/v) was employed and the applicator was operated at 2 km/h 15 cm above the pasture. Boerboom and Wyse (35) suggested that an insufficient dose of glyphosate was applied to Canada thistle shoots by ropewick treatment. In their research, Canada thistle shoot control improved 1 month and 1 yr after glyphosate application by ropewick or roller (36 or 120 g ae/L) as the number of passes was increased over Canada thistle-infested birdsfoot trefoil (*Lotus corniculatus* L.). A single pass did not provide either short- or long-term control, but a double pass prevented shoot emergence for at least 1 yr.

The foliar absorption, translocation, and metabolism of glyphosate in Canada thistle has been studied using radiolabeled herbicide (104). Foliar retention of glyphosate on Canada thistle has not been reported. Most researchers converted the acid of ^{14}C-glyphosate to its isopropylamine salt and added various surfactants before microdrop application in order to enhance foliar uptake (103, 185, 211) and to adequately simulate field spraying. Surfactants enhanced both glyphosate phytotoxicity and foliar absorption (103). The fate of ^{14}C-glyphosate in small Canada thistle plants with fibrous roots was studied in the greenhouse or growth chamber, with one exception (165). Small plants are unlikely to have root and root bud "sinks" large enouth to be comparable to field-grown plants. The ecotypes or subspecies used in these experiments were not identified despite known differences in subspecies' response to glyphosate in the field (Table 10) (209); reportedly, the 'horridum' subspecies was much more sensitive to glyphoste than the 'arvense (mite)' subspecies.

In several studies, percent recovery of radiolabel was not reported (149, 211), or was low (< 80%), or was variable between treatments (103, 165, 185). Reporting of results also has been nonuniform and included percent of applied, percent of all recovered (without presenting total percent recovery), and dpm/mg. The latter expression can be misleading if the herbicide treatment alters tissue dry weight differently in different plant parts or if plant part dry weights are not presented. In few instances have plants been sprayed with formulated unlabeled glyphosate in addition to single-leaf treatment with microdrops of ^{14}C-herbicide. This critique of published methodology applies to research on other ^{14}C-herbicides on Canada thistle, as well.

Reports of foliar absorption of ^{14}C-glyphosate by Canada thistle are conflicting. Sandberg et al. (211) observed that 14- to 18-cm-tall vegetative plants absorbed only 6.8 to 7.8% of applied radiolabel between 1 and 14 days after treatment. O'Sullivan and Kossatz (185) reported 43% uptake in 24 h with little further uptake at 72 h. Uptake in these studies did not increase over time as it did over 7 days research by Gottrup et al. (103). At high (unreported) relative humidity ^{14}C-glyphosate on the leaf surface decreased from 60 to 18% between 12 h and 7 days after treatment (103). This radiolabel was absorbed, presumably, because recoveries remained constant and glyphosate is neither volatile nor photodecomposed (104). The reasons for these conflicting reports of ^{14}C-glyphosate uptake are unknown.

Glyphosate concentration, surfactant concentration, and droplet size interact to modify ^{14}C-glyphosate uptake, translocation, and phytotoxicity to potted Canada thistle at the bud stage (32, 34). When two adjacent leaves halfway up the stem were treated with various concentrations of glyphosate (9 to 108 μg/μl) and MON 0818 surfactant (4.5 or 54 μg/μl) holding the dose per plant constant (432 μg/plant), 2 μl droplets with low glyphosate (9 to 18 μg/μl) and surfactant levels were more phytotoxic to shoots and prevented regrowth better than more concentrated droplets. The authors suggested that high glyphosate concentration may damage the phloem locally, limiting glyphosate movement to the roots.

Greenhouse or growth chamber research on ^{14}C-glyphosate translocation in Canada thistle following foliar treatment is summarized (Table 23). In all studies, more radiolabel moved into the rest of the shoot, excluding the treated leaf, than moved into the roots following foliar application. The amount reaching the roots ranged from 5% of that recovered after 8 days (165) to 33% of that recovered after 14 days (211). Movement to daughter shoots was significant (38% of that recovered after 14 days) in the one study in which it was determined (211). Apparently, untreated growing shoots can act as sinks for ^{14}C-glyphosate applied to other shoots, supporting field observations of visible damage (31).

Increasing amounts of radiolabel moved to the roots between 1 to 7 days (103), 3 to 14 days (211), or 1 to 3 days (185) after treatment. However, shoots of plants treated with over-the-top sprays of phytotoxic doses of glyphosate died in 7 to 14 days, depending upon dose (44). Surfactant (Tween 20 at 0.5% v/v) enhanced ^{14}C-glyphosate uptake into leaves at low and high relative humidity, but did not increase

Table 23. ^{14}C-glyphosate translocation in Canada thistle following foliar application (adapted by the permission of the Weed Science Society of America and Blackwell Scientific Publications, Ltd.).

Study	Time	Plant part	Radiolabel	Reference
1[a]	1 day	Rinse	34	(102)
		Treated leaf	43	
		Shoots	12	
		Roots	11	
	2 days	Rinse	53	
		Treated leaf	26	
		Shoots	13	
		Roots	9	
	7 days	Rinse	18	
		Treated leaf	33	
		Shoots	30	
		Roots	19	
2	3 days	Shoots	62[b]	(211)
		Daughter shoots	17	
		Roots	22	
	14 days	Shoots	29	
		Daughter shoots	38	
		Roots	33	
3	1 day	Treated leaf	23	(185)
		Apex	10	
		Shoot	10	
		Root	0.4	
	2 days	Treated leaf	52	
		Apex	17	
		Shoot	17	
		Root	13	
	3 days	Treated leaf	47	
		Apex	20	
		Shoot	18	
		Root	15	
4	8 days	Treated leaf	77	(165)
		Apex	4	
		Shoot	14	
		Root	5	
			(dpm/mg dry tissue)	
5[c]	1.7 days (unstressed)	Treated leaf	69	(149)
		Apex	42	
		Shoot	11	
		Root tip	20	
	1.7 days (stressed)	Treated leaf	20	
		Apex	12	
		Shoot	12	
		Root tip	3	

[a]Data for high humidity plus surfactant treatment.
[b]Data said to be reported as % of applied by the authors, but it must have been expressed as % of recovered.
[c]Water stress versus unstressed plants.

translocation to roots at either relative humidity (103). Short-term water stress (−20.1 vs. −4.3 bars leaf water potential) reduced accumulation of ^{14}C-glyphosate in root apices of Canada thistle but did not influence total root radiolabel concentration (Table 23) (149).

Metabolites of ^{14}C-glyphosate have not been isolated from treated Canada thistle in major amounts (103, 211). Only thin layer chromatography has been used to separate and tentatively identify glyphosate from aminophosphonic acid, glycine, and sarcosine, the presumed metabolities. Samples were analyzed 1 week (103, 211) to 3 weeks (211) after foliar treatment. When only microdrops of ^{14}C-glyphosate were applied to otherwise unsprayed plants, total radiolabel decreased over 30 days, presumably by mineralization of the herbicide (211). Whether radiolabel would be gradually lost over such a long time if plants were sprayed with a phytotoxic dose of glyphosate is uncertain.

Foliar uptake, translocation, and metabolism are most directly studied using radioisotopes, but the response of Canada thistle to a herbicide can only be studied by bioassay. For example, when foliarly applied at 0.28 kg ae/ha in the greenhouse, glyphosate totally prevented adventitious shoot growth from root buds to zero between 2 and 3 days after treatment (44). This was measured by harvesting roots and washing them from soil before segmenting them to study later adventitious shoot growth. Adventitious shoot dry weight and number were reduced to zero 5 weeks after only 2 and 3 days uptake of glyphosate, respectively, even though root fresh weight was unchanged 3 days after foliar treatment. Thus, a phytotoxic dose moved to the roots shortly after treatment. When glyphosate-treated shoots were cut off at intervals after treatment in the field, enough herbicide moved through connected roots to injure shoots of neighboring, untreated plants in only 3 or 4 h (31). Shoots in a circular area were affected 30 cm from individual treated shoots and 122 cm from the edge of a sprayed nursery. It took 10 to 14 days for untreated affected shoots to be killed.

Phenoxy Herbicides. Canada thistle control with 2,4-D has been erratic despite its initial promise. By the late 1040s, researchers recognized that a single phenoxy application would be insufficient for long-term control (26). The time of spraying during the Canada thistle life cycle (109) and differences in ecotypic response (Table 10) may be responsible for unpredictable control. On a tilled site in Montana, nine ecotypes of Canada thistle collected from Montana, Wyoming, and Idaho survived 43 to 65% following 2,4-D at 1.7 kg ae/ha applied in June (129). Also, ester formulations were more phytotoxic to Canada thistle shoots than were amine formulations (26).

The highest U. S. registered rate for 2,4-D use on wheat is now 0.6 kg ae/ha. Unfortunately, the 2,4-D formulation used, the treatment time, the Canada thistle growth stage at the time of treatment, and the time between treatment and observation often were not reported in early research (129). In related research initiated on 2-yr-old stands of the same Canada thistle ecotypes, 2,4-D at 1.7 kg ae/ha reapplied to the same plots for 3 yr controlled adventitious shoot emergence better when applied at the bud stage than at the bloom stage (127) (Table 24). Only one of nine ecotypes was controlled better at the bloom than at the bud stage. After 3 yr, shoot survival in June ranged from 38 to 95% (averaging 65%) when ecotypes were treated with 2,4-D at the bud stage, but only 22 to 75% (average 43%) when sprayed at the bloom stage. The artificially established stands in both studies were considered "heavy", but densities were not reported, only percentage change. It is unknown whether susceptibility to 2,4-D or any other control method depends on stand density, but sparser stands are likely to be more susceptible to herbicides than dense stands because they are likely to be less well established. Control would probably have been better if Canada thistle had been treated with 2,4-D while competing with a crop.

Other research supports the contention that 2,4-D applied repeatedly for several years suppresses Canada thistle adventitious shoot emergence better when applied at the bud stage than earlier or later (Table 25). 2,4-D isopropyl ester applied at 1.3 to 4.0 kg ae/ha at the bud stage to the same noncropped plots over 4 yr gradually reduced Canada thistle stands (202). Reapplication of the same rates to other plots at the bloom and mature seed stage was much less effective and rates greater than 1.3 kg/ha were not advantageous.

Table 24. Response of Canada thistle ecotypes to three annual 2,4-D retreatments at 1.7 kg ea/ha (1959 to 1962) on a noncropland site in Montana (127; adapted with the permission of the Weed Science Society of America).

	Percent survival of Canada thistle after herbicide treatments[a]	
Ecotype[b]	Bud stage	Bloom stage
	(%)	
A1	60 b-c	75 b
G1	52 c-g	95 a
G4	75 b	64 b-d
G3	35 g-m	67 bc
LW	39 e-k	58 b-f
FM	22 i-n	79 ab
F1	36 g-l	66 bc
G2	45 d-h	38 f-l
PW	30 h-n	53 c-g
YM	33 g-m	52 c-g
Means	43 x	65 z

[a]Data are averages of four replications for 4 yr of each ecotype and treatment. Numbers with different letters differ as determined by Duncan's multiple range test at P = 0.05.

