Chapter 14

Difenzoquat[1]

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I. INTRODUCTION

Wild oats (*Avena fatua* L. #3 AVEFA) is a major problem weed in spring-sown cereals, as well as fall-sown cereals in some parts of the United States and Canada. The biology of wild oats and the extent to which it reduces cereal yields have been reviewed (52, 83, 192). Herbicides continue to be the most effective short-term method of controlling wild oats in cereals. Difenzoquat (1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium) is one of the several postemergence herbicides that are used for wild oat control (Figure 1). Prior to commercialization, difenzoquat was coded as AC-84,777 by the manufacturer, American Cyanamid. Barban (4-chloro-2-butynyl 3-chlorophenylcarbamate), diclofop [(±)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid], and flamprop [*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-*DL*-alanine] also are used as postemergence sprays, whereas triallate [*S*-(2,3,3-trichloro-2-propenyl)bis(1-methylethyl)carbamothioate] must be applied and incorporated before planting. All are registered for use in wheat (*Triticum aestivum* L.) in the United States except flamprop,

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[1] Mention of trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable.

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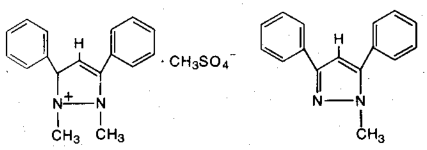

Difenzoquat
1,2-Dimethyl-3,5-Diphenyl-1H-
Pyrazolium Methyl Sulfate

1-Methyl-3,5-Diphenyl Pyrazole

Figure 1. The chemical structure of difenzoquat and its photodegradation product, 1-methyl-3,5-diphenylpyrazole.

which is registered only in Canada. Difenzoquat first was registered for use in wheat in 1975 and 1976 in the United States and Canada, respectively.

The physical characteristics of difenzoquat are described below (13). The pure chemical is a white to off-white, odorless, crystalline solid. The commercial formulation contains the methyl sulfate salt of difenzoquat and is nonvolatile and freely soluble in water. The water solubility of difenzoquat increases with temperature (173). At 0, 32, and 56 C, it is 26.8, 76.5, and 86.5% (w/w) soluble in water, respectively. Consequently, the commercial formulation is marketed in North America as an aqueous solution with added surfactant (173). Commercial formulations marketed in Europe lack surfactant. Because difenzoquat is stable to hydrolysis over a wide pH range from 5 to 9 (173), differences in water pH or hardness are unlikely to chemically modify it. In Canada and the United States, the formulation is 200 and 240 g ai/L, respectively (13), but the concentration ranges from 200 to 400 g ai/L in international markets. In 1983, 8% (w/w) urea was added to the formulation in North America as an antifreezing agent. If stored at 5 C or below, the chemical will crystalize, but redissolves when shaken. Because difenzoquat is fairly resistant to photodecomposition, it is marketed in translucent plastic containers. Aqueous solutions of difenzoquat do not attack stainless steel but do attack aluminum, zinc, or tin. The technical solid is stable at temperatures up to 50 C for an indefinite period. The commercial formulation is stable for at least 2 yr at 25 C.

II. AGRONOMIC ASPECTS OF DIFENZOQUAT USE

Rates, application methods, and spray additives. Effective wild oat control is achieved with difenzoquat at doses ranging between 0.75 and 1.4 kg ai/ha when applied with hydraulic nozzle spray systems (2, 83, 113). In the United States and Canada, more usual rates are between 0.84 and 1.12 kg ai/ha. Wild oat densities have been reduced 60 to 96% at 0.8 to 1.2 kg ai/ha difenzoquat. According to the registration label in both countries, higher rates should be applied to heavier stands of wild oats. Rates of 0.70, 0.83, and 1.12 kg ai/ha are recommended for densities of 10 to 108 wild oats per m^2, 108 to 269 wild oats per m^2, and greater than 269 wild oats per m^2, respectively. Whether the higher recommended rates are more effective in controlling denser stands of wild oats has not been extensively documented in the scientific literature. Carlson et al. (44) examined the effectiveness of difenzoquat in controlling various densities of wild oats growing in semidwarf 'Anza' spring wheat in California. Wheat yield was decreased as much as 25% as wild oat densities increased from 0 to 25 plants per m^2. Difenzoquat at 1.1 kg ai/ha did not completely control the densest stands of wild oats because yield decreased, but not as severely as for untreated controls.

The usual ranges of carrier volumes (50 to 190 L/ha) and postemergence pressures (140 to 280 kPa) were not critical factors for effective wild oat control with hydraulic nozzle sprayers (83). Difenzoquat provided adequate weed control at 1 kg ai/ha in volumes of 400 to 500 L/ha and 25 to 50 L/ha by ground and aerial application, respectively. In other research, 1 kg ai/ha was less effective when applied in 15 L/ha versus the more usual 150 L/ha (177). Wild oat control was increased at the lower carrier volume compared to that achieved by the higher carrier volume when a 10% solubilized oil additive was used. In a third study, difenzoquat in carrier volumes of 200 to 400 L/ha provided better wild oat control than in 100 L/ha over a dose range of 0.75 to 1.0 kg ai/ha (19, 20, 188). Carrier volume was varied by changing nozzle tips in a hydraulic system. According to the label, 47 to 187 L/ha carrier volumes are recommended for ground application of difenzoquat and 28 to 97 L/ha for aerial application.

Controlled droplet applicators (CDA) were used to apply difenzoquat in comparison trials with conventional hydraulic sprayers in the greenhouse and the field. Generally, wild oat control with difenzoquat at 1 kg ai/ha applied by CDA was inconsistent and unsatisfactory relative to conventional sprayers (18, 21, 98, 101, 178, 183, 187, 203). CDA with carrier volumes of 15, 30, and 45 L/ha was less consistent than hydraulic applications at 225 L/ha in winter wheat in the field (18) and greenhouse

(21, 178). In the field, 10 L/ha carrier volume gave poor wild oat control; 20 to 40 L/ha was needed for consistent control (21). In other greenhouse studies, CDA treatment at 40 L/ha provided better wild oat control than at 10 or 20 L/ha, but was still less satisfactory than conventional hydraulic nozzles (183). From an academic standpoint, these various studies confounded carrier volume, droplet size, and herbicide concentration.

Conceivably, difenzoquat cannot be applied effectively by CDA. However, CDA is a relatively new and untested technology which may require special herbicide formulations (95). To date, the comparisons between CDA and hydraulic sprayers have employed formulations of difenzoquat that were developed for hydraulic systems. Because the carrier volume is much lower with CDA than with hydraulic systems, the herbicide concentration must be raised to apply the same rates of herbicide per unit area. Thus, the amount of active ingredient contained in each droplet is greater in CDA (99). The droplet concentration applied by CDA may cause localized foliar necrosis, limiting foliar uptake and translocation to the sensitive shoot meristems (99, 183). This possibility warrants laboratory study. Wild oat control improved in growth chamber work as droplet concentration was decreased from 200 to 25 g ai/L, holding spray droplet diameter constant at 300 μm (100). In addition, comparisons of difenzoquat efficacy by CDA and hydraulic sprayers at equivalent rates are confounded by droplet size differences and different droplet densities and distributions on target surfaces. In fact, slightly more herbicide is retained on erect plant parts following CDA application relative to conventional applications (100). Droplet size cannot be varied easily without changing the number of droplets per unit area.

Foliar retention of difenzoquat on wild oats was greater for CDA than conventional hydraulic nozzles despite poorer control (98, 100). In these greenhouse trials, the carrier volumes were 20 L/ha with 250-μm droplets and 200 L/ha for CDA and hydraulic nozzles, respectively. Not only was more herbicide retained from the lower carrier volumes, but a greater proportion of the spray was intercepted by young or erect plant parts with the CDA, compared to the hydraulic nozzles. However, less spray was intercepted by the leaf sheath shrouding the apical meristem (99). Other research demonstrates that this is an important site of uptake (51, 179).

