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Influence of Drought on Graminicide Phytotoxicity in Wild Oat (*Avena fatua*) Grown under Different Temperature and Humidity Conditions

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Abstract. Controlled environmental experiments were carried out to determine the phytotoxicity of several graminicides on wild oat (*Avena futua* L.) as influenced by combination of drought and temperature stress or drought and low relative humidity. Compared with unstressed conditions (20/15°C plus adequate soil moisture), imazamethabenz phytotoxicity to wild oat was reduced significantly when plants were exposed to a combination of drought and high temperature (30/20°C) stress. Imazamethabenz phytotoxicity was reduced almost as much by high temperature stress alone as by a combined temperature and drought stress. When herbicides were applied to wild oat plants subjected to drought alone or to drought plus high temperature, the observed reduction in phytotoxicity from greatest to least was: fenoxaprop = diclofop > flamprop > imazamethabenz. Fenoxaprop performance was most inhibited by the combination of drought plus high temperature, although drought alone and to a lesser degree, high temperature alone, inhibited fenoxaprop action. High temperature had an adverse effect on the efficacy of fenoxaprop at lower application rates. Raising fenoxaprop application rates to 400 g ha^{-1} overcame the inhibition caused by high temperature alone but only partially alleviated the effect of drought combined with high temperature. When plants were grown under a low temperature regimen the imposition of drought stress had little effect on imazamethabenz phytotoxicity but did reduce fenoxaprop phytotoxicity. At 25/15°C drought reduced the phytotoxicity of fenoxaprop and diclofop greatly but had no significant impact on the performance of any of the herbicides examined, regardless of soil moisture regimen.

Key Words. Diclofop—Drought—Fenoxaprop—Flamprop—Humidity—Imazamethabenz—Multiple stress—Phytotoxicity—Temperature—Wild oat

The performance of postemergent herbicides can be affected by a number of environmental factors (Gerber et al. 1983, Kudsk and Kristensen 1992). Under natural conditions, the change of one environmental factor is frequently accompanied by other changes (Chapin et al. 1987). For instance, drought stress is often accompanied by high temperature and/or low relative humidity (RH). Therefore, it would be desirable to examine concurrently the influence of two or more environmental factors on herbicidal phytotoxicity. Beghun and Nalewaja (1984) demonstrated a reduced phytotoxicity of barban (4-chloro-2-butynyl 3-chlorophenylcarbamate) to wild oat (*Avena fatua* L.) in an ''unfavorable'' environment (30°C, 11% RH, poor soil fertility, and low soil moisture) compared with phytotoxicity in a ''favorable'' environment (10°C, 80% RH, high soil fertility, and adequate soil moisture). Drought reduced diclofop {(±)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid} in barnyard grass [*Echinocloa crus-gali* (L.) Beauv.], but the effect was alleviated by relatively high temperature (West et al. 1980). In contrast, the tendency for drought to reduce glyphosate [*N*-(phosphonomethyl)glycine] phytotoxicity in liverseed grass (*Urochloa panicoides* Beauv.) was more evident at high temperatures (Tanipat and Adkins 1992). The adverse drought effect on glyphosate applied to purple nutsedge (*Cyperus rotundus* L.) was partly alleviated by high RH, which could be attributable to enhanced herbicide translocation under high RH (Chase and Appleby 1979). Similar results were obtained when poverty brome (*Bromus sterilis*) was treated with metoxuron [3-(3-chloro-4-methoxyphenyl)-1,1-dimethylurea] (Blair et al. 1983). Nevertheless, pre-

Abbreviations: RH, relative humidity; LSD, least significant difference.

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vious studies have focused mostly on the influence of an individual environmental factor (e.g. temperature, soil moisture, or RH), and there is limited information on the impacts of combined environmental factors on herbicide performance.

Drought reduced the phytotoxicity of fenoxaprop {(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy] phenoxy]propanoic acid} in wild oat (Xie et al. 1993, 1994b) and in smooth crabgrass [*Digitaria ischaemum* (Schreb. ex Schweig) Schreb. ex Muhl] (Rossi et al. 1994). High temperature and, to a lesser extent, low temperature stresses had an adverse effect on fenoxaprop performance (Xie et al. 1994a). The performance of diclofop was also decreased by stresses in soil moisture (Akey and Morrison 1983, Dortenzio and Norris 1980) or high temperature (Donn and Bieringer 1980, Hassawy and Caseley 1983). Drought reduced flamprop [*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl-DL-alanine] phytotoxicity in *Avena sativa*, although this effect was not as profound as the effect of low temperature (Jeffcoat et al. 1977). The phytotoxicity of imazamethabenz {(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2yl]-4 and 5-methylbenzoic acid (3:2)} and flamprop in wild oat was relatively insensitive to drought or temperature stresses (Miller et al. 1979, Xie et al. 1993, 1994a, 1994b). The objective of the present study was to examine the effect of the combined stresses of drought and high temperature, drought and low temperature, or drought and low RH on the phytotoxicity of imazamethabenz, fenoxaprop, diclofop, and flamprop in wild oat.