[b]The ecotypes were designated by letters and numbers according to place of origin as follows: A1, Ada County, ID; G1, G2, G3, G4, Gallatin County, MT; LW, Laramie, WY; FM, Fergus County, MT; F1, Fremont County, ID; PW, Prosser, WA; YM, Yellowstone County, MT.

Even when Canada thistle was treated with 2,4-D at recommended rates and stages, additional control measures generally were needed 1 yr later to prevent crop losses (25). 2,4-D is unlikely to replace repeated cultivation in summer fallow for Canada thistle control in the following growing season (91, 98, 135, 151, 175).

2,4-D can delay and reduce flowering of Canada thistle, except when applied too early (100). When applied at the late bud stage, 2,4-D at 0.6 kg ae/ha or greater prevented flowering (58, 105). Lower rates were ineffective.

Canada thistle control requires a concerted management program over several years if well-established Canada thistle roots are to be eliminated (58, 59, 124, 126, 168). In only one instance has repeated use of phenoxy herbicides been shown to prevent Canada thistle from encroaching on uninfested land (201). In Germany, MCPA or 2,4-D as dimethylamine salts prevented encroachment of Canada thistle when applied yearly for 10 yr to separate plots in a continuous cereal rotation of winter wheat, oats, winter rye (*Secale cereale* L.), and barley. Canada thistle density increased where MCPA was applied only once every 4 yr and other less effective herbicides were applied in other years. No data are available on the use of other herbicides to prevent Canada thistle encroachment, even as periodic treatments. However, 2,4-D treatment killed newly emerged seedlings (168).

In Montana, the density of established stands of Canada thistle decreased when 'Thatcher' spring wheat was sprayed with 2,4-D at 0.8 kg ae/ha and fertilized with nitrogen (with or without 56 kg/ha) for 3 yr, although 4 yr were needed for eradication (124, 126) (Table 18). Canada thistle density decreased when 2,4-D was applied in the absence of a crop but more slowly than when competing with spring wheat. Because Canada thistle stands increased when wheat was fertilized with nitrogen, but not sprayed, Hodgson (124) did not consider spring wheat to be a good "smother" crop. Canada thistle densities increased more rapidly in unsprayed spring wheat which was fertilized than in unfertilized plots. Spring wheat yields were inversely related to Canada thistle density.

Long-term studies of Canada thistle control with 2,4-D in irrigated spring wheat in Idaho (168) did not verify all of Hodgson's observations (124, 126) (Table 18). However, much

Table 25. The relative efficacy of 2,4-D reapplied for several years at various growth stages of Canada thistle on control (adapted with the permission of the Weed Science Society of America).

Treatment	Rate	Canada thistle Stage	Canada thistle Density	Crop	Year	Units	Reference
	(kg/ha)					(% survival)	
2,4-D	1.7	Bud	Dense	None	1	72 b	(127)
					2	59 c	
					3	31 de	
					4	9 g	
		Bloom	Dense	None	1	89 a	
					2	85 a	
					3	55 c	
					4	30 de	
						(% cover)	
2,4-D as isopropyl ester	1.3	Bud	Dense	None	2	78	(202)
					3	31	
					4	6	
		Bloom	Dense	None	2	86	
					3	40	
					4	12	
		Mature	Dense	None	2	157	
					3	108	
					4	13	
	2.6	Bud		None	2	74	
					3	39	
					4	3	
		Bloom		None	2	84	
					3	74	
					4	8	
		Mature		None	2	182	
					3	143	
					4	19	
	4.0	Bud		None	2	61	
					3	27	
					4	4	
		Bloom		None	2	124	
					3	44	
					4	6	
		Mature		None	2	188	
					3	74	
					4	13	
						(% control)	(46)
2,4-D	0.56	Vegetative		Corn	1	38 h-k	
					2	81 a-h	
					3	100 a	
		Bud		Corn	1	76 b-h	
					2	88 a-h	
					3	93 a-f	
						(bu/A)	
2,4-D as propylene glycol butyl ester	0.8	Vegetative		Wheat	1	28	(126)
		Early Bud			1	24	
		Late bud			1	20	
	1.1	Vegetative		Wheat	2	44	
		Early bud			2	44	
		Late bud			2	41	
		Bloom			2	36	

higher than registered rates of 2,4-D were used in this Idaho study (2.2 to 3.4 kg/ha) (168) than in the Montana study (1.1 kg ae/ha) (123, 124, 126). 2,4-D alone was much less effective for long-term control in unfertilized wheat than wheat fertilized each year with 90 kg/ha nitrogen (168). Under irrigation, nitrogen increased the competitiveness of spring wheat, but Canada thistle control gradually increased to acceptable levels when 2,4-D was applied in-crop over 4 yr without N fertilization.

Fertilized wheat was somewhat more competitive with Canada thistle than unfertilized wheat as judged by control ratings in this study

(168), in contrast to Hodgson's study (126); however, control was not total even after 4 yr of repeated treatments. The differences between these two studies may reflect the different criteria used to measure control (shoot density versus visual evaluation) or the influence of irrigation on Canada thistle growth.

In a 3 yr oat-corn-flax (*Linum usitatissimum* L.) rotation in South Dakota, long-term reductions in Canada thistle density were achieved most quickly by combinations of fall moldboard plowing, postharvest field cultivation, and in-crop treatment with 2,4-D (59) (Table 26). There were several alternative combinations of control measures that reduced Canada thistle stands equally well. In-crop treatments with phenoxy herbicide plus various kinds of fall tillage were superior to other treatments for killing shoots and preventing seed production. For example, fall moldboard plowing enhanced the effectiveness of 2,4-D applied in early June in first-year oats.

While 2,4-D is registered for use in corn, treatment of Canada thistle at the bud stage allows 6 to 10 weeks of competition (46). The recommended application time for Canada this-

Table 26. Percentage Canada thistle control by use of adapted annual crops, cultivation and 2,4-D (mean of two 3-year experiments) (59; adapted by permission of the Weed Science Society of America).

	First year		Second year		Third year[a]
Trt. No.	Treatment[b]	Control	Treatment[c]	Control	Control
		(%)		(%)	
1	Untreated	30	Untreated	88	100
2	Untreated	30	2,4-D 6/20	0	95
3	Untreated	30	2,4-D 6/20 & 8/20	84	100
4	Untreated	30	2,4-D 6/20 & silage	82	98
5	Plow 10/15	54	Repeat 1st yr	66	50
6	Plow 10/15	54	2,4-D 6/20	50	95
7	Plow 10/15	54	2,4-D 6/20 & 8/20	92	100
8	Plow 10/15	54	2,4-D 6/20 & silage	52	97
9	2,4-D 8/25	79	Repeat 1st yr	97	100
10	2,4-D 8/25	79	2,4-D 6/20	41	85
11	2,4-D 8/25	79	2,4-D 6/20 & 8/20	96	100
12	2,4-D 8/25	79	2,4-D 6/20 & silage	83	99
13	2,4-D 8/25, plow 10/15	89	Repeat 1st yr	100	100
14	2,4-D 8/25, plow 10/15	89	2,4-D 6/20	33	99
15	2,4-D 8/25, plow 10/15	89	2,4-D 6/20 & 8/20	92	98
16	2,4-D 8/25, plow 10/15	89	2,4-D 6/20 & silage	97	100
17	Plow 8/11, cult. 9/5 & 9/25	88	Repeat 1st yr	100	100
18	Plow 8/11, cult. 9/5 & 9/25	88	2,4-D 6/20	62	92
19	Plow 8/1, cult. 9/5 & 9/25	88	2,4-D 6/20 & 8/20	95	100
20	Plow 8/11, cult. 9/5 & 9/25	88	2,4-D 6/20 & silage	87	98
21	Plow 8/11, cult. 9/5 & 9/25	88	Cult., sudan, plow	99	99
22	Plow 8/11, cult. 9/5 & 9/25	88	2,4-D 6/20	62	99
23	Plow 8/11, cult. 9/5 & 9/25	88	2,4-D 6/20 & 8/20	95	99
24	Plow 8/11, cult. 9/5 & 9/25	88	2,4-D 6/20 & silage	87	97
25	Plow 8/11, cult. 9/5, 9/25 & 10/15	83	Repeat 1st yr	98	99
26	Plow 8/11, cult. 9/5, 9/25 & 10/15	83	2,4-D 6/20	49	99
27	Plow 8/11, cult. 9/5, 9/25 & 10/15	83	2,4-D 6/20 & 8/20	97	100
28	Plow 8/11, cult. 9/5, 9/25 & 10/15	83	2,4-D 6/20 & silage	77	100
29	Plow 8/11, 2,4-D 9/25	88	Repeat 1st yr	98	100
30	Plow 8/11, 2,4-D 9/25	88	2,4-D 6/20	76	93
31	Plow 8/11, 2,4-D 9/25	88	2,4-D 6/20 & 8/20	98	100
32	Plow 8/11, 2,4-D 9/25	88	2,4-D 6/20 & silage	89	97
33	Plow 8/11, 2,4-D 9/15, cult. 10/15	92	Repeat 1st yr	99	100
34	Plow 8/11, 2,4-D 9/15, cult. 10/15	92	2,4-D 6/20	90	99
35	Plow 8/11, 2,4-D 9/15, cult. 10/15	92	2,4-D 6/20 & 8/20	99	98
36	Plow 8/11, 2,4-D 9/15, cult. 10/15	92	2,4-D 6/20 & silage	81	100

[a]All plots except 21, 22, 23, 24 repeated the first year's treatment; those four plots grew flax, treated with 0.84 kg ae/ha MCPA.

[b]Oats seeded on all plots April 20; 0.84 kg ae/ha of alkanolamine salt of 2,4-D applied on all plots on June 7; plowing on moldboard plow and cultivation with duckfoot cultivator on dates indicated.

[c]Three-fourths of treatments included corn planted June 5, sprayed with 0.84 kg ae/ha of alkanolamine salt of 2,4-D on dates indicated and cultivated 3 times. In other treatments oats was seeded April 20 on Piper sudangrass was seeded June 20 after 2 cultivations. Silage and sudangrass hay were harvested the first week in September and fall plowed.

tle control in corn is much earlier than this according to the U. S. registration label. 2,4-D or MCPA were considered less effective on Canada thistle growing in corn than in cereals (58), but this opinion was not substantiated. The influence of crop species on the relative effectiveness of Canada thistle herbicides has not been studied. Two yr of fall-applied phenoxy herbicides followed by in-crop retreatment in continuous corn provided high levels of control (251). 2,4-D ester or amine at 1.1 kg ae/ha in the fall followed by in-crop treatment with the same formulation provided 97 to 100% control by the 3rd growing season. Similar treatment with MCPA was much less effective (79%) at the end of the second growing season.