While some studies suggest that spray additives, such as ionic surfactants, improve selective control (75, 83, 203), other results are equivocal. Surfactants at 0.5% (v/v) added to difenzoquat at 0.8 kg ai/ha neither enhanced wild oat control in the field nor changed the margin of safety of the herbicide to wheat (193). Triton X-100 (iso-octyl phenoxy-polyethoxy ethanol, nonionic), Irol (nonylalkyl phenol, nonionic), Citowett (octylphenyl polyoxyethylene, isopropyl alcohol and water, nonionic), and Multifilm X-77 (alkylaryl-polyoxyethylene glycols, free fatty acids and isopropanol, nonionic) were tested in this work (193). However, surfactants enhanced injury to wheat in Europe (83). When X-77 at 0.4% (v/v) was added to difenzoquat at normal use rates, the herbicide also damaged barley (*Hordeum vulgare* L. #HORVX) and reduced yields in Wyoming (9). There appears to be little advantage to adding surfactant to the commercial formulation for improving wild oat control. However, according to the 1988 U.S. label, surfactants are recommended when applying difenzoquat at carrier volumes in excess of 93 L/ha at 138 to 276 kPa.

Surfactants enhanced foliar uptake of radiolabel from [^{14}C]difenzoquat in wild oats (167, 169). As the levels of the surfactant octoxynol were raised form 0.01 to 0.3% (v/v), herbicide uptake was increased, although there was little additional radiolabel uptake at surfactant levels greater than 0.3%. Likewise, [^{14}C]difenzoquat penetration increased when combined with commercial formulations of bromoxynil plus MCPA (1:1) at 0.58 kg ai/ha, 2,4-D ester at 0.56 kg ai/ha, and barban at 0.14 kg ai/ha (169). Parallel studies were not conducted on the effect of surfactant on either difenzoquat phytotoxicity to wild oats or selectivity with cereals. Other studies do not suggest large effects of these other herbicides on difenzoquat activity (see below).

Ammonium sulfate at 1 to 2.5% (w/v) enhanced the activity of difenzoquat on wild oats without reducing selectivity to barley in growth chamber research (167). Wild oat control at 0.56 kg ai/ha plus ammonium sulfate was equivalent to that normally achieved with 0.84 kg ai/ha.

The site of foliar application markedly influences the herbicidal activity and uptake of difenzoquat (45, 99). Toxicity to wild oats increased as the herbicide was applied toward the base of the leaves, close to the shoot meristem in greenhouse studies (51, 179). Difen-

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[3] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Weed Sci. 32, Suppl. 2. Available from WSSA, 309 W. Clark St., Champaign, IL 61820.

zoquat was most phytotoxic when the youngest fully expanded leaf was treated. More radiolabel from [^{14}C]difenzoquat was taken up from the inside of the leaf sheath than from the outside of the leaf sheath or either surface of the leaf blade. The reasons for enhanced uptake remain obscure. Conceivably, treatment of the inside of the leaf sheath makes the herbicide more available to vascular tissues of the apical meristem of the plant (51). Coupland et al. (51) also suggested that a humid microclimate may also favor entry at this site and that the cuticle is thinner there because of its immaturity, which favors penetration. There may be both qualitative and quantitative differences in the wax deposits of the cuticle on the inside of the leaf sheath, relative to other regions of the leaf surface. The relative contribution of these alternative explanations to site-specific uptake merit further study (51).

Wild oat control. Most field studies of difenzoquat efficacy have defined "control" of wild oats in terms of subjective ratings. Fewer studies document control in terms of either reductions in wild oat numbers per ha or improvements in cereal yield versus untreated controls. Likewise, year-to-year or place-to-place variability in wild oat control has not been well documented.

Difenzoquat has a narrow spectrum of weed control. While active on wild oats at 1.12 kg ai/ha, difenzoquat fails to control other important grass weed species in spring wheat, such as foxtails (*Setaria* spp.) (72, 104, 133). Several other oat species such as slender oats (*Avena barbata* Brot. # AVEBA) and winter wild oats (*Avena ludoviciana* Durien # AVELU) are controlled by difenzoquat.

Stage of treatment. Wild oats are susceptible to difenzoquat over a narrow range of growth stages (83). Optimum control was achieved when difenzoquat was applied to wild oats between the 3- to 6-leaf stage in spring-sown cereals. In general, wild oat control was better when applied at the 5-leaf than at the 3-leaf stage when growing in hard red spring wheat, durum wheat (*Triticum durum* Desf.), or barley (113). Occasionally, equivalent control was achieved at both stages in spring wheat (134). There are also occasional reports of higher crop yields when wild oats were treated at the 3-leaf stage than at the 5-leaf stage when growing in barley (61). When difenzoquat was applied at the 1- to 3-leaf stage, wild oat seedlings often recovered. It was suggested that recovery was due to the ability of the plants to form new tillers which then assumed the role of the main culm. These field observations are consistent with growth chamber studies in which difenzoquat controlled wild oats better at the 4-leaf stage than the 2-leaf stage (166).

The results of these trials in spring wheat, durum wheat, and barley were not verified in field studies using difenzoquat in ryegrass (*Lolium* spp.) grown for seed in the United Kingdom (96, 189). Conventional rates of 1 kg ai/ha gave better control at the 2- to 3-leaf stage than at the 5- to 6-leaf stage of wild oats (96, 189). Mild winters in the United Kingdom allow wild oats to emerge in winter cereals or forages over a protracted period during the fall or winter and then overwinter (96). The reasons why early fall treatment was more effective than later fall treatment are unknown (189). Because later fall treatments were applied when wild oats were in the less susceptible 5- to 6-leaf stage, a more complete ryegrass canopy could have intercepted more spray, reducing the dose reaching the weed. Sequential treatments of 1 kg ai/ha applied in both the fall and spring were more effective than single applications in either season. Undoubtedly, such sequential treatment was better tailored to controlling seedlings that emerged in both fall and spring. A single spring treatment was less effective than a single fall application. Early treatment of wild oats when winter wheat was tillering in the fall did not provide complete control, but it was superior to late treatment in spring at the time of wheat stem extension (172). Reapplication in the spring improved control above that achieved with only a single fall application.

Time of application during the day. The time of day when difenzoquat is applied may modify herbicidal activity. For instance, in four of six field experiments in North Dakota in hard red spring wheat, wild oat control was better between 1300 and 1700 h than at other times of day (154).

Ecotypes. Extreme differences in susceptibility to difenzoquat between 230 selections of wild oats were observed in field and greenhouse trials in North Dakota (124, 125, 201) and in 7 populations of slender oats from California (199). Control of shoot dry weight ranged between 41 and 97% with 1 kg ai/ha when applied at the 3- to 4-leaf stage. Attempts to correlate difenzoquat susceptibility with seed coat color of wild oats were unsuccessful (83). Wild oat tolerance was not related to leaf surface area, vigor, height, or tillering ability (201). Neither was difenzoquat tolerance related to area of origin or previous difenzoquat treatment. The genetic and physiological basis for these different responses deserves further study. Moreover, there are no data documenting shifts in wild oat populations toward greater resistance to difenzoquat in farmers' fields.

Comparisons with other herbicides. There are relatively few well-conducted field studies documenting the effectiveness of difenzoquat to enhance wheat yield by controlling wild oats relative to other herbicides (86). Most studies fail to include handweeded checks or consider only one or two other wild oat herbicides in comparisons. In one study from Alberta, difenzoquat enhanced wheat yield in one of three years at one site and four of four years at a second site (86). Difenzoquat at 0.84 kg ai/ha enhanced yields to the same extent as barban at 0.35 kg ai/ha, flamprop at 0.55 kg ai/ha, and diclofop at 0.70 kg ai/ha. In no-till spring wheat in Washington, difenzoquat at 1.4 kg ai/ha was inferior to either diclofop at 0.8 kg ai/ha or postplant incorporated or postplant surface-applied triallate at 2.8 kg ai/ha when wild oat control was evaluated visually; wheat yields of the three treatments were equivalent to a weed-free check (194). The authors noted wild oat emergence after herbicide application but concluded that late-emerging seedlings were not competitive with wheat.