Materials and Methods

General Procedure

Growth chamber experiments were conducted at the Agriculture Canada Regina Research Station. A natural population of wild oat collected from the Regina area was used. The seeds were pregerminated in Petri dishes for 4 days at room temperature. Two germinating seedlings were planted in each plastic pot (10-cm diameter) filled with dark brown Chernozemic soil (loamy sand, 36 ppm NO_3-N, 30 ppm phosphorus, and >300 ppm potassium). The fluorescent and incandescent lighting provided an average photosynthetic photon flux density of 400 $\mu E\ m^{-2}s^{-1}$ (25–30% of maximum summer intensity) over a 16-h photoperiod. Unless stated otherwise, long term drought was imposed by withholding water for 7 days before herbicide spraying, with only sufficient water added after spraying to keep the plants alive for 10 more days (soil moisture was still less than 35% field capacity), and daily watering was then resumed. The plants in the drought treatment showed signs of water deficit during herbicide application (Xie et al. 1994b). The plants in the well watered treatment were watered daily to maintain >80% field capacity of soil moisture. To ensure that all plants reached a similar growth stage at the time of spraying, the seedlings designated for drought treatment were planted 2 days ahead of well watered plants. Commercially formulated imazamethabenz-methyl (300 g ai L^{-1}), fenoxaprop-ethyl (90 g ai L^{-1}), diclofop-methyl (284 g ai L^{-1}), and flamprop-methyl (52.5 g ai L^{-1}) were applied to wild oat plants at the three-leaf stage with an overhead trolley sprayer cabinet. A flat-fan nozzle (TeeJet 730039, Spraying System Co., Wheaton, IL) was calibrated to deliver 100 L ha^{-1} at 207 kPa. During spraying, the soil surface was covered with a layer of coarse vermiculite to exclude soil contact with, and possible root absorption of, the herbicides. The vermiculite was removed immediately after treated leaves were dry, and plants were placed back in their respective environments.

The above-ground plant parts (shoots) were harvested 3 weeks after herbicide application, and shoot dry weight was determined after oven-drying at 70°C for 48 h. Herbicide phytotoxicity to wild oat was assessed by expressing treated shoot dry weight as a percentage of the respective untreated check. Within the same environmental regimen, the pots were completely randomized with seven replicates/herbicide treatment. The data were subjected to analyses of variance with the general linear model procedure of Statistical Analysis System (SAS Institute Inc., Cary, NC). The treatment means were separated with the least significant difference (LSD) test at $p = 0.05$.

Combined Effect of Drought and High Temperature

Experiment 1. Plants were grown in a growth chamber set at 30/20°C day/night temperature during the entire experimental period. Plants were grown under either well watered or drought conditions. Imazamethabenz at 150 g ai ha^{-1} and fenoxaprop at 150 g ai ha^{-1} were applied. The experiment was repeated once and the data pooled for analysis because there was no interaction between experiments.

Experiment 2. Plants were grown in a growth chamber set at 30/20°C during the entire experimental period. Plants were grown under either well watered or drought conditions. Fenoxaprop at 100, 200, and 400 g ai ha^{-1} was applied

Experiment 3. Plants were grown in two growth chambers set at either 20/15°C or 30/20°C during the entire experimental period. Within the same temperature regimen, plants were grown under either well watered or drought conditions. Imazamethabenz at 200 g ai ha^{-1}, fenoxaprop at 100 g ai ha^{-1}, diclofop at 400 g ai ha^{-1}, and flamprop at 125 g ai ha^{-1} were applied.

Combined Effect of Drought and Low Temperature

Plants were grown in a growth chamber in which the temperature was lowered gradually from 20/15°C to 15/10°C over a 9-day period and held at 10/5°C for 7 days immediately before spraying. After an additional 7 days at 10/5°C following spraying, the temperature was raised gradually over 7 days to 15/10°C until harvest. Plants were grown under either well watered or drought conditions. Long term drought was imposed by withholding water for 15 days before spraying, with only minimal water for survival added after spraying for 10 more days, after which daily watering was resumed. Imazamethabenz at 100 g ai ha^{-1} and fenozaprop at 100 g ai ha^{-1} were applied. The experiment was repeated once, and the data were pooled for analysis because there was no interaction between experiments.

Effect of Drought under Different Humidities

Plants were grown in a growth chamber set at 25/15°C. Immediately after spraying, half of the plants were moved to a dark incubator set at 20°C with high RH level (95%), and the remaining plants were moved

Table 1. Effect of drought on the phytotoxicity of imazamethabenz and fenoxaprop applied to wild oat plants grown at high temperature.[a]

Herbicide rate (g ai ha^{-1})	Shoot dry weight (%)[b]	
	Well watered	Drought[c]
Imazamethabenz (150)	52	53
Fenoxaprop (150)	81	86
LSD (0.05)	16	

[a] The plants were grown at a growth chamber set at 30/20°C during the entire experimental period.
[b] Shoot dry weight percentage is based on shoot dry weight of herbicide-treated plants over the weight of untreated plants grown in the same environmental regimen.
[c] Drought was imposed