Phenoxy herbicides, including 2,4-D, 2,4-DB [4-(2,4-dichlorophenoxy) butanoic acid], MCPA, MCPB [4-(4-chloro-2-methylphenoxy)butanoic acid], and mecoprop [(±)-2-(4-chloro-2-methylphenoxy)propanoic acid], have been tested for Canada thistle control in pastures for several years. The pasture species determines which phenoxy herbicide can be used (7). 2,4-D and MCPA are used on grass pastures, whereas 2,4-DB and MCPB are used on small-seeded legume pastures either seeded alone or with companion grass species. The alkanolamine formulation of 2,4-D at 0.8 to 1.7 kg ae/ha did not control Canada thistle as well as the propylene glycol butyl ether ester applied at the same rates in a timothy and red clover pasture when reapplied to the same plots over 3 yr (200). Even though there were differences in control rating and Canada thistle density after 3 yr of 2,4-D treatment, residual differences between formulations were not observed in soybeans [*Glycine max* (L.) Merr.] grown on the treated plots after 4 yr of pasture treatment. Again, several years of phenoxy retreatment are needed for Canada thistle suppression (7, 17, 113, 123, 124, 126, 213, 214).

An attempt was made to improve the selectivity of MCPA in birdsfoot trefoil by using ropewick or roller applicators for treating Canada thistle shoots (35). However, neither short- nor long-term control was achieved when shoots at the bud stage were treated with MCPA (48 and 160 g/L) in early July.

Repeated use of phenoxy herbicides on Canada thistle in pastures was ineffective for long-term control (Table 27). Despite the reputation of alfalfa and/or pasture as so-called "smother crops" for Canada thistle control, their use with or without phenoxies provided disappointing levels of residual control after 3 to 4 yr (214). In fact large decreases in Canada thistle stand in the absence of control measures were observed in some research (17, 124, 214). Perhaps, short-term climatic effects, such as drought, were responsible for such changes (45). Decreased Canada thistle stands were frequently accompanied by increased forage production (17, 124, 126, 200, 214) as measured by forage density, percent forage cover, yield, or animal production (113).

Natural forage stand thinning over time may reduce the ability of some small-seeded legumes, such as alfalfa, to compete with Canada thistle (124, 126, 214), reducing long-term Canada thistle control. Hodgson (126) suggested rotation to alternative crops to prevent Canada thistle reinvasion.

Mowing provided better long-term control of Canada thistle than repeated use of phenoxy herbicides in forages (17, 214). The relative success of mowing a timothy and red clover pasture in Australia either with or without MCPB at 2.2 kg ae/ha for Canada thistle control depended on the timing and frequency of either mowing or phenoxy herbicide application (17). Infrequent mowing or infrequent MCPB application at 1.5 kg ae/ha was less effective in controlling Canada thistle in mixed pastures in New Zealand than was more frequent treatment (113). MCPB at 1.5 kg ae/ha, MCPA at 1.0 kg ae/ha, and MCPB plus MCPA at 1.0 plus 0.33 kg ae/ha did not provide residual Canada thistle control 1 yr after treatment in a New Zealand white clover pasture, whether the pasture was mowed or not mowed (170). 2,4-D butyl ester at 1.12 kg ae/ha failed to control Canada thistle in red fescue (*Festuca rubra* L.) grown for seed in Canada beyond the season of application even when applied at the bud stage (100). Harvesting would have been relatively late for a red fescue seed crop compared to normal forage mowing, permitting Canada thistle to grow and compete longer. Red fescue was undamaged by 2,4-D.

Relatively little is known about how environment influences Canada thistle control with 2,4-D. Increasing temperature from 16 to 32 C enhanced 2,4-D phytotoxicity to Canada thistle shoots (153) and roots (52, 136). 2,4-D at 1.12 kg ae/ha reduced root dry weight of 5-week-old potted plants 46 to 88%, depending on ecotype (136). Low temperatures delayed and reduced foliar phytotoxicity from 2,4-D (153). When plants were sprayed in high light, foliar necrosis was greater than when shaded plants were treated in the field (76). Erickson et al. (76) suggested that rapid foliar necrosis prevented herbicide

Table 27. The efficacy of phenoxy herbicides reapplied for up to 5 yr for Canada thistle control in pasture (adapted by the permission of the Weed Science Society of America and Blackwell Scientific Publications, Ltd.).

Pasture	Herbicide	Rate	Year	Canada thistle		Refer-ences	
		(kg ae/ha)		(% control)	(% survival)	(no./m²)	
Grass in Montana	2,4-D as propylene glycol butyl ether ester for 4 yr	0.8	1	—	100	—	(124)
			2	—	13	—	
			3	—	3	—	
			4	—	0.1	—	
	2,4-D without a crop for 4 yr	0.8	1	—	100	—	
			2	—	29	—	
			3	—	49	—	
			4	—	39	—	
Timothy in Maryland	2,4-D as propylene glycol ether ester for 3 yr	0.8	1	20	—	—	(200)
			2	37	—	2.3	
			3	45	—	2.0	
			4	30	—	—	
		1.7	1	30	—	—	
			2	37	—	3.3	
			3	52	—	1.0	
			4	42	—	—	
	2,4-D as alkanolamine for 3 yr	0.8	1	37	—	—	
			2	52	—	2.0	
			3	25	—	4.8	
			4	37	—	—	
		1.7	1	20	—	—	
			2	50	—	2.6	
			3	65	—	1.9	
			4	57	—	—	
	No herbicide	0	1	0		—	
			2	0		6.8	
			3	0		10.1	
			4	0		—	
Alfalfa in Indiana	2,4-DB as isooctyl eater	1.1	1	—	—	16.5	(214)
			2	—	—	16.5	
			3	—	—	5.8	
			4	—	—	8.2	
			5	—	—	1.6	
		0	1	—	—	16.5	
			2	—	—	26.7	
			3	—	—	26.7	
			4	—	—	18.5	
			5	—	—	8.2	
Timothy + red clover in Australia	MCPB	2	2	10	—	—	(17)
			4	8	—	—	
		4	2	4	—	—	
			4	4	—	—	
	2,4-D ester	2	2	22	—	—	
			4	7	—	—	
		4	2	25	—	—	
			4	8	—	—	
	2,4-D amine	2	2	18	—	—	
			4	4	—	—	
		4	2	22	—	—	
			4	6	—	—	
	Control	0	2	44	—	—	
			4	19	—	—	

translocation to the roots because 1 yr after spraying, more adventitious shoots emerged when plots were sprayed under high light.

Information on the fate of ^{14}C-2,4-D or other phenoxy herbicides in Canada thistle is limited although much is known about phenoxy metabolism in other plants (157). 2,4-D metabolites in Canada thistle have not been characterized.

^{14}C-2,4-D rapidly penetrated leaves of 7- to 8-leaf stage hydroponically grown Canada thistle 1 day after treatment (244) (Table 28). Little further radiolabel was absorbed 3 to 9 days after spraying and less than 30% of the radiolabel remained in the shoots after 9 days. But in-

Table 28. Distribution of ^{14}C from ^{14}C-2,4-D over time, as a percentage of the total ^{14}C, applied to the youngest fully expanded leaf of rosette stage Canada thistle (244; adapted by permission of the Weed Science Society of America).

Days after applications	^{14}C-recovered[a]					
	Treated leaf wash	Treated leaf	Distal foliage	Proximal foliage	Roots	Unrecovered
	(%)					
1	16	57 a	2	3 ab	7	15 bc
3	10	51 ab	3	5 a	10	21 b
9	1	22 c	3	2 b	15	57 a

[a]Means within a column followed by the same letter did not differ significantly at P = 0.05 by Duncan's multiple range test.

creases in root radiolabel could not account for this change; up to 49% of applied ^{14}C-2,4-D was exuded into the nutrient medium. Time-course studies suggested that exudation began between 12 and 24 h after foliar application. It is unknown whether exudation would be as extensive for older plants, plants grown in soil, or those receiving over-the-top application of unlabeled 2,4-D.

Decapitation of shoots altered the partitioning of later foliar-applied ^{14}C-2,4-D between the shoot and roots of Canada thistle (167). Two- to 3-fold more ^{14}C-2,4-D moved to the roots following basal leaf treatment in decapitated plants compared to intact plants. In contrast, removing the shoot apex alone reduced radiolabel movement to the roots. Removing the shoot apex as well as shoot lateral buds in the leaf axils enhanced radiolabel movement to the roots.

Dicamba. Dicamba[9] most effectively controlled Canada thistle when applied at the late vegetative to bud stage (160). Dicamba at 0.28 kg ae/ha controlled Canada thistle in corn much better when applied at the bud stage compared to the early vegetative stage (46). However, poor control in the following growing season was reported after bud stage treatment with dicamba at 0.6 to 3.4 kg ae/ha (98). As with the phenoxy herbicides, annual in-crop retreatment with dicamba was necessary to suppress Canada thistle stands over several growing seasons.

Early researchers explored the potential of using dicamba at high rates (11.2 to 22.4 kg ae/ha) for eradication of Canada thistle in noncropland for 2 to 3 yr after treatment (126). It is now known that dicamba applied at rates greater than 1.1 kg ae/ha can persist to damage sensitive rotational crops depending upon application timing, crop species, climate, and soil pH (158). In Montana, dicamba at 11.2 kg ae/ha applied in early November controlled adventitious shoot emergence for two growing seasons, whereas early July applications began to fail after 1 yr (126). When Canada thistle was treated with 0.6 to 4.5 kg ae/ha dicamba in early July, only 4.5 kg ae/ha provided acceptable control (≥ 90%) into the following fall without retreatment. Dicamba at 1.7 kg ae/ha applied in early August provided poor Canada thistle control in the following June (63). In Canada, dicamba applied in early October after summer fallow at 1.1 to 4.5 kg ae/ha provided excellent control (≥ 95%) when observed in late June 1 yr later (175). However, fall-applied dicamba at 1.1 to 4.5 kg ae/ha in Wyoming was more variable and afforded 70 to 90% control of Canada thistle in the following growing season without reducing barley yield (10). Fall-applied dicamba has been registered in the United States to control Canada thistle for one growing season.

Foliar-applied dicamba can reduce Canada thistle root biomass. In Nebraska, an artificially established uncropped stand of Canada thistle was treated with dicamba at 1.1 kg ae/ha at the flower bud stage, and roots were sampled 0.9 m deep 1 yr later (149). In Trials 1 and 2 of this experiment, dicamba reduced roots to 28 and 7% of controls, respectively (Figure 11). Roots were reduced fairly uniformly with depth to 0.9 m deep.

Dicamba has potential for selectively controlling emerged Canada thistle shoots in some annual crops, such as corn. For example, dicamba at 0.28 kg ae/ha applied at the bud stage of Canada thistle growing in corn achieved 61, 100, and 97% control in corn in September of the 1st, 2nd, and 3rd yr of repeated treatment, respectively (46). If retreatment was discontinued in either the 2nd or 3rd yr, residual control of adventitious shoot emergence was only 64 and 90%, respectively, by the fall of the third summer. Dicamba applied in both fall at 0.56 kg ae/ha and in-crop at 0.28 kg ae/ha for two growing seasons in continuous corn provided

[9]U. S. trade name is Banvel.