Subjective ratings and yield were used to measure relative efficacy in other field studies. In these experiments in the Northern Great Plains, difenzoquat generally provided control equivalent or superior to that provided by diclofop at recommended rates (14, 32, 65, 120, 132). Similar results were observed in barley (5, 121, 158). Difenzoquat and diclofop provided better wild oat control than triallate in 1-yr trials in Idaho (132) and North Dakota (118).

Response of cereal crops. *Crop varietal response.* Cereals differ in their tolerance to difenzoquat. Barley is more tolerant than wheat whereas both winter wheat and durum wheat are more tolerant than spring wheat (42, 49, 55, 59, 83, 103, 109, 155, 160, 161). The varietal susceptibility of spring wheat and durum to difenzoquat has been studied extensively in field trials throughout North America (Table 1). In fact, current registrations in Canada and the United States limit difenzoquat use to particular hard red spring wheat varieties (Table 2). Certain varieties of durum wheat and winter wheat also cannot be treated with the herbicide without being damaged.

Limited data on the genetic basis of spring wheat response to difenzoquat demonstrate that resistance was a dominant Mendelian trait (22, 40). When tolerant 'Era' and 'Marshall' spring wheat were crossed in all combinations with susceptible 'Waldron' and 'Eureka' and treated with 1.7 kg ai/ha difenzoquat, the progeny of resistant and susceptible crosses segregated in a Mendelian fashion. These studies were verified and the dominant locus for difenzoquat resistance (Dfql) was located on chromosome 2B (200). Difenzoquat resistance was demonstrated to be dominant using F_2 monosomic analysis of crosses between resistant 'Chinese Spring' and susceptible 'Sicco' spring wheat after treatment with difenzoquat at 4.8 kg ai/ha. Crosses between 'Sicco' spring wheat and resistant winter wheat varieties also segregated in a 3:1 ratio in the F_2 for resistant:susceptible plants.

Generally, cereal crops are treated with difenzoquat between tillering and early jointing (83). Best wild oat control in barley was achieved from the middle to the end of tillering (152). While barley tolerated treatment at the 1- to 2-node stage, wild oat control was less satisfactory than with earlier treatment. Undoubtedly, wild oat seedlings were at a more advanced growth stage and were less sensitive to the herbicide. It is likely that the relative phenological development of crop and weed can influence the selectivity of difenzoquat.

Stage of growth at the time of difenzoquat application can influence spring wheat tolerance. Irrespective of spring wheat variety, greatest crop stand reductions occurred when the herbicide was applied between the 2- and 4-leaf stages (12). However, greater crop injury was observed at the 4-leaf stage than at the 2-leaf stage (107). Tolerance increased as the herbicide was applied progressively later during crop tillering (79, 175, 184, 185). The 2-to 4-leaf stage was more susceptible to damage than the boot, flowering, or heading stages (175). Depending upon the time of treatment, wheat maturity can be delayed (1).

Treating winter wheat with difenzoquat at high rates of 2 kg ai/ha at early tillering was less damaging than at later stages (176, 204). Fall application at early tillering caused increased tillering in the spring, resulting in more ears with smaller and fewer kernels. Later difenzoquat treatments reduced plant height and yield; seedheads often failed to emerge through the

Table 1. Varietal response of cereals to difenzoquat in terms of yield reduction, height reduction, or phytotoxicity (R = resistant, S = susceptible, I = intermediate).

Variety	Rate (kg/ha)	Response	Location	Reference
Hard red spring wheat:				
Aim	1.12	S	AZ	(76)
Alex	1.12	R	ND	(66, 119)
	1.68	S	MN	(30)
Angus	0.84–1.12	R	ND	(54, 108)
Anza	1.12	R	CA	(79, 128)
Bonanza	0.70–1.12	S	SD	(12)
Borah	1.12	S	ID	(130)
Bounty 208	0.70–1.12	S	SD	(12)
Butte	0.84–1.12	R	ND	(54, 110, 119)
		S	ND	(108)
	1.68	R	MN	(30)
Cajeme	1.12	R	AZ	(79)
		S	ND	(109)
Chris	0.70–1.12	S	SD	(12)
	0.84–1.12	S	MN	(37)
Coteau	0.84–1.12	R	ND	(54, 119)
		S	ND	(108)
Ellar	0.56	S	ND	(108, 113)
	0.84–2.24	I-R	ND	(103, 110)
Era	0.56	R	ND	(113)
	0.84–2.24	I-R	ND	(103, 108)
	1.12	R	ND	(119)
	0.84–1.12	R	MN, various	(37, 188)
	0.70–1.12	I	SD	(12)
Fielder	1.12	R	CA	(127)
Fieldwin	1.12	R	ID	(130)
Fletcher	0.70–1.12	R	Various	(180)
Fontana	0.84–1.12	R	MN	(37)
James	1.12	S	ND	(119)
Kitt	0.56–2.24	R	ND	(108, 113)
	0.70–1.12	R	SD	(12)
	1.68	R	MN	(30)
Len	1.12	S	ND	(110, 119)
	1.68	S	MN	(30)
Marshall	1.12	R	ND	(66)
	1.68	R	MN	(30)
Morloc	1.12	I-R	CA	(127)
M-711	1.68	R	MN	(30)
Marquis	1.68	R	MN	(30)
McKay	1.12	R	ID	(130)
Napayo	0.70–1.12	R	Various	(12, 181)
Neepawa	0.56–1.12	R	Various	(181)
ND600	1.12	R	ND	(66)
ND597	1.12	R	ND	(66)
NK Probred	1.12	R	AZ	(76, 77)
Nowesta	0.70–1.12	S	SD	(12)
Olaf	0.56	R	ND	(54, 113)
	0.70–2.24	I-R	ND	(103, 108)
	0.70–1.12	S	SD	(12)
Olaf	1.68	R	MN	(30)
Oslo	1.12	R	ND	(119)
	1.68	R	MN	(30)
Owens	1.12	R	ID	(130)
PB711	1.12	R	ND	(119)
Pioneer W3702	0.84–1.12	I	ND	(54)
Pioneer W6753	0.84–1.12	I	ND	(54)
Pioneer W4771	0.84–1.12	I	ND	(54)
Profit 75	0.84–2.24	R	ND	(103)
PR2360	1.68	R	MN	(30)
Polk	0.70–1.12	R	SD, various	(12, 181)
Prodax	0.70–1.12	R	SD	(12)
	0.84–2.24	R	ND	(103)
Protor	0.70–1.12	R	SD	(12)
	0.84–2.24	R	ND	(103)
Red River-68	0.70–1.12	R	Various	(181)

Table 1. *(Continued)*

Variety	Rate (kg/ha)	Response	Location	Reference
Sheridan	0.70–1.12	I	SD	(12)
Solar	1.12	R	ND	(110, 119)
	1.68	R	MN	(30)
Stoa	1.12	R	ND	(66)
Tenori	1.12	R	AZ	(77)
Tioga	0.56, 0.84–2.24	S	ND	(103, 113)
	0.70–1.12	S	SD	(12)
TL 75-409	1.12	I-R	CA	(127)
W51809	0.70–1.12	S	SD	(12)
	0.84–1.12	I	MN	(37)
Waldron	0.56	S	ND	(113)
	0.84–2.24	S	ND	(54, 103, 108)
	1.12	S	ND	(119)
	0.70–1.12	S	SD	(12)
	0.84–1.12	S	MN	(37)
Walera	1.68	R	MN	(30)
Ward	0.70–1.12	R	SD	(12)
	1.68	R	MN	(30)
WS-3	0.70–1.12	I	SD	(12)
WS-13	1.12	S	AZ	(76)
Yecora Rojo	1.12	R	AZ	(76, 77)
		R	CA	(127)
Yolo	1.12	R	CA	(127)
Zaragosa	1.12	S	AZ	(76, 78)
		R	AZ	(77)
99-AR	1.68	R	MN	(30)
Durum wheat:				
Aldure	1.12	S	AR	(78)
Botno	0.70–1.12	R	Various	(181)
Bugby	1.68	R	MN	(30)
Cando	1.68	R	MN	(30)
Crane	1.12	S	AZ	(77)
Crosby	1.68	R	MN	(30)
Edmore	0.70–1.12	R	ND	(108)
Gem	1.12	R	AZ	(78)
Hercules	0.70–1.12	R	Various	(181)
Jori	1.12	R	AZ	(77)
	1.12	S	AZ	(78)
Leeds	0.70–1.12	R	Various	(181)
Mexicali	1.12	S	AZ	(76, 78)
NK Aldura	1.12	S	AZ	(76)
Produra	1.12	R	AZ	(77)
Rolette	0.70–1.12	R	Various	(181)
Vic	1.12	S	ND	(66)
	1.68	S	MN	(30)
Ward	0.70–1.12	R	Various	(181)
		R	ND	(66, 108)
	1.68	R	MN	(30)
WPB 1000 D	1.12	R	AZ	(76, 77)
Wells	0.70–1.12	R	Various	(181)
		R	ND	(108)
Yavaros	1.12	R	AZ	(78)
Winter wheat:				
Triumph 64	1.12	R	OK	(94)

boot. When 10 English winter wheat varieties were sprayed at tillering with difenzoquat at 1 to 4 kg ai/ha, yields were reduced less than when plants were treated later at pseudostem elongation (204).

As Evans (58) points out, the yield components of wheat form at different times during the growing season. Ear and spikelet number is determined before anthesis. Grain number and grain size are determined at and after anthesis, respectively. The stage of crop growth at spraying can modify the total yield reduction, if there is any at all. Crop growth stage alters which yield components are most seriously affected by difenzoquat. In one study on Era and Waldron spring wheat, crop stand was most reduced,

Table 2. Label registration in 1985 for use on selected varieties of wheat in Canada and the United States.

Wheat type	United States	Canada
Winter wheat	All varieties except: Borah WS1877 WS1809 WS1859 Klassic Problend 771	
Soft white wheat	All varieties	
Spring durum	All varieties except: Edmore Lakota Wascona Vic	
Spring wheat	Only these varieties: Butte Coteau Era Fortuna Kitt Olaf Probrand 711 Solar Walera	Only these varieties: Chester Glenlea Macoun Neepawa Selkirk

whereas the number of kernels per spike was the next most significantly affected yield component (1). These components would contribute to yield before and at anthesis, respectively (58). In other trials, yield reductions could not be attributed to reduced numbers of spikelets per head nor reduced numbers of seeds per spikelet (54). Instead, there were fewer tillers per plant, especially when difenzoquat was applied early in plant development. Later applications of the herbicide decreased yield less, chiefly by reducing spikelet fertility. Thus, fewer kernels formed per seedhead. This was verified in the greenhouse. Difenzoquat damage to susceptible 'Modoc' and 'Portola' spring wheat was most pronounced when plants were sprayed at tiller initiation, and decreased when sprayed later in plant development (79). These latter results should be tested in the field and repeated over time. Path coefficient correlation analysis might put such studies on a more objective statistical basis and shed light on the effect of the herbicide on the relative contribution of different yield components to total yield, as well as possible mechanisms of yield component compensation. Such an analysis is useful in analyzing systems where variables are interrelated (53).

The physiological basis for difenzoquat susceptibility was studied using tolerant 'Maris Huntsman' winter wheat and susceptible 'Score' (176). When difenzoquat was applied at 0.01 to 4 kg ai/ha at the 4-leaf stage, plant height and leaf lamina length were reduced whereas tillering was increased. The latter effect was attributed to loss of apical dominance when the main shoot was killed. [^{14}C]difenzoquat retention, penetration, and translocation were similar in these wheat lines. Greater accumulation of difenzoquat in shoot meristems was believed to be responsible for susceptibility in sensitive varieties. DNA synthesis in sensitive Score also was inhibited to a greater extent than in tolerant Maris Huntsman.

Contribution of wheat competition to efficacy. Cereal competition may improve the efficacy of difenzoquat, but data are limited. Difenzoquat at 0.84 kg ai/ha reduced shoot dry weight of wild oats more in the presence of wheat than without crop competition in preliminary unrepeated field work (25). Barley was just as effective as wheat in this regard (166). One would expect an increase in crop stand to enhance wild oat control with difenzoquat. However, in Darling Downs, Australia, reducing wheat row spacing from 35.6 to 17.8 cm did not affect wild oat control with difenzoquat (184).

Response of other crops. Difenzoquat can be used safely in a number of broadleaf crops at rates of 0.75 to 1 kg ai/ha (Table 3). Difenzoquat had not been registered on any of these crops in 1988.

Environmental effects on efficacy. *Rainfall.* Difenzoquat is highly water-soluble (76.5%, w/

Table 3. Response of other crops to difenzoquat at 0.84 to 1.12 kg ai/ha (R = resistant, S = susceptible, I = intermediate).

Species	Variety	Response	Reference
Barley (*Hordeum vulgare* L.)		R	(13)
Broadbean (*Vicia faba* L.)		R	(41)
Buckwheat (*Fagopyrum sagittatum* L.)		R	(141)
Canarygrass (*Phalaris canariensis* L.)		R	(27, 197)
Corn (*Zea mays* L.)		R	(13)
Flax (*Linum usitatissimum* L.)		R	(4, 102, 105, 135)
Lentil (*Lens culinaris* Medic.)	'Common'	R	(73, 88)
	'Red Chief'		
	'Teko'		
	'Chilion'		
	'Laird'		
Lupin (*Lupinus albus*)	'Kiev mutant'	R	(39)
(*Lupinus angustifolius*)	'Unicrop'	R	(39)
Pea (*Pisum sativum* L.)	'Fenn'	R	(13)
	'Melrose'		(74)
	'Latah'		(75)
	'Garfield'		
	'Tracer'		
Rape (*Brassica napus* L.)	'Polish'	R	(83)
	'Argentine'	S	(6, 162)
Rye (*Secale cereale* L.)		R	(13)
Ryegrass (*Lolium perenne* L.)		R	(13)
Soybeans (*Glycine max* L.)	'Evans'	S	(13)
Sugarbeet (*Beta vulgaris* L.)		S	(6)
Sunflower (*Helianthus annuus* L.)		S	(115, 139, 140, 202)

w) at 25 C (38, 180). It is washed off leaves easily if rainfall occurs soon after application. The United States and Canadian registration labels caution that difenzoquat should not be applied if rain is forecast to occur within 6 hr. Independent research showed that at least 4 hr without rainfall must elapse for herbicide uptake to achieve adequate wild oat control (45, 83). Control progressively improved as rainfall was delayed from 30 min to 8 h after spraying in field trials in which 10 mm of simulated rain was applied at intervals after difenzoquat treatment (175). In greenhouse trials, 1 to 4 h were needed for herbicide uptake (147), and temperature modified plant responses. Difenzoquat at 0.5 kg ai/ha that was "washed off" leaves 1 h after treatment still controlled wild oats when the plants were grown at 27 C in a growth chamber (50), but control was decreased if plants were grown at 18 or 10 C after washing. Relatively light, simulated rains of 0.5 mm removed up to 29% of difenzoquat at 1 kg ai/ha without a loss of control (45). Light rainfall redistributed herbicide deposits from the lamina toward the base of the leaf. In the greenhouse, difenzoquat at 0.3 kg ai/ha plus surfactant controlled wild oats better 2 or 5 hr after simulated rain when applied by a conventional hydraulic application at 150 L/ha than by CDA (203). An oil/surfactant mixture increased difenzoquat phytotoxicity applied by CDA.

Temperature. Environmental factors following difenzoquat treatment can modify both weed control and crop selectivity. However, it is usually impossible to separate the effects of climate on herbicide efficacy from climatic effects on plant growth, except under carefully controlled growth chamber conditions. Wild oat control with difenzoquat at rates of 0.28 to 1.12 kg ai/ha was better at 30 or 20 C, compared to 10 C (50, 113, 122, 153). Shoot dry weight of wild oats was reduced more if high temperatures of 28/20 C (day/night) followed difenzoquat treatment at 0.56 to 1.12 kg ai/ha compared to low temperatures of 10/10 C (167). However, Retzinger and Nalewaja (154) were unable to verify these earlier studies. In other growth chamber studies, increasing rates of difenzoquat from 0.5 to 1 kg ai/ha overcame the detrimental effect of low temperature on wild oat control (113, 153). Temperature modified herbicidal activity only at rates that provided marginal control in the field. Wild oat control by difenzoquat at 0.7 kg ai/ha remained the same whether frost (−4 C) of 4-h duration occurred 12 h before spraying or either 6 or 12 h after spraying (191, 206). The physiological basis of how temperature changes wild oat susceptibility to difenzoquat warrants study.