79% control by the end of the second full growing season in Minnesota (251). Perhaps such sequential fall plus summer treatments might be more effective if higher rates of fall-applied dicamba were used. Other annual crops, such as wheat, cannot tolerate dicamba applied postemergence above 0.28 kg ae/ha and lower rates are ineffective on Canada thistle.

Dicamba may have greater potential for Canada thistle control in some perennial crops which tolerate higher application rates. For example, in asparagus (*Asparagus officinalis* L.) dicamba at 0.6 kg ae/ha or dicamba plus 2,4-D at 0.3 to 0.6 plus 1.1 kg ae/ha afforded 97% control of Canada thistle shoots if early May treatments were followed by mid-June retreatments (191, 192). However, in other instances, rates that effectively control Canada thistle (2.24 kg ae/ha) damaged forage grasses such as red fescue planted 1 yr after application at some sites (39), but not at others (100). Yearly retreatment of Canada thistle with dicamba at 1.1 kg ae/ha in pastures may gradually suppress Canada thistle stands over 2 to 3 yr (200, 203). An attempt to use dicamba to selectively control Canada thistle in birdsfoot trefoil by ropewick or roller application was unsuccessful (35).

Little is known about how environment modifies dicamba phytotoxicity to Canada thistle. In the growth chamber, increasing temperature from 16 to 27 C increased the phytotoxicity of foliar-applied dicamba at 1.1 kg ae/ha to Canada thistle roots (136). Foliar necrosis was fastest at high temperatures, as well.

Applying as little as 0.01 mg dicamba to single leaves of Canada thistle in the greenhouse or field injured other untreated plant parts (49). Shoot tips became swollen in 7 to 10 days. In the field, newly emerging shoots 1 m from treated plants became damaged. Dicamba applied to leaves (0.1 mg/plant) killed the shoot apex. When the shoot was removed 4 h after treatment, new growth was uninjured. However, enough herbicide moved to untreated plant parts after 6 to 8 h to injure new growth.

The degradation of dicamba in plants has been reviewed elsewhere (97), but information on its metabolism in Canada thistle is limited (49, 149). ^{14}C-dicamba moved acropetally or basipetally after root or shoot application, respectively, in young 6- to 20-cm tall plants that had 6 to 10 leaves (49). It is unknown whether dicamba pretreatment modifies its own translocation. Relatively little herbicide was transported out of treated leaves. Of the radiolabel recovered in treated leaves, 63% remained as parent dicamba even after 54 days, using thin layer chromatography to separate metabolites. Time course studies demonstrated that the roots failed to retain radiolabel from dicamba over 54 days. This loss could be due to exudation since safflower (*Carthamus tinctorius* L.) became injured when planted into pots which previously had held microdrop-treated Canada thistle plants.

Short-term water stress limited dicamba translocation in 8-week old Canada thistle (149). Water stress 6 days before treatment caused the lower leaves of greenhouse-grown plants to wilt and necrose. Most radiolabel from ^{14}C-dicamba remained in the shoot although the concentration in root tips increased following water stress.

Pyridinecarboxylic Acid Herbicides. *Picloram.* Field research on the use of picloram[10] for Canada thistle control was conducted at about the same time as that of dicamba, and frequently both herbicides were compared to phenoxy herbicides. Picloram at high rates ($\geq$ 0.6 kg ae/ha) had potential for eradicating this perennial weed in early field research (Table 29). Later recognition that picloram residues persist in soil long enough to damage rotational crops has limited the rates that can be used and also restricted picloram use to range, pasture, and noncropland sites (248). Of course, even in pas-

Table 29. Control of Canada thistle with picloram in pasture, along roadside, and in summer fallow based on stand counts or visual evaluations.

Picloram rate	Application time	Persistence of control: Time	Persistence of control: Control	Reference
(kg ae/ha)		(years)	(%)	
1.1 to 3.3	Early July	1	100	(98)
0.6 to 1.7	Late October	1	100	(12)
0.2 to 0.5	—	2	80	(250)
0.8 to 1.6	—	2	100	
1.1	Late September	2	100	(151)
1.0	July (split)	1	98	(2)
2.0	July (split)	1	100	
2.0	September	1	100	
0.8	Late June	1	98	(94)
	Mid-October	1	89	
0.28 to 0.56	Mid-September	1	>95	(133)
3.2	Mid-September	1	81	(248)
1.1	July	1	100	(148)
2.2	July	2	100	
0.28 to 1.1	June to September	1	Good to Excellent	(100)
0.28	—	1	—	(200) (39)
2.2	—	4	—	(8)
0.6 to 3.3	Late September	1	—	(10)
0.6 to 1.1 to 4.9	Early July	1 1	90 —	(126)

[10]U. S. trade name is Tordon.

tures, the rate of picloram must be adjusted to minimize grass damage, and planting small seeded legumes is not possible (8, 39, 94, 141).

An attempt to selectively apply picloram to Canada thistle in birdsfoot trefoil with ropewick and roller applicators resulted in excellent short-term Canada thistle shoot control, but crop damage was unacceptable (35). Multiple and sequential applications of picloram (24 to 80 g ae/L) with these applicators were superior to a single pass 1 yr after treatment. This method of selective, positional treatment holds promise for Canada thistle control in those pasture species with greater tolerance to picloram. Reed canarygrass, orchardgrass, and bluegrass tolerated 0.28 to 0.56 kg ae/ha picloram applied in mid-September (133). Red fescue and timothy tolerated up to 0.56 kg ae/ha applied up to 1 yr prior to seeding (100). Although Russian wildrye and green needlegrass (*Stipa viridula* Trin.) were stunted by picloram at 1.7 kg ae/ha applied in mid-June, seed production and germination of Russian wildrye were unaffected (11).

Whereas numerous studies demonstrate that picloram at 1.1 kg ae/ha or more controlled Canada thistle for 1 or more yr (Table 29), claims of eradication are problematic unless treated areas are reexamined for several years after spraying. Alternatively, roots can be sampled. Lauridson et al. (149) demonstrated that root biomass (cm root/dm^3 soil) was reduced to between 3 and 17% of control values to a depth of 90 cm 1 yr after treating artificially established stands of Canada thistle with picloram at 2.5 kg ae/ha at the flower bud stage (Figure 11).

Picloram at 20 to 70 g ae/ha successfully prevented seed production by Canada thistle (53, 105) when applied at the late flower bud to flowering stages.

Information on how environment modifies Canada thistle control is as limited for foliar-applied picloram as it is for dicamba. Increasing temperature from 16 to 27 C in the growth chamber progressively reduced root dry weight in four of five Canada thistle ecotypes (136). Relative reductions of root dry weight ranged from 52 to 72% at 16 C and from 67 to 94% at 27 C with picloram at 0.14 kg ae/ha. Canada thistle foliage also was damaged more quickly at higher temperature, as was observed following either 2,4-D or dicamba treatment.

Picloram damage to Canada thistle differs from that of either dicamba or phenoxy herbicides. Damage to leaves was limited soon after treatment, except in some subspecies, such as 'mite' (136, 154). Shoots surviving treatment were stunted, twisted, and had swollen shoot apices (100). Stems began to bend in as little as 10 h, and leaves died after 1 to 2 weeks (218). Picloram also delayed budding and flowering.

Roots were more sensitive than shoots to foliar-applied picloram, even at rates as low as 0.14 to 0.28 kg ae/ha (136). Typically, roots became swollen and split before the cortex disintegrated (146, 218). The cambium and phloem may be destroyed in as little as 2 weeks depending on foliar dose (154). Hunter and Smith (136) attributed the extensive root damage to good basipetal translocation of picloram from the foliage because leaves were only slightly damaged soon after treatment.

Picloram applied at 25 to 200 g ae/ha to the foliage and soil of potted Canada thistle with 8 to 10 leaves was much more phytotoxic than when only the leaves were treated (107). Apparently root uptake contributed to picloram phytotoxicity to Canada thistle. However, the relative contribution of root uptake alone could not be ascertained from these studies because soil-applied picloram was not included as a separate treatment. Picloram was somewhat less damaging than clopyralid at equal rates, as measured by shoot regrowth. Foliar uptake and transport between 3 and 6 days after foliar treatment significantly inhibited later shoot regrowth compared to shorter intervals of exposure, particularly at 25 to 50 g ae/ha.

These biological observations are consistent with suggestions that picloram injures the roots as much as it does because it does not quickly damage the foliar translocation system of treated plants (136). In the field, picloram injured untreated shoots as far as 1 m away from treated shoots, indicating translocation from one shoot to another through the interconnected root system (218).

The fate of picloram in plants other than Canada thistle was reviewed (96).

Autoradiographs demonstrated that hydroponically grown Canada thistle transported ^{14}C-picloram from the roots to the shoots (219, 220). One day after application, radiolabel accumulated along the margins of mature leaves of 5-week old plants, as one would expect of a water-soluble herbicide moved in the transpiration stream.

^{14}C-picloram applied in microdrops to the leaves of 5-week old unsprayed Canada thistle was translocated to the new foliage 1 day after application (219, 220). Autoradiographs demonstrated phloem mobility in that radiolabel movement was from older to younger leaves and concentration in the veins of the young leaves. Little apparent metabolism occurred after

20 days, based on solvent partitioning and thin layer chromatography. The authors suggested that low recovery (64%) was due to picloram volatilization since only 0.05% of the dose was collected as $^{14}CO_2$. No further foliar uptake of ^{14}C-picloram occurred from day 10 to 20; 15% of that applied remained on the surface, 50% remained in the treated leaf, and 30% was translocated out of the treated leaf. Short-term water stress did not influence the relative concentration of radiolabel in different plant parts, other than the treated leaf (149).

Clopyralid. Clopyralid[11] holds promise for postemergence Canada thistle control in a wide range of crops, including wheat, barley, corn, sugarbeets (*Beta vulgaris* L.), rapeseed, and pasture (Table 30). Crop safety has been excellent with clopyralid on registered crops, except for transient leaf curling when applied to sugarbeets beyond the 8-leaf growth stage (101). Ropewick or roller-applied clopyralid to tall-growing Canada thistle shoots in short crops holds promise for selective Canada thistle control where crops have insufficient tolerance to clopyralid (35). However, sequential multiple applications needed for long-term Canada thistle control were too damaging to birdsfoot trefoil for recommendation. Clopyralid applied postemergence at 70 to 200 g ae/ha effectively controlled Canada thistle from when plants were 5 to 15 cm tall to flowering. Two month old seedlings of Canada thistle were controlled better by clopyralid at 70 to 560 g ae/ha than were plants established from root cuttings (254). Thirty-cm tall flowering shoots treated with clopyralid at 100 to 200 g ae/ha were not completely killed although shoot growth ceased and shoots became chlorotic and distorted (101). Eighty-cm tall flowering Canada thistle was not controlled at all.