High temperatures following application also caused greater cereal crop injury (83). As the temperature was raised from 10 to 30 C, penetration of [^{14}C]difenzoquat into leaves was enhanced. The reasons why elevated temperatures increase foliar penetration of herbicides are not well understood (138). It was not determined whether elevated temperatures also increased translocation from the foliage to the site of action in the shoot meristem to the same relative extent as foliar penetration. Enhanced translocation rates at high temperatures would increase the herbicide concentration gradient between the cuticular surface and the leaf interior, and facilitate penetration of difenzoquat.

Relative humidity. In general, high relative humidity enhances herbicide uptake and weed control with postemergence herbicides. Wild oat control with difenzoquat at 0.5 kg ai/ha was greater when plants were grown at 20 C and 90% relative humidity compared to 60% relative humidity (111). This was verified in related studies in which 85% and 35% relative humidity was tested (113). Increasing rates from 0.5 to 1.0 kg/ha overcame the effect of low relative humidity (111, 167). Relative humidity did not change the tolerance of wheat, barley, flax (*Linum usitatissimum* L.), or rapeseed (*Brassica napus* L.) to difenzoquat (167). High relative humidity (90 versus 30% at 10 to 30 C) enhanced [^{14}C]difenzoquat uptake by wild oat foliage (169).

Other factors. Soil moisture or fertility conditions that enhance wild oat growth also improve control. Drought reduced control in greenhouse and field trials (84, 113). Control of wild oats was improved if the soil was moist following difenzoquat treatment to greenhouse-grown plants. Soil moisture conditions after spraying influenced efficacy more than those before spraying. Long-term soil moisture stress only slightly reduced difenzoquat phytotoxicity to wild oats at the 3-leaf stage in related growth chamber research (207). Differences in expressing the data in different studies make it impossible to explain these contrasting results. Drought enhanced the phytotoxicity of sublethal (0.25 kg ai/ha) rates of difenzoquat to slender oat, in contrast to wild oats (199).

Increasing rates of fertilizer nitrogen ranging between 35 and 125 kg/ha enhanced the level of wild oat control achieved with 0.28 to 1.12 kg ai/ha difenzoquat in pot experiments in the greenhouse (113).

Although high light enhances the activity of some postemergence contact herbicides, increasing light intensities from 40 to 120 W per m^2 during the 8-h period immediately following difenzoquat treatment at 0.5 kg ai/ha had no effect on phytotoxicity in the growth chamber (50). However, Sharma et al. (167) observed greater wild oat susceptibility to difenzoquat at the 3-leaf stage when low light intensity of 9 klux followed application than with high intensities of 21.5 or 34 klux. Field studies need to be conducted to consider the effect of full sunlight on phytotoxicity.

Generally, difenzoquat is most effective when environmental conditions are conducive to active wild oat growth. The physiological basis for environmental effects on herbicide action remains largely unexplained (138).

Pesticide and growth regulator combinations. *Broadleaf herbicides.* Combinations of difenzoquat with other herbicides have been tested to broaden the spectrum of weed species controlled in wheat. Herbicide combinations may enable the rates of more expensive components to be lowered, as well as reduce the number of trips over the field. Thus, combination treatments may contribute to more economical chemical weed control. The 1985 United States registration permits the use of mixtures of difenzoquat with the ester and amine formulations of MCPA [(4-chloro-2-methylphenoxy)acetic acid] or 2,4-D [(2,4-dichlorophenoxy)acetic acid], bromoxynil (3,5-dibromo-4-hydroxybenzonitrile), chlorsulfuron {2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide}, and bromoxynil plus MCPA. In Canada, only mixtures with MCPA esters, 2,4-D esters, bromoxynil, or MCPA ester plus bromoxynil are registered.

Most research on difenzoquat has been concerned with compatible tank mix combinations for postemergence control of wild oats and broadleaf weeds, rather than sequential herbicide treatments (Table 4). Field studies document that formulated difenzoquat is physically compatible with several broadleaf herbicides: clopyralid, 2,4-D, 2,4,5-T [(2,4,5-trichlorophenoxy)acetic acid], MCPA, dichlorprop [(±)-2-(2,4-dichlorophenoxy)propanoic acid], bromoxynil, and ioxynil (4-hydroxy-3,5-diiodobenzonitrile) (16, 23, 24, 28, 33, 35, 43, 71, 83, 111, 112, 114, 116, 146, 174, 198). However, neither ioxynil nor 2,4,5-T is registered for use on wheat in either the United States or Canada. The sodium, potassium, and amine salts of the phenoxy herbicides 2,4-D and MCPA reduced wild oat control by difenzoquat (33, 83, 111, 137, 146), but the ester formulations of these herbicides did not affect control. It was

Table 4. Interactions between difenzoquat and other herbicides on wild oat control.

Herbicide	Broadleaf herbicide rate	Difenzoquat rate	Interaction on wild oat control[a]	Field (F) or greenhouse (G) reference
	— (kg ai/ha) —			
Broadleaf herbicides:				
2,4-D–Na +				
–K +				
–amine	0.56	1.12	A	F (91, 137)
–dimethylamine	0.28	0.84	A	F (111)
–ester	0.56	1.12	None	F (91, 137)
–ester	0.28	1.12	None	F (15)
–alkanolamine	0.28	1.12	A	F (15)
MCPA–amine	0.28	0.84	None	F (25)
	0.42	0.56	None	G (61)
	0.56	0.70–1.12	None	F (23, 24, 25)
–dimethylamine	0.56	0.84	A	G (143)
–ester	0.28	0.84	None	F (25)
	0.28	1.12	None	F (15)
MSMA	1.7	0.6	None	F (24, 112, 116, 123)
			S	F (90, 163)
Pendimethalin	1.0	1.0	S	F (64)
Fluorochloridone	1.12	0.56	None	F (67, 92)
		1.12	None	F (67, 136)
	1.12	0.56	None	F (157)
DPX-T6376	.007	1.12	None	F (129)
	.02	0.56	S	F (56)
Metsulfuron	0.017	1.12	None	G (57)
	0.02	0.84	None	F (31)
Chlorsulfuron	0.01	1.12	A	F (156)
	0.03	0.56	A	F (26, 36)
	0.03	1.12	None	F (10, 33)
	0.04	0.84	A	F/G (145)
	0.06	0.56	A	F (10, 33)
Metribuzin	0.21–0.28	0.84	A	F/G (142)
Linuron	0.21–0.28	0.84	A	F/G (143)
Picloram				
–triisopropanolamine		0.84	None	F (144)
Propanil	1–1.3	0.6–0.9	A	G (165)
	1.68	0.70	A	F (35, 174)
	1.68	0.84	A	F (111)
Dicamba	0.11	0.56	None	G (61)
Bromoxynil	0.28	0.84	None	F (23, 35)
	0.28	1.12	None	F (16)
+ MCPA (1:1)	0.42	0.56	None	G (61)
Wild oat herbicides:				
Triallate	1.12	1.12	None	F (7)
			S	F (6, 8, 11)
Barban	0.14	0.24	None	F (146)
	0.28	0.84	None	F (133)
	0.28	0.56	None	F (129)

[a] A = reduced activity or antagonism.
S = enhanced activity or synergism.
None = no interaction.

suggested that tank mixture incompatibility caused this interaction (137). In Minnesota, wild oat control by difenzoquat at 0.71 kg ai/ha was reduced by an amine formulation of MCPA (23), but higher rates of difenzoquat overcame the antagonism, which is a characteristic response of incompatible chemical combinations. However, later studies by the same authors failed to substantiate these initial observations of antagonism (24, 35).