Because clopyralid controls a narrow weed spectrum, it is usually marketed in combination with other herbicides for broad spectrum weed control. Clopyralid is registered in wheat and barley in combination with MCPA (56, 143, 144, 145). In sugarbeets and noncompetitive, slow-growing vegetable crops which form a canopy slowly, sequential retreatment with clopyralid has been recommended (147). Clopyralid applied once was insufficient in vegetables in England because Canada thistle emergence continued for over 3 weeks after spraying. In contrast Canada thistle stands in cereals often were reduced 80 to 85% or more with clopyralid at 100 to 140 g ae/ha and control often lasted 1 yr after treatment (6, 56, 85, 140, 142). Clopyralid at 800 g ae/ha provided more than 2 yr of Canada thistle control in ryegrass pasture in Australia as a spot treatment but killed white clover in mixed pastures (17). In Wyoming, clopyralid at 1.1 to 2.2 kg ae/ha provided more than 4 yr of control when Canada thistle was sprayed at the bloom stage of wheatgrass (8).

Clopyralid at rates as low as 0.2 kg ae/ha reduced both Canada thistle root fresh weight and adventitious shoot emergence (186). Plants were grown outdoors in buckets for 12 months prior to treatment. Four months after spraying clopyralid at 0.1 to 1.1 kg/ha, roots were unearthed and replanted in untreated soil, then shoot regrowth was measured 5 weeks after re-

[11]U. S. trade names are Lontrel and Stinger. Curtail-M is a mixture of clopyralid plus MCPA.

Table 30. Canada thistle control with clopyralid in various crops.

Crop	Crop stage	Rate	Growth stage	Control[a]	Reference
		(kg ae/ha)			
Barley	3 to 5 leaf	0.1 to 0.2	5 to 15 cm tall	E	(56)
	3 to 6 leaf	0.1 to 0.9	NA	E	(143, 144, 145, 183, 188)
Corn	—	0.4	—	E	(173)
Crested wheatgrass	—	1.1 to 2.2	Bloom	E	(8)
Rapeseed	—	0.15 to 0.3	8 to 12 cm tall	E	(186)
	—	0.2 to 0.3	4 leaf to bud stage	E	(184)
Ryegrass	—	0.8		E	(17)
Spring wheat	3 to 5 leaf	0.1 to 0.2	5 to 15 cm tall	E	(56)
Sugarbeet	Cotyledon to 8 leaf	0.2	20 cm tall, Late rosette to flowering	G	(101)
	NA	0.2 to 0.6	10 to 25 cm tall, vegetative	E	(217)
Winter wheat	Tillered	≥ 0.07	NA	E	(84, 85)

[a]G = good, E = excellent.

planting. Foliar-applied clopyralid at 75 g ae/ha also reduced root regrowth potential of unearthed Canada thistle roots in England (57).

Clopyralid can be combined with several grass control herbicides without reducing either grass or Canada thistle control in cereals (183). Clopyralid at 300 g ae/ha was effectively mixed with barban (4-chloro-2-butynyl 3-chlorophenylcarbamate) at 0.35 kg ai/ha, diclofop-methyl {(±)-2-[4-(2,4-dichlorophenoxy)phenoxy] propanoic acid} at 0.7 kg ae/ha, difenzoquat (1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium) at 0.84 kg ai/ha, and flamprop-methyl [*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-*DL*-alanine] at 0.56 kg ai/ha.

Soil uptake of clopyralid at 25 to 200 g ae/ha contributes to its phytotoxicity to Canada thistle since soil plus foliar treatment was more damaging than foliar treatment alone (107). If shoots were removed and clopyralid was applied in the greenhouse to the soil alone, shoot regrowth was reduced by clopyralid at 50 g ae/ha or more. Hall et al. (107) suggested that the soil activity of clopyralid would depend on soil properties, such as organic matter, clay, and silt, soil moisture, and the distance between Canada thistle roots and the soil surface. Fifty-three percent of ^{14}C-clopyralid applied to the roots of hydroponically grown Canada thistle was recovered in the foliage after 9 days (244), establishing that clopyralid was moved acropetally in the transpiration stream.

The foliar penetration and translocation of ^{14}C-microdrop-applied clopyralid in Canada thistle determined at various times after treatment in three different studies are summarized in Table 31 (61, 197, 244). All plants were at the 8-leaf stage at treatment but were grown in sand (61), soil (187), or hydroponics (244). None of the authors treated foliage with phytotoxic rates of unlabeled clopyralid. All authors reported relatively rapid initial foliar absorption of clopyralid over 24 h with uptake values of 61% (187), 64% (244), and 85% (61) of that applied. Uptake was nearly complete (100%) over more protracted periods (Table 31) (61, 244). Low relative humidity can drastically restrict foliar absorption of ^{14}C-clopyralid (187). After 48 h, leaves absorbed 41 and 84% of that applied when grown in 40 and 90% relative humidity, respectively. Stage of growth at spraying may modify foliar penetration of ^{14}C-clopyralid since vegetative Canada thistle absorbed 81% of that applied whereas flowering plants absorbed only 65% after 1 week of uptake (187).

The ^{14}C-clopyralid distribution and partitioning in young Canada thistle is summarized (Table 31). Roots accumulated 29% (61), 33% (244), and 8% (187) of the ^{14}C-clopyralid applied after 144, 196, or 48 hr, respectively. However, differences in ^{14}C-clopyralid transport to the roots cannot be explained solely by differences in sampling interval since transport out of the treated leaf was limited after 72 h (61, 244). Differences may be related to the media used to grow the plants because significant root exudation (20%) was noted after 192 h from hydroponically grown plants (244).

Despite significant translocation to the roots, the leaves were major sinks for ^{14}C-clopyralid (Table 31). Foliar metabolism of ^{14}C-clopyralid was limited and little ^{14}C-CO_2 was released (61, 244). Even though foliar penetration of ^{14}C-clopyralid was twice as great at 90% relative humidity as at 40%, translocation to the roots or leaves was unaffected by humidity after 48 h (187). Likewise, vegetative and flowering

Table 31. Partitioning of clopyralid in Canada thistle at various times after foliar treatment (adapted by permission of the Weed Science Society of America and Blackwell Scientific Publications, Ltd.).

Plant part	Time	Distribution of clopyralid	Reference
	(h)	(% of applied)	
Experiment 1			
Leaf wash	144	0.2	(61)
Treated leaf		1.7	
Upper shoot		39.8	
Lower shoot		9.7	
Taproot		11.0	
Fibrous roots		6.4	
Developing root buds		11.7	
Unrecovered		19.6	
Experiment 2			
Leaf wash	24	32	(244)
Treated leaf		44	
Upper shoot		4	
Lower shoot		3	
Roots		13	
Unrecovered		4	
Leaf wash	72	3	
Treated leaf		40	
Upper shoot		13	
Lower shoot		4	
Roots		24	
Unrecovered		16	
Leaf wash	196	1	
Treated leaf		25	
Upper shoot		15	
Lower shoot		5	
Roots		33	
Unrecovered		21	
Experiment 3			
Treated leaf	48	51	(187)
Apex		35.6	
Shoot		5	
Root		8.3	
Unrecovered		14.7	

Canada thistle partitioned ^{14}C-clopyralid between the apex, shoot, and roots similarly when the upper leaves were treated. However, at flowering, more radiolabel was translocated to the shoot apex when the upper leaves on the plants were treated than when the lower ones were treated (28.0 versus 16.5% of that applied, respectively).

New adventitious shoot emergence has been used to estimate how rapidly a phytotoxic dose of clopyralid translocates from the shoots to the roots of Canada thistle (61). When 10-leaf-stage plants were sprayed with clopyralid at 100 g ae/ha and shoots were removed at intervals after spraying, some new shoots later emerged when parent shoots were excised at 72 h, but almost none regrew after 144 h of herbicide uptake. In these experiments, the soil surface was covered to exclude herbicide uptake from the soil, unlike earlier research (254).

Sulfonylurea Herbicides. The maximum registered rates of chlorsulfuron[12] (26 g ai/ha) and metsulfuron[13] {2- [[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl] benzoic acid} (4.2 g ai/ha) are recommended to suppress Canada thistle in cereals. Two objectives were envisioned in early research on Canada thistle control: immediate control of shoot growth and long-term control of perennial roots in subsequent years. It was not recognized in early research (14, 212, 257) that low rates of chlorsulfuron or metsulfuron would provide season-long control, and that application rates could be reduced significantly by adding surfactant without sacrificing control or selectivity in cereals.

Chlorsulfuron at 18 g ai/ha applied midseason prevented Canada thistle seed production in Wyoming (13). Chlorsulfuron can effectively suppress Canada thistle shoot growth in wheat at rates lower than 30 g ai/ha if surfactant is added. In the greenhouse, added surfactant also enhanced chlorsulfuron damage to Canada thistle shoots (68, 69, 70). Chlorsulfuron at 67 g ai/ha prevented regrowth of secondary shoots from root buds only when applied postemergence with surfactant [Tween 80 at 0.2% (v/v)]. However, surfactant failed to enhance parent shoot control with chlorsulfuron at 35 to 140 g ai/ha in Utah (81, 82). The highly phytotoxic rates used probably masked the effect of added surfactant in the field.

O'Sullivan (182) controlled Canada thistle shoots with foliar- or soil-applied chlorsulfuron at 50 g ai/ha in the field and greenhouse. Postemergence chlorsulfuron at 50 to 150 g ai/ha not only controlled Canada thistle shoots and increased wheat and barley yield but provided residual control of adventitious shoot emergence 1 yr after treatment. Treated plots had 6 to 23% of the shoot density and 1 to 8% of the shoot fresh weight of control plots. However, Donald (68) observed that chlorsulfuron applied to the foliage plus soil controlled adventitious shoot emergence from root buds just as well as foliar treatment alone in the greenhouse. Foliar- or foliar- plus soil-applied chlorsulfuron controlled adventitious shoots much better than soil treatment alone, suggesting that soil residues alone were not responsible for persistent adventitious shoot control.

In subsequent field experiments (see below), residual control of Canada thistle with chlorsulfuron also was noted but it could not be attributed to either shoot or root absorption alone. In Colorado, chlorsulfuron applied at 35, 70, and 140 g ai/ha to Canada thistle in summer provided residual control 17 months later (118). Chlorsulfuron at 18, 35, or 70 g ai/ha applied to Canada thistle at the 5-leaf stage reduced stands 23, 52, and 90%, respectively, 1 yr later in Montana (73, 74). However, control in the following year was reduced significantly when chlorsulfuron was applied at the bud stage. In the greenhouse, chlorsulfuron treatment at flowering also was less effective in preventing adventitious shoot emergence than at earlier growth stages (68), substantiating these field observations (73).

Fall-applied chlorsulfuron at 26 g/ha did not control Canada thistle in the growing season following treatment (86, 141, 260). In Colorado, 35 to 140 g ai/ha chlorsulfuron applied at the rosette stage in mid-May, the prebud stage in early June, the bud or flower stage in late June, or in the fall all provided greater than 90% control in mid-September (117). However, only excessively high rates prevented adventitious shoot emergence in the following growing season.

These observations are substantiated by studies on a nontilled, noncropped site in Nebraska in which chlorsulfuron at 9 to 270 g ai/ha was applied to Canada thistle at the spring rosette, the bud stage, and the fall rosette stage (259, 260). Chlorsulfuron at the highest rate was more effective when applied at the bud and fall rosette stage than the spring rosette stage, as measured by reduced Canada thistle stand, root length, or secondary shoot density in the spring

[12]U.S. trade name is Glean.
[13]U.S. trade name is Ally.

ollowing treatment. Roots were not eradicated to a depth of 90 cm in the soil profile with chlorsulfuron applied once in fall, even at the highest rate, 270 g ai/ha. Chlorsulfuron residues may limit rotational crop options.

Several other sulfonylurea herbicides also suppressed Canada thistle. Metsulfuron at 35 g ai/ha applied in mid-July provided excellent shoot suppression (64). The 1990 registered rate for use of metsulfuron in wheat was 7.2 g ai/ha. DPX-L5300[14] {methyl-2-[[[[3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)-*N*-methylamino] carbonyl]amino]sulfonyl]benzoate} at 11 to 67 g ai/ha applied to Canada thistle in barley at the 3- to 4-leaf stage provided acceptable shoot suppression 80 days later (156). In England, foliar-applied DPX-L5300 at 23 g ai/ha or metsulfuron at 6 g ai/ha controlled Canada thistle shoots in winter wheat but failed to control regrowth (57). Roots unearthed 2 months after foliar treatment were capable of forming new shoots from root buds. DPX-M6316[15] {methyl-3-[[[[(4-methoxy-6-methyl)-1,3,5-triazin-2-yl]aminocarbonyl]aminosulfonyl]-2-thiophenecarboxylate} did not control Canada thistle (73, 88, 179).

The potential of chlorsulfuron reapplied annually to eradicate Canada thistle in continuous wheat has received limited attention. Chlorsulfuron at 17, 35, or 70 g ai/ha applied at the bud stage of Canada thistle provided limited residual control in the following year (75, 87). However, Canada thistle stands gradually decreased when chlorsulfuron was reapplied annually to the same plots over 3 consecutive years in Montana spring wheat (90) (Table 32).

Chlorsulfuron effectively controlled Canada thistle shoots in pastures. Chlorsulfuron at 280 to 560 g ai/ha controlled Canada thistle for one

Table 32. Effect of chlorsulfuron reapplied annually to the same plot land on Canada thistle shoot density in spring wheat at the time of harvest over 3 yr (1983 to 1985) in Montana (87).

Chlorsulfuron	Canada thistle shoot density[a] 1983	1984	1985
(g/ha)	(no./m²)		
0	39	37	27
17	27	25	9
35	18	13	5
70	13	7	2
LSD (0.05)	9	9	5

[a]Evaluations were made between August 19 and September 4 each year.

[14]U.S. trade name is Express.
[15]U.S. trade name is Harmony or Pinnacle.

growing season in Wyoming (9). Good control was achieved at these rates even when applied at full bloom in August under drought conditions. Chlorsulfuron at 280 g ai/ha to 2.2 kg ai/ha provided 4 yr of total Canada thistle control, although crested wheatgrass [*Agropyron desertorum* (Fisch. ex Link) Schutt.] was stunted at rates above 280 g ai/ha. In North Dakota, chlorsulfuron at 280 g ai/ha provided good control of Canada thistle for 1 yr following a June application to 30- to 45-cm-tall Canada thistle at the midbud stage (171). However, adventitious shoots emerged 15 months later (172).

Chlorsulfuron injury symptoms to Canada thistle have been described (68). The shoot apex and young leaves became chlorotic within 5 days of treatment and failed to expand, resulting in a small chlorotic rosette. In 1 to 2 weeks after treatment, the lower leaves became chlorotic and yellowing progressed up the stem. Petioles became discolored and weakened. Then the petioles of lower leaves collapsed along the side of the stem, but the leaves maintained their turgor for several weeks. Finally, necrosis developed up the stem as the shoot died. When chlorsulfuron at 9 and 67 g ai/ha was applied only to the soil, it stimulated adventitious root bud growth, although adventitious shoots did not emerge through the soil surface (69). At higher rates, adventitious shoot emergence through the surface was reduced further.

With such drastic effects on shoot development, it is not surprising that chlorsulfuron and metsulfuron also inhibit Canada thistle seed production. Chlorsulfuron at 18 g/ha prevented seed production (13).

Leaves of Canada thistle at the 7- to 8-leaf stage absorbed 39% of applied ^{14}C-chlorsulfuron 48 h after treatment (199). Seventy-five percent of applied ^{14}C-chlorsulfuron was absorbed after 72 h with little further uptake after 144 h (61).

Foliar-applied chlorsulfuron at 67 g ai/ha was more phytotoxic to Canada thistle than soil-applied chlorsulfuron (68). Foliar or foliar plus soil treatments with chlorsulfuron at 67 g ai/ha were equally effective in reducing Canada thistle adventitious shoot emergence. In contrast, root treatment was thought to contribute significantly to the decreased shoot growth of Canada thistle in other greenhouse (107) and field research (182). However, this contribution was noted in the greenhouse only at the highest tested rates, 100 and 200 g ai/ha, which are five- to tenfold greater than commercial rates (107). Similar results were found for metsulfuron.

When hydroponically grown Canada thistle at the 7- to 8-leaf stage was root treated with ^{14}C-chlorsulfuron, only 16% of the radiolabel was absorbed after 48 h (199). This was roughly half of that absorbed by the foliage at the same time. Root uptake of chlorsulfuron is likely to be less important than shoot uptake for Canada thistle control.

Movement of ^{14}C-chlorsulfuron in Canada thistle from the shoots to the roots also is limited (199). When Canada thistle was grown hydroponically and the foliage was treated at the 7- to 8-leaf stage with ^{14}C-chlorsulfuron, only 10% of applied radiolabel moved to the roots. In other studies with 7- to 8-leaf Canada thistle grown in quartz sand, only 5% of foliar-applied radiolabel moved to the roots of Canada thistle after 144 h (61). In both studies, most of the translocated radiolabel moved to young shoots. Transport from the roots to the foliage following root application also is limited (199). When roots were treated in hydroponics, only 10% of chlorsulfuron applied moved in the transpiration stream to the shoots.

Canada thistle did not metabolize chlorsulfuron following foliar treatment or when chlorsulfuron was added to Canada thistle cell suspensions (232, 234, 235). Although the leaves did not metabolize the herbicide, the roots converted 25% of the applied chlorsulfuron into polar conjugates. Other researchers also have isolated, but not identified, degradation products of chlorsulfuron in Canada thistle (62).

Photosynthesis Inhibitor Herbicides. Several photosynthetic inhibitor herbicides have been tested for their efficacy on Canada thistle. Early research with urea herbicides, such as fenuron (*N,N*-dimethyl-*N'*-phenylurea), linuron [*N'*-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea], and monuron [*N'*-(4-chlorophenyl)-*N,N*-dimethylurea], uracil herbicides, such as isocil [5-bromo-6-methyl-3-(1-methylethyl)2,4-(1*H*, 3*H*)- pyrimidinedione], and triazine herbicides, such as simazine and atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine], employed rates of 22.4 kg ai/ha or more (59, 77, 126). Perhaps the intent of this early research was to determine whether these herbicides could be used as soil sterilants for spot treatment of dense patches of Canada thistle. The goal also may have been to ascertain the potential of these herbicides for eradication, even if residues left the soil bare of vegetation for several years (77).

As new photosynthetic inhibitor herbicides were introduced, they have been examined for their efficacy on Canada thistle, including tebuthiuron {*N*-[5-(1,1- dimethylethyl)-1,3,4-thiadiazol-2-yl]-*N,N'*-dimethylurea} (8) and hexazinone [3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine - 2,4 (1*H*,3*H*)-dione] (89). Paraquat (1,1'-dimethyl-4,4'-bipyridinium ion)[16] has only postemergence contact activity and kills foliage. Because it is not translocated to the roots, control is short lived and new adventitious shoots develop from root buds. So far, only atrazine, bentazon [3 - (1-methylethyl) - (1*H*) - 2,1,3-benzothiadiazin-4(3*H*)-one-2,2-dioxide], metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one], and bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) have shown promise for selective suppression of Canada thistle shoot growth in certain crops. The foliar penetration, translocation, and metabolism of triazine herbicides in plants has been well reviewed (80), although information on Canada thistle is limited.

Triazines. Triazine herbicides, chiefly atrazine[17], have potential for shoot suppression of Canada thistle in corn. Even so, reports of poor shoot suppression are common (66, 173, 242). After 7 yr, Canada thistle encroachment occurred in no-till corn despite planting-time treatments with triazine herbicides, such as atrazine or simazine, at registered rates (242). In other research, atrazine applied for 3 yr at 2.2 or 4.5 kg ai/ha in corn was less effective than hand hoeing (46).

Reduction in the severity of Canada thistle required a multiyear program if triazine herbicides were used (46, 66, 193). For example, residual Canada thistle control in corn decreased only 1 yr after treatment with atrazine at rates of 2.2 or 4.5 kg ai/ha. Control was only good (≤ 85%) in the year of treatment (Figure 12) (193). Likewise, atrazine at 4.5 kg ai/ha reapplied annually for up to 3 consecutive yr was necessary to achieve near total Canada thistle shoot control in corn (Table 33) (46).

Tillage practice and the timing of atrazine application affected Canada thistle control (46, 193). In the field and greenhouse, Canada thistle roots absorbed phytotoxic doses of atrazine (193). Atrazine at 2.2 or 4.5 kg ai/ha applied to Canada thistle shoots prior to (moldboard?) plowing more effectively suppressed Canada thistle shoots in corn than preemergence treatment in late May to mid-June following spring plowing and seedbed preparation by discing (Figure 12) (193). The shoot suppression achieved in the first year persisted but was re-

[16]U.S. trade names are Gramoxone Super or Cyclone.
[17]U.S. trade name is Aatrex, among others.