There has been some interest in combining difenzoquat with propanil [*N*-(3,4-dichlorophenyl)propanamide], a postemergence herbicide that can be used to control foxtails (*Setaria* spp.) and certain broadleaf weed species in wheat. Unfortunately, propanil and difenzoquat combinations decreased wild oat control relative to difenzoquat alone when applied between the 4- and 4½-leaf stages of wild oats (25, 106, 111, 174) (Table 4). There was no indication of chemical reaction or incompatability when difenzoquat and propanil were mixed (165). However, propanil severely reduced [^{14}C]difenzoquat uptake on the leaf surface. Surfactants, such as Triton X-100, did not reverse this effect.

Combinations of MSMA (monosodium methanearsonate) with difenzoquat at 1.7 and 0.6 kg ai/ha, respectively, were tolerated by wheat when applied at the 4- to 5-leaf stage (116, 123). Wild oat control in wheat was inconsistent, but control of redroot pigweed (*Amaranthus retroflexus* L. # AMARE) and green foxtail [*Setaria viridis* (L.) Beauv. # SETVI] was acceptable. Other studies document better wild oat control by these combinations than by difenzoquat alone (90, 163). Other researchers (24, 112) observed no statistically significant enhancement of wild oat control with the combination. When difenzoquat rates were increased to 1.12 kg ai/ha, there was no antagonism. MSMA was not registered in 1988 for use in wheat in the United States or Canada.

Canadian researchers attempted to widen the spectrum of weed control by combining metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] and difenzoquat (142). Tank mixtures of 0.21 to 0.28 and 0.84 kg ai/ha, respectively, reduced wild oat control. However, this interaction was not due to inert ingredients in the metribuzin formulation. In greenhouse trials, when difenzoquat treatment was followed after several days by metribuzin, wild oat control was not decreased.

There is no indication that difenzoquat decreases broadleaf weed control from broadleaf herbicides used in combination (16, 83). Common lambsquarters (*Chenopodium album* L. # CHEAL) or kochia [*Kochia scoparia* (L.) Schrad. #KCHSC] control was unaffected when difenzoquat was combined with MCPA, bromoxynil, dicamba (3,6-dichloro-2-methoxybenzoic acid), or 2,4-D ester (16). Combinations of difenzoquat and metribuzin did not influence the control of Tartary buckwheat [*Fagopyrum tatarium* (L.) Gaertn.] by metribuzin (142). In fact, difenzoquat alone or in combination with barban reportedly increased the activity of broadleaf herbicides on Tartary buckwheat (146).

Wild oat herbicides. Occasionally, interactions between difenzoquat and other wild oat herbicides have been studied (Table 4). The overall goal of such work is to reduce the rate of application of the most expensive wild oat herbicide in the combination or to achieve more complete wild oat control.

Combinations of barban and difenzoquat have been tested to extend the activity of these herbicides on wild oats. Barban must be applied at the 1- to 2-leaf stage of wild oats, whereas difenzoquat is most active at the 3- to 5-leaf stage. Barban at 0.14 kg ai/ha combined with difenzoquat at 0.42 kg ai/ha acted in an additive fashion to control wild oats at the 2- to 4-leaf stage (146). In Arizona, the combination of barban and difenzoquat at 0.42 and 1.12 kg ai/ha, respectively, was phytotoxic to 'Crane 56 M' durum wheat (81). The combination decreased durum wheat yields and stunted plants compared to difenzoquat alone. Crop maturity was delayed and test weight was reduced. There are no reports of grass or broadleaf herbicides that synergize the action of difenzoquat on wild oats.

In Canada, difenzoquat at 1 kg ai/ha applied after preplant-incorporated triallate at 1.4 kg ai/ha did not increase either wild oat control or Neepawa spring wheat yields beyond triallate alone (195). In one of four years wheat was visually damaged and stunted by difenzoquat applied after either triallate at 0.7 kg ai/ha or trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine] at 0.7 kg ai/ha, but wheat yields were not reduced.

Fertilizers, fungicides, and insecticides. There has been some interest in reducing the number of trips over the field by application of herbicides and fertilizers together. Studies in Idaho indicated that difenzoquat at 0.84 to 1.12 kg ai/ha could be combined successfully with 28 kg/ha of granular nitrogen or 'SOL 32' nitrogen to achieve wild oat control (89). The wheat was injured only at higher rates of nitrogen and difenzoquat.

Difenzoquat is compatible with several postemergence cereal fungicides: benomyl {methyl[1-(butylamino)carbonyl]-1*H*-benzimidazol-2-yl]carbamate}, carbendazin, ethirinol [5-butyl-2-(ethylamino)-6-methyl-4(1*H*)-pyrimidinone], thiophanate-methyl {dimethyl[1,2-phenylenebis(iminocarbonothioyl)]bis-[carbamate]}, tridemorph (2,6-dimethyl-4-tridecylmorpholine), and maneb {[[[1,2-ethanediylbis]carbamodithioato]](2-1)[manganese]}(180). Only benomyl is currently registered for use as a foliar spray in wheat in the United States. Likewise, difenzoquat was found to be compatible with a variety of insecticides used on spring wheat: disulfotan {*0,0*-diethyl *S*-[2-(ethylthio)ethyl] phosphorodithioate} and carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate) at 1.12 kg ai/ha applied as granules at planting. Phorate {*0,0*-diethyl *S*-[(ethylthio)methyl]phosphorodithioate}, applied at 1.12 kg ai/ha at planting, decreased wheat yields with difenzoquat applied at the 3-leaf stage (15). Weed control was not affected by the insecticides. Difenzoquat is also compatible with several plant growth regulators, although cereals may be injured by some of them. It is compatible with chlormequat [(2-chloroethyl)-trimethylammonium chloride], ethephon (2-chloroethylphosphonic acid), triacontanol (1-hydroxytriacontane), mefluidide {*N*-[2,4-dimethyl-5-[[(trifluoromethyl)sulfonyl]amino]-phenyl]acetamide}, and chlorflurenol (methyl 2-chloro-9-hydroxy-9*H*-fluorene-9-carboxylate) (106). Only ethephon is registered in wheat, although it generally is applied much later than difenzoquat in wheat development as an antilodging agent.

Implications of long-term use of difenzoquat. While there is a great deal of information about the use of herbicides for short-term weed control, the long-term implications of repeated treatment of the same land have been ignored. Is there any possibility of achieving eradication of a particular weed? If eradication is not possible, how many years of repeated herbicide application would be needed to reduce weed populations below the economic threshold of crops? In Australia, Wilson (184) found panicle production of wild oats was decreased from 1500 to 500 panicles per m^2 following difenzoquat application at 1 kg ai/ha to wheat. However, panicle number gives only a rough estimate of reproductive output because of wide plant-to-plant variability in seed production. With such incomplete control, repeated use of difenzoquat alone probably would not reduce wild oat populations in subsequent years. In other studies on wild oat control in winter wheat in the United Kingdom, difenzoquat decreased seed production between 72 and 99%, depending upon the time of treatment and the density of wild oats present during spraying (184, 185). Few researchers have studied how thoroughly seed production must be prevented to eradicate weeds on farmland. Allen and Smallridge (3) calculated that 95% control of wild oat panicles would be needed for eradication in New Zealand. More studies are needed in a greater range of environments to test this concept more fully.

For wild oat eradication to be possible it will require a much better understanding of how herbicide use can be integrated with other crop management practices. The relative contribution and date of crop rotation, crop species, variety, row spacing, planting rate, and weed phenology to herbicide efficacy must be studied. For example, Jarvis and Clapp (82) pointed out the importance of crop competition to the long-term efficacy of difenzoquat control of wild oats. Difenzoquat applied annually to continuous winter wheat over 3 yr decreased wild oat panicle numbers exponentially. However, in barley, wild oat panicle numbers increased slightly although somewhat less than for the untreated controls.

In winter wheat in Spain, difenzoquat reapplied to the same land at 0.99 kg ai/ha over 3 years severely reduced new seed production and populations of winter wild oat (*Avena ludoviciana* Durien # AVELU) (196). Whereas difenzoquat did not reduce seedling emergence or the fecundity of survivors, seedling survival was reduced to between 28 and 48% of control survival. The net effect was to reduce the soil seed reserve of winter wild oats over time, but this decrease was not large enough to eliminate herbicide treatment after 3 years. Control improved over time due to both residual reductions in winter wild oats and direct herbicide phytotoxicity.