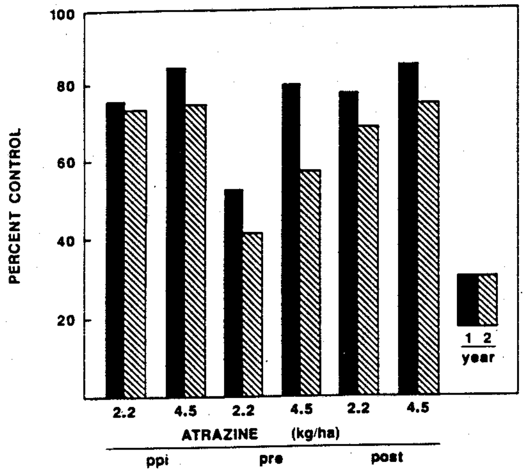

Figure 12. Canada thistle control (3 yr average) from atrazine applied before plowing (ppi), preemergence (pre) or postemergence (post) in corn in the initial year (year 1) and 1 yr later (year 2). Columns of the same year with the same letter did not differ by Duncan's multiple range test at P = 0.05 (193; reprinted by permission of the Weed Science Society of America).

duced 1 yr later, even without supplemental tillage or atrazine retreatment. Residual control in the second year after 14 months was good if atrazine was either applied before spring plowing or postemergence in July or August.

As Carson and Bandeen (46) pointed out, however, late herbicide applications permit long periods of competition between Canada thistle and corn, and subsequent corn yield loss. Adequate residual control has not been achieved with atrazine in all environments and rates as high as 6.7 kg ai/ha did not provide more than one season of adequate control in Nebraska (161).

Hand hoeing to simulate cultivation provided quicker and more total shoot control of Canada thistle than atrazine, especially in a multiyear program designed to eradicate this weed in continuous corn. Because atrazine provided only partial control of shoots, root carbohydrate reserves may not have been reduced as effectively. Atrazine is moved in the apoplast following foliar treatment and is not translocated directly to the roots (41). Potted Canada thistle plants with long root segments (10 cm) experienced foliar damage more slowly than plants from short segments (5 cm) by postemergence-applied atrazine, presumably because they had more root storage reserves.

Carson and Bandeen's (46) control program of split applications of atrazine repeated for three growing seasons may have suppressed Canada thistle shoot regrowth more quickly than a single application at the same total rate by more effectively preventing assimilate movement to the roots (Table 33). The contribution of tillage to Canada thistle control with triazine herbicides may partially explain why Canada thistle encroached in no-till corn even when atrazine or simazine was sprayed (242).

As Doll (66) pointed out, crop rotations must be planned for several years in advance when a multiyear program of atrazine use is planned for Canada thistle control in continuous corn. Triazine residue carryover on alkaline soils or

Table 33. Control of Canada thistle with atrazine in continuous corn as influenced by application time, herbicide, and 1, 2, and 3 annual applications in corn (46; adapted by permission of the Weed Science Society of America).

Atrazine rate and time of application	No. annual application	Canada thistle control[a] Sept. 71	Sept. 72	Sept. 73
	(no.)	(%)		
4.5 prior to plowing	1	31 c-g	51 k-m	70 b-h
	2	48 c-e	96 a-g	83 a-h
	3	49 c-e	90 a-j	100 a-d
2.2 preplant + 2.2 early post in oil[b]	1	57 cd	64 h-m	68 c-j
	2	64 c	92 a-h	100 a-e
	3	66 bc	97 a-g	100 a-d
2.2 preplant incorporated +	1	57 cd	64 h-m	68 c-j
2.2 early postemergence	2	66 c	95 a-g	99 a-e
in oil	3	70 b	94 a-g	100 a-c
2.2 prior to plowing[c] +	1	51 c-e	70 g-l	70 b-h
2.2 early postemergence	2	59 c	93 a-h	100 ab
in oil	3	52 cd	93 a-h	100 ab

[a]Means within the same column followed by similar letters did not differ at the 5% level by Duncan's multiple range test.
[b]Nonphytotoxic emulsified mineral oil at 17 L/ha.
[c]Applied only in the first year of treatment.

in low temperature environments may limit the use of atrazine at rates above 2.2 kg ai/ha. Switching to less persistent corn herbicides in the second or third growing season after using high rates of atrazine in the first year is one potential, but undocumented, option (66).

Metribuzin, a triazinone, can suppress Canada thistle shoot growth (17, 22, 42, 258). However, rates that provided only good control (≤ 80%) are usually so high that they had potential only for use in chemical fallow.

Bentazon. Bentazon[18] can suppress shoot growth of Canada thistle as a split postemergence application at 1.1 to 2.2 kg ai/ha. A single application usually is insufficient to provide adequate in-crop control (39, 40, 173). Bentazon is selective at rates that control Canada thistle shoots in many crops including soybean (66, 196), cereals (210), mint (*Mentha* sp.) (39, 40), and corn (173), but not potatoes (*Solanum tuberosum* L.) (42) or birdsfoot trefoil (33). Split applications usually are made 7 to 14 days apart (39, 40, 66) and are most effective on small vegetative shoots (15 to 25 cm tall) (33, 210). Bentazon, like the triazine herbicides, failed to provide residual control in subsequent growing seasons (39, 40, 210).

^{14}C-bentazon was transported acropetally after foliar application to small vegetative Canada thistle (196). However, untreated shoots of container-grown plants became necrotic after other shoots connected to them by roots were sprayed with 1.1 or 2.2 kg/ha bentazon (39). These observations provide indirect evidence that bentazon can move in the phloem in a source-to-sink fashion in the field.

Differential rates of metabolism may explain selective control of Canada thistle in soybean (196). Foliage of 8-leaf-stage Canada thistle retained roughly twice the herbicide/cm^2 as did soybean leaves, but metabolism of ^{14}C-bentazon was faster in soybean leaves than in Canada thistle foliage. Metabolism was based on differential extraction and thin-layer chromatographic separation of putative metabolites. One day following bentazon treatment, photosynthesis was inhibited in both Canada thistle and soybean shoots. Although photosynthesis recovered in soybean, it remained inhibited in Canada thistle 6 days after treatment.

These physiological responses are consistent with metabolic detoxification of parent bentazon, rather than differences in site of action, as a basis of selectivity in resistant soybean and susceptible Canada thistle. Bentazon-induced shoot death forces the surviving root system of Canada thistle to use its carbohydrate reserves for respiration and growth; total nonstructural carbohydrates (TNC) of the roots were reduced in the greenhouse and field (33). Multiple bentazon applications over time reduced TNC more than single high doses (e.g., 1.1 kg ai/ha).

Herbicide Combinations. *Combinations of Herbicides.* Tank-mix combinations of Canada thistle herbicides for 1988 are summarized for wheat and barley (Figure 13), oats (Figure 14), corn (Figure 15), sorghum (*Sorghum* sp.) (Figure 16), fallow (Figure 17), rangeland or pasture (Figure 18), and noncropland (Figure 19).

Tank-mix combinations of herbicides for in-

WHEAT BARLEY	BROMOXYNIL	CHLORSULFURON	CLOPYRALID *	2,4-D	DICAMBA	MCPA	METSULFURON	PICLORAM
BROMOXYNIL		R	R	R	R	R		
CHLORSULFURON			R	R	R	R	R	
CLOPYRALID *				R	R			
2,4-D					R		R	R
DICAMBA						R	R	
MCPA							R	R
METSULFURON								
PICLORAM								

* CURTAIL

Figure 13. Combinations of herbicides with activity on Canada thistle registered (R) in the United States in 1989 for use in wheat or barley.

OATS	BROMOXYNIL	CHLORSULFURON	2,4-D	DICAMBA	MCPA
BROMOXYNIL		R	R		R
CHLORSULFURON			R		
2,4-D					
DICAMBA					R
MCPA					

Figure 14. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in oats.

[18]U.S. trade name is Basagran.

CORN	ATRAZINE	BENTAZON	BROMOXYNIL	2,4-D	DICAMBA	SIMAZINE
ATRAZINE		R	R		R	
BENTAZON						
BROMOXYNIL				R	R	
2,4-D					R	
DICAMBA						R
SIMAZINE						

Figure 15. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in corn.

SORGHUM	ATRAZINE	BENTAZON	BROMOXYNIL	2,4-D	DICAMBA	SIMAZINE
ATRAZINE		R	R		R	
BENTAZON				R	R	
BROMOXYNIL						
2,4-D						
DICAMBA						
SIMAZINE						

Figure 16. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in sorghum.

FALLOW	ATRAZINE	CHLORSULFURON	CYANAZINE	2,4-D	DICAMBA	GLYPHOSATE	METSULFURON	PICLORAM
ATRAZINE						R	R	
CHLORSULFURON				R		R	R	
CYANAZINE							R	
2,4-D					R	R	R	R
DICAMBA						R		
GLYPHOSATE							R	
METSULFURON								
PICLORAM								

Figure 17. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in fallow.

RANGE/PASTURE	ATRAZINE	BROMOXYNIL	CHLORSULFURON	2,4-D	DICAMBA	MCPA	PICLORAM	TRICLOPYR	2,4,5-T
ATRAZINE					R				
BROMOXYNIL						R			
CHLORSULFURON					R				
2,4-D					R		R	R	
DICAMBA							R		R
MCPA							R		
PICLORAM									
TRICLOPYR									
2,4,5-T									

Figure 18. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in range or pasture.

NONCROPLAND	AMITROLE	ATRAZINE	CHLORSULFURON	2,4-D	DICAMBA	GLYPHOSATE	HEXAZINONE	MCPA	PICLORAM	SIMAZINE	SULFOMETURON	TEBUTHIURON
AMITROLE					R					R		R
ATRAZINE						R						
CHLORSULFURON				R	R	R						
2,4-D					R	R			R			R
DICAMBA						R	R		R		R	R
GLYPHOSATE											R	R
HEXAZINONE											R	
MCPA									R			
PICLORAM												
SIMAZINE												
SULFOMETURON												R
TEBUTHIURON												

Figure 19. Combinations of herbicides with activity on Canada thistle registered in the United States in 1989 for use in noncropland.

crop use are commonly applied to 1) broaden the spectrum of weeds that are controlled, 2) take advantage of herbicide synergism to improve shoot control of troublesome, hard-to-kill weeds, such as Canada thistle, or 3) lower the rate of residual herbicides to minimize the risk of carryover damage to rotational or replanted crops.

Most herbicides used to control Canada thistle in crops must be combined with grass herbicides for broad-spectrum weed control. Of the various Canada thistle herbicides, only the triazine and some sulfonylurea herbicides can partially control or suppress certain grass weeds. Tank-mix antagonisms resulting in reduced grass control have been reviewed (114) and are beyond the scope of this summary.

While clopyralid has excellent postemergence activity on Canada thistle, it must be combined with other herbicides for broad spectrum weed control (e.g., 2,4-D in cereals) because it controls only weeds in the Compositae, Leguminoseae, and Polygonaceae. While phenoxy herbicides kill a wide spectrum of weeds, they can be combined with other herbicides to manage phenoxy-tolerant species in addition to Canada thistle [e.g., MCPA plus bromoxynil or 2,4-D plus clopyralid for wild buckwheat (*Polygonum convolvulus* L. # POLCO) control in cereals].