More well-designed field studies are needed for other combinations of crop management strategies and herbicide use for wild oat control in cereals. Despite the numerous studies on wild oat control with difenzoquat, most field work has neglected to document the density, biomass, or seed production of wild oats that was present. These data gaps limit modeling efforts which attempt to project changes in wild oat populations over time under a given management strategy.

Environmental fate. With the exception of abstracts, little has been published about the fate of difenzoquat in the soil. According to unpublished reports of American Cyanamid, it is not degraded by soil microorganisms and is not active in inhibiting microorganisms in the soil (38, 83). Independent laboratory studies (17) support this latter assertion, since difenzoquat at rates equivalent to 0.9 to 9 kg ai/ha failed to influence the oxidation of gelatin, cellulose, or chitin to carbon dioxide by mixtures of soil microorganisms. Neither nitrification, as measured by NO_3- formation, nor sulfur oxidation, as measured by SO_4- formation, was affected by the herbicide. Difenzoquat at 1 kg ai/ha did not affect the microbial degradation of bromoxynil or its octanoyl ester in field and laboratory studies (170). Despite this, the persistence of difenzoquat in the field was limited (83). In five field experiments, it was found that the half-life of difenzoquat was about 3 months (83). At a rate of 1.12 kg ai/ha, 45% of radiolabel from ring- and N-methyl-labeled difenzoquat was lost in 16 weeks (62). The herbicide was relatively tightly adsorbed on soil and was not leached into the soil profile (38). Residues were not detected in soil within 1 yr following treatment.

In cereals treated in the field, difenzoquat on crop residues was much less persistent and had a half-life of about 4 days (173). These plant residue analyses (173) contrast with the assertion that difenzoquat is not metabolized in plants (38, 83). Because of its short persistence in wheat and the environment, there are no label restrictions on rotational crops in either the United States or Canada. Wheat grain and straw can be used legally for livestock feed, although the growing crop should not be grazed.

III. SELECTIVITY AND PHYSIOLOGICAL ASPECTS OF DIFENZOQUAT USE

Foliar retention. Foliar retention did not provide a basis for selectivity of difenzoquat between wild oats and 'Larker' barley at the 3- and 5-leaf stages (153). Barley retained more herbicide per plant or per unit of leaf area than wild oats, although retention was similar on a fresh weight basis. Wild oats had 48% less fresh weight and 37% less leaf area than barley. More herbicide was retained by both species at the 5-leaf stage than the 3-leaf stage, whether it was expressed per plant, per gram of fresh weight, or per unit of area. However, phytotoxicity was greater if the herbicide was applied close to the shoot meristem. The amount of herbicide reaching the meristem was not determined but may differ between different leaf stages. Likewise, the surfaces of younger plants may absorb more herbicide near sensitive meristems than older plants. Also, higher herbicide doses may be needed to control wild oats as plants age.

Foliar penetration. Uptake of [^{14}C]difenzoquat into the expanded leaves of susceptible wild oats and resistant barley also was similar (167, 169, 182). After 24 and 72 h, 40% and 80 to 90%, respectively, was absorbed by these two species. Detailed time-course studies of [^{14}C]difenzoquat penetration into wild oat leaves verify these results (205). While selectivity could not be explained by differences in foliar uptake of [^{14}C]difenzoquat by mature leaves, there may be differences in uptake between these species for other leaf surfaces. The wild oat leaf cuticle limits the rate of foliar penetration of [^{14}C]difenzoquat, since penetration was stimulated after cuticles were stripped from the leaf with cellulose acetate or damaged by brushing (205).

Translocation and metabolism. Most studies of [^{14}C]difenzoquat transport in plants are qualitative. There has been relatively little effort to quantify the movement of radiolabel from [^{14}C]difenzoquat within susceptible wild oats or to relate the amounts of radiolabel entering leaves to that which is translocated. Autoradiographs indicate that movement is chiefly acropetal following foliar treatment (169). Most radiolabel appeared to accumulate in the treated leaf area and several mm distal to it (45, 61). One day following postemergence treatment, some radiolabel was found in the roots (169). However, radiolabel accumulating within the growing tip was not quantified in these studies. Some unpublished work suggests that only 0.5% of the radiolabel from [^{14}C]difenzoquat applied to the upper surface of wild oat leaves reached the apical meristem in 48 h (cited in 80). Increasing difenzoquat concentration from 25 to 200 g/L decreased translocation from the treated leaf to the apical meristem from 2.5 to 1.3%, respectively, of the applied dose (99). The authors attributed this to localized damage to the phloem. In earlier work, when difenzoquat was injected just below the shoot apex, it moved to the new leaves (61). It would be of interest to determine if difenzoquat moves acropetally into the xylem of excised leaves immersed in herbicide, particularly in light of its limited acropetal movement from the roots to the shoots (169).

Translocation was influenced by the site of difenzoquat uptake and by environmental conditions. Translocation from the inner sheath to other plant parts was 100 times greater than from other regions of the shoot (45). Radiolabel transport from the site of application was greater in otherwise unsprayed plants of wild oats at 30 C than at 10 C. It was suggested that greater movement resulted from greater cuticular penetration (169), but enhanced translocation at elevated temperatures was not excluded. In addition, the extent of translocation of [^{14}C]difenzoquat may be changed by whole-plant spray treatment or spray concentration.

Generally, difenzoquat is not believed to have activity when applied via the root system. Roots of hydroponically grown wild oats absorbed [^{14}C]difenzoquat (169); radiolabel from difenzoquat was not removed from the root system by ordinary washing. However, there appeared to be little entry into the xylem following root uptake since there was little movement of radiolabel to the shoot in autoradiographs, except after a 72-h period (169). In other greenhouse trials with wild oats at the 2-leaf stage, sufficient root uptake of difenzoquat via the soil or nutrient solution occurred to inhibit shoot growth (179).

Reportedly, difenzoquat is not metabolized by plants (83). During a 15-day incubation period in a growth chamber, metabolites of the parent compound were not found in wheat, barley, or wild oats (169). Since total recoveries were not reported, relative comparisons between species may be misleading. A balance sheet approach to account for applied radiolabel was not used. Losses could have been due to photolysis, volatilization, or conversion to [^{14}C]carbon dioxide, without accumulation of intermediates. Photolytic demethylation of difenzoquat to 1-methyl-3,5-diphenyl pyrazole results in a product that is volatile and can be lost to the aerial environment (38) (Figure 1). Relative to the parent material, the breakdown product is slightly toxic to wild oats, but quantitative reports of its relative phytotoxicity were not presented. More recent methods of separating difenzoquat by high-pressure liquid chromatography might be used in studies of herbicide metabolism (87). Residue analysis of wheat foliage demonstrated that difenzoquat had a half-life of only 4 days (173). The routes of this rapid and extensive loss were not determined.

Despite these studies of foliar retention, penetration, translocation, and metabolism of [^{14}C]difenzoquat in susceptible and resistant species, the selective action of difenzoquat in controlling wild oats in cereals remains to be explained. The reasons for ecotypic differences in difenzoquat activity between different strains of wild oats have not been studied. One important requirement is to quantify how much unlabeled difenzoquat reaches sensitive shoot meristems following spray treatment as a function of that intercepted. The threshold doses that cause growth inhibition at the shoot meristem need to be determined before the relative contribution of herbicide retention, penetration, translocation, and metabolism to phytotoxicity can be determined. Threshold doses should be determined in shoot meristems of intact plants when growth is first inhibited following herbicide treatment. Direct injection of solutions of difenzoquat into shoot meristems of intact susceptible and resistant plants might be instructive. Alternatively, the dose-response relationships of actively growing suspension cell cultures of wheat or barley and wild oats to difenzoquat might be useful in defining critical doses affecting cell division, enlargement, or other sites of action.