Some combinations of broadleaf herbicides are more phytotoxic to Canada thistle shoots than either herbicide would be alone at comparable rates. As early as 1968, MCPA plus bromoxynil at 0.24 plus 0.24 kg ae/ha was recognized to provide adequate shoot control of Canada thistle in spring wheat, at least for sparse stands (5). In an unrepeated trial on 2.5- to 22-cm tall Canada thistle growing in wheat, bromoxynil plus MCPA at 0.21 to 0.35 kg/ha each was more damaging to Canada thistle shoots than either herbicide applied alone (51). Bromoxynil plus MCPA at 0.35 plus 0.35 kg ae/ha was as effective on Canada thistle as 2,4-D as the butoxyethyl ester at 0.38 kg ae/ha.

Most research on herbicide combinations for Canada thistle control consist of 1-yr trials that were not repeated in time or location. Therefore the results should be considered preliminary. In no case has a wide enough range of rates been tested for the various combinations to demonstrate synergism of in-crop tank mixes on Canada thistle in either the greenhouse or field using the criteria reviewed by Hatzios and Penner (114).

Herbicide combinations at high rates may be useful to 1) improve long-term Canada thistle control, 2) reduce the cost of control by reducing the rate of the more persistent of the two herbicides, and 3) minimize the risk of herbicide residual carryover by reducing the rate of the more expensive of the two herbicides. Use of chlorsulfuron, metsulfuron, atrazine, picloram, clopyralid, or dicamba in-crop may limit cropping alternatives either for replanting in the case of crop failure or for rotational crops in the following growing season. Herbicide antagonism and reduced long-term control also are possible.

Glyphosate at 1.0 to 1.5 kg ae/ha provided residual control of new shoot emergence of Canada thistle when shoots at the bud stage were sprayed (185). However, picloram at 70 g ae/ha reduced the level of regrowth control when combined with this rate of glyphosate. Antagonism also was observed in the greenhouse between picloram at 18 to 70 g ae/ha and glyphosate at 0.42 to 0.84 kg ae/ha. Picloram reduced foliar absorption of ^{14}C-glyphosate and prevented radiolabel movement to the rest of the plant after 72 h. Extremely rapid foliar necrosis with the combination was suggested to be the basis for this antagonism.

Combinations of Herbicides and Growth Regulators. Growth regulators have the potential to enhance foliar necrosis and shoot control of Canada thistle by contact herbicides. Fluridone {1-methyl-3-phenyl-5- [3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone} at 2.7 to 5.3 g ai/ha enhanced short-term foliar phytotoxicity achieved with bentazon at 27 g ai/ha in the greenhouse (226). In the field, a mixture of fluridone at 5.6 g ai/ha plus bentazon at 28 to 2800 g ai/ha and oxysorbic surfactant (0.5% v/v) was more phytotoxic to Canada thistle shoots 2 weeks after treatment than either herbicide alone. When GA_3 at 25 g/ha was applied to Canada thistle in the field 2 weeks prior to bentazon at 0.28 to 1.12 kg ai/ha, later shoot phytotoxicity was improved (227). More research is needed to verify these interactions in the field and to determine whether the enhancement is selective and economically profitable enough to warrant registering such combinations.

Various growth regulators have been combined with translocated Canada thistle herbicides to enhance herbicide movement to roots by stimulating dormant root bud outgrowth and enhancing root bud sink activity for herbicides (247). Chlorflurenol (2- chloro-9-hydroxy-9H-fluorene-9-carboxylic acid), a morphactin, at 0.1 to 1.1 kg ai/ha stimulated root bud outgrowth 3 weeks after spraying the foliage (28). In the field, chlorflurenol plus dicamba at 0.6 plus 0.6 or 1.1 plus 1.1 kg ae/ha did not improve later control when applied at the bud stage in May and June. In Colorado, chlorflurenol at 0.6 to 2.2 kg ai/ha did not enhance later Canada thistle control when combined with dicamba at 1.1 to 2.2 kg ai/ha and applied in August and September (258). Despite these disappointing field results, ^{14}C-dicamba translocation to roots of 4-week-old, hydroponically grown Canada thistle was enhanced 2- to 10-fold by chlorflurenol spray treatment at 0.6 kg ai/ha (28).

Nitrogen can stimulate preformed adventitious root buds to grow in the greenhouse (110, 166) and field (see section on fertilization), as can soil-applied chlorsulfuron in the greenhouse (70). In the greenhouse foliar-applied glyphosate (44), chlorsulfuron (68), or clopyralid (71) did not stimulate adventitious shoot growth when applied over a wide range of rates. Whether fertilizer or herbicide pretreatment has potential to enhance the phytotoxicity of subsequently sprayed herbicides to the roots and enhance long-term control in the field remains to be determined.

RESEARCH NEEDS

The terminology of field research on Canada thistle control needs to be better defined and standardized to avoid ambiguity. Multiple terms for adventitous shoots should be eliminated and the correct botanic terms used to describe the parts of the root system. Also, management of perennial weeds has been described as "suppression", "control", and "eradication", but none of these terms has been defined by the WSSA Terminology Committee.

Parameters used for gauging control of Canada thistle could include 1) visual evaluation (rating) as a percentage, 2) shoot density, 3) shoot cover, 4) shoot height, 5) shoot fresh or dry weight, 6) root length, 7) root fresh or dry weight, 8) adventitious root bud numbers, or 9) crop yield. Shoot control often is expressed in the literature as a percent without providing enough information on control plot densities so that absolute shoot densities could be calculated. This may be important in explaining inconsistent control in the field because herbicidal control may depend on initial Canada thistle stands.

Shoot parameters usually are expressed per soil surface area, but root parameters usually are not expressed on a common basis. While root parameters could be expressed per volume of soil, per root length, or per projected soil surface area (for a given constant soil sample volume), sampling units and methodology should be well enough documented that the reader can convert between units. Expressing root parameters per unit root length is likely to be more variable between sampling units and across time at the same site than expressing root parameters per area or soil volume.

The variability in measured parameters is seldom documented in the literature by presenting standard deviations or coefficients of variation for parameter means. This information is especially valuable for developing adequate, statistically valid sampling methods for root parameters. Control parameters that are useful to document control in long-term multiyear management research may be useless in short-term research on herbicide efficacy (e.g., Canada thistle stand). In this connection, crop yield is a relatively insensitive measure of herbicide efficacy on Canada thistle.

Control of Canada thistle has been inconsistent with either herbicides or other control methods. At least part of this inconsistency may be due to different definitions of control and different researchers' expectations. Several potential reasons for variability in control include:

1) Canada thistle subspecies (Table 7) or ecotypes within a subspecies may respond differently to control measures, yet few researchers report which subspecies were treated or submit voucher plant samples with seed to herbaria for documentation.

2) Artificially established stands for research may be more easily controlled than natural stands on farms. Stand age and density, and the distribution and density of roots in the soil profile have never been reported before control studies were started.

3) Sparse stands of Canada thistle may be more easily controlled than dense stands. Root density and distribution in the soil profile may increase as stands age and become denser making control more difficult.

4) Canada thistle growing on no-tilled annually cropped land may be harder to control than where tillage disrupts the weed root system and provides partial control (1).

5) Environment, crop species, and management practices (e.g., cultivation, mowing, fertilization) or timing may change the relative emergence times, growth phenology, and competitiveness of Canada thistle and the crop, and may modify control either directly or indirectly. Herbicidal control is reduced by temperature or moisture stress, but little is known about how Canada thistle biology is changed by these stresses in the field.

Methodology for conducting long-term control research on Canada thistle eradication requires attention. Plot size and dimensions, replication, and criteria for blocking require further refinement for different control parameters. The rate of Canada thistle root encroachment or spread between the borders of adjacent plots in an experiment is unknown in a cropped or tilled situation, but probably puts an upper limit on the length of time that a research area will remain uninfested following eradication of Canada thistle roots.

In the absence of competition, rates of patch spread of 2.4 to 3.7 m per year were observed (194, 195) although rates in the presence of competition of 0.80 ± 0.23 to 1.57 ± 0.40 m per year (16) or 0.75 to 3.5 m per year (27) have been reported. Pavlychenko (194) recognized plot-to-plot encroachment of Canada thistle roots as a problem and sprayed a soil residual sterilant (sodium chlorate) between the borders of adjacent Canada thistle plots to limit root encroachment. But, since the 1940s no researchers have adopted his approach to solving this legitimate experimental concern. The influence of type of cropping (e.g., perennial pasture versus annual crops) and tillage (e.g., no-till versus moldboard plowing) on the rate of spread of Canada thistle requires study. Canada thistle root encroachment into long-term experiments from external borders should be minimized by herbicide treatment (e.g. clopyralid) of the area surrounding an experiment.

Sampling strategy, method, timing, and frequency requires further research, especially for root parameters of control. The use of mechanical soil corers for gathering soil samples and root washers or extractors for semiautomatic separation of roots from soil (43) should expedite gathering and measurement of root parameters.

Lactic acid root clearing (166) for estimating adventitious root bud number was developed for young potted Canada thistle plants. But it has not been used for roots gathered from the field (164). However, in the author's experience, it is limited for field use by incomplete clearing of thickened roots which have browned and by an element of subjectivity in identification of root buds (45). Its use for field root samples should be reevaluated and the method should be improved or replaced by shoot meristem-specific stains.

Economic analyses of systems of managing Canada thistle are needed for a range of crops. Integrated management using mowing frequency and MCPB for Canada thistle control in New Zealand pastures was analyzed economically after measuring the improvement in pasture dry matter production and sheep weight gains (113). More complete YLA information and weed surveys for more crops would improve the utility of economic analyses. Information on yield losses due to low densities of Canada thistle is lacking and would help farmers make more profitable decisions on which control strategies to adopt. How can multiyear control programs be made most profitable? Is eradication a viable economic alternative in localized areas?

More effective and predictable multiyear programs or systems of Canada thistle control are needed, not only for cereals, but for other crops as well. While Canada thistle can be controlled or suppressed with herbicides in some major field crops, horticultural crops and minor field crops, such as flax, lentils (*Lens culinaris* Medic.), millet (*Panicum* sp.), tame mustard (*Brassica* sp.), potato, safflower, and sunflower (*Helianthus annuus* L.), have no registered herbicides that are effective on this weed.

To be accepted, such programs must conform with farm practice. Such programs also should include management that helps prevent Canada thistle from developing as a problem, especially in no-till. Most control studies have been conducted in fields with high densities of Canada thistle, yet this weed is often sparser on farmers' fields. How does Canada thistle density and degree of establishment influence its response to control measures? Can sparser, less well-established patches or stand be more easily managed and more quickly controlled by spot treatment?

While the efficacy of several herbicides and various cropping practices on Canada thistle shoots is well established, our knowledge of how these control measures influence the population biology of this weed is incomplete. For long-term control, is it useful to stimulate dormant root buds to grow and, thus, act as better sinks for later applied herbicides? To what extent does root bud stimulation deplete root reserves of assimilates? What is the relative contribution of tillage or mowing to control of roots or root buds versus herbicides where such control practices are used together? How do these practices influence root survival or root bud dynamics? How persistent is control once control measures end? Where control is short lived, what mechanism is responsible for Canada thistle shoot escapes? Can herbicides actually make root buds dormant?

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