Mode of action. Some aspects of the mode of action of difenzoquat have been reviewed recently (164). The type of injury symptoms observed must be considered in any explanation of the mode of action of difenzoquat. Injury to wild oats takes several days to develop following postemergence treatment in the field (83). Symptoms can take as little as 4 to 5 days or as much as 10 to 14 days to develop following spraying (188), depending on environmental conditions. Growth inhibition is often accompanied by a deeper green coloration of the young expanding leaves. Foliar chlorosis and eventual necrosis of susceptible wild oats follows. When 3- to 5-leaf stage wild oat seedlings were treated with 1.1 kg/ha difenzoquat and observed 6 days later, chlorophyll a and b had decreased by only 11% (47). Because the ratio of chlorophyll a/b was the same in both treated and control plants, the herbicide did not affect the conversion of chlorophyll a to b. In susceptible lines of wheat and barley, transient foliar chlorosis disappeared in leaves formed within a 2-week period following spray treatment. Tiller number can be increased in wild oats treated with difenzoquat, but the tillers often are stunted (80, 83). Sometimes tillers escape injury and help reestablish viable plants (61). Light is not needed for herbicidal injury to wild oats (70). If plants are kept in light after treatment, membrane damage is less extensive than in the dark.

Ultrastructural changes induced by 1 to 2 kg ai/ha difenzoquat were similar in susceptible ‘Sicco’ and tolerant ‘Maris Butler’ spring wheat (149). Mitochondrial disruption was preceded by damage to other organelles. Seven days following treatment, chloroplasts were swollen and had large starch grains. The tonoplast also was disrupted at 14 days, and chloroplast thylakoids were swollen and disorganized. Starch was absent at that time and there were numerous plastoglobuli.

Wild oats surviving postemergence treatment with difenzoquat at 0.75 kg ai/ha had decreased reproductive potential (83, 97). Panicle number, panicle weight, and the number of seeds per panicle were all decreased in surviving plants. However, the effect on the seed size and its germination capacity was not statistically significant (83, 97). Wheat injury from difenzoquat did not involve parent-progeny effects (1). In resistant Era wheat, germination was unaffected, whereas in susceptible Waldron, germination was only slightly reduced.

Part of the action of difenzoquat is inhibition of leaf elongation. In susceptible wheat lines, new leaf elongation was reduced and the leaf spacing on the axis was abnormal, even though the rate of leaf initiation was unchanged (148, 151). Both cell elongation and division were disrupted by difenzoquat (83, 151). DNA synthesis in susceptible Sicco spring wheat was inhibited, whereas it was not in resistant 'Butler' (151), suggesting that differential response of DNA synthesis to difenzoquat was a basis of varietal susceptibility in wheat.

There have been few studies of the ultrastructural effects of difenzoquat following foliar treatment of wild oats. In one anatomical study 10 μl of a 1% solution of difenzoquat was injected into the base of the shoot (61). Not only is this method of treatment suspect, but comparisons were made with uninjected controls. Since difenzoquat is applied as a postemergence spray, direct injection into the shoot meristem could apply a higher dose than normal, swamping normal detoxification pathways and causing more rapid injury symptoms than would develop normally. Controls injected with solutions lacking difenzoquat also should have been included.

Another difenzoquat symptom is foliar chlorosis and necrosis. Seven days following treatment with 1.12 kg ai/ha difenzoquat at the 3-leaf stage, photosynthesis was inhibited only 18% (46) and assimilate translocation also was decreased. Difenzoquat at 1 mM did not inhibit photosynthesis, uncouple electron transport, or reduce proton uptake of either isolated chloroplasts or protoplasts of wheat or wild oats (70). These authors concluded that difenzoquat could act as a weak electron accepter and energy transfer inhibitor because it inhibited photophosphorylation. In other studies, the transpiration rate of wild oats was decreased 2 days after treatment (168). The relative contribution of chlorosis and photosynthetic inhibition to decreased leaf growth from difenzoquat remains to be determined.

Difenzoquat was fungicidal to downy mildew (*Erisyphe graminis*) in the field in the United Kingdom (190). Mildew control was rated as a percentage of the wheat or barley leaf area infested. As rates of the herbicide and surfactant were increased from 0.5 to 1 kg ai/ha and 0.05 to 0.5%, respectively, the fungicidal activity of difenzoquat increased. However, this effect was not reflected in cereal yields, perhaps because yields were not limited by the disease. Abnormally hot dry weather following herbicide treatment limited foliar reinfection by downy mildew. Consequently, infections were light.

IV. DISCUSSION

Because it lacks soil activity, difenzoquat must be applied postemergence. Thus, the added cost of incorporation is unnecessary, in contrast to triallate. If infestations of wild oats are sparse, the decision to control them with a herbicide can be delayed until after wild oat emergence. As a postemergence herbicide, difenzoquat is adapted to minimum-tillage agriculture. Thus, difenzoquat can be used for wild oat control in reduced-tillage spring cereals, following application of paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) or glyphosphate [*N*-(phosphonomethyl)glycine] at planting. Farmers should not apply the herbicide until wild oat seedlings have emerged and reached the 3-leaf stage. While time of application is important, it may be extended over a longer period than for some other postemergence wild oat herbicides, such as barban. Wild oat seedlings also can be sprayed at later growth stages after planting than barban. Consequently, a greater proportion of wild oats seedlings likely to emerge in a given growing season have emerged by the time of spraying. Unlike barban, flamprop, benzoylprop, or diclofop, difenzoquat can be combined with a range of broadleaf herbicides. Thus, fewer trips over the field are needed to apply herbicides. Later treatment of wild oat seedlings coincides with the time for treating broadleaf weed seedlings. Because of its specificity, difenzoquat does not represent a drift hazard to most nearby crops.

Like triallate and barban, difenzoquat is highly specific for wild oats. In contrast, postemergence treatments of diclofop control a wider spectrum of grass weeds in addition to wild oats. As conservation tillage becomes more widely adopted, shifts in the weed spectrum and reductions in wild oat infestations may result in decreased use of this wild oat-specific herbicide. Difenzoquat also cannot be used on all cereal varieties and some varieties will show severe phytotoxicity and decreased yields if treated. As new wheat varieties are introduced, they must be screened to determine whether difenzoquat injures them or reduces yield under weed-free conditions. Unfavorable weather conditions at the proper stages to treat wild oats can limit the efficacy of difenzoquat. Likewise, environmental conditions following spraying may either predispose normally tolerant cereal varieties to injury or may reduce wild oat control. Wild oat seedlings that emerge following spraying also escape treatment, form new seeds, and may reduce yields. No currently registered (1985) wild oat herbicide can be used to control broadleaf weeds.

Short-term research should be initiated to explore some of the unanswered questions concerning the use of difenzoquat. More applied and fundamental research should be directed at exploring how to modify spray retention and difenzoquat uptake and translocation. Effective use of new application technology, such as CDA or electrodyn applicators, requires a better understanding of herbicide formulation in relation to herbicide retention and uptake. Likewise, laboratory studies of new sprayer technologies should be combined with detailed field biology studies of why wild oats escape treatment. Perhaps a better knowledge of weed phenology in relation to crop development would be helpful. Certainly, agronomic practices, such as delayed crop planting and crop variety, will influence how well synchronized the growth of wild oats is with that of the crop. Tillage practices will also determine whether wild oat emergence will or will not extend over a protracted period. The relative effect of wheat variety and planting rate on control of wild oats with difenzoquat should be explored.

For all practical purposes, the basic mode of action of difenzoquat has not been determined. Understanding the selectivity mechanisms for the response of crop varieties and wild oat ecotypes to difenzoquat will require new research approaches. Likewise, the basis for herbicide interactions with difenzoquat needs detailed study. Field studies of herbicide interactions were seldom complete enough to permit regression modeling of wild oat growth reductions in response to various herbicide combinations. Such an approach is valuable in generating three-dimensional response surfaces of the interaction. Neither were interactions subjected to thorough statistical analysis. Prediction of potential interactions between herbicides will be hampered without greater attention to herbicide mode of action. By default, interaction research will remain largely empirical for a long time to come. Likewise, the mechanism of how temperature and water stress modify plant response to difenzoquat is unknown. If such stress-related effects are to be predicted for other herbicides, at least a few must be understood in physiological and biochemical terms.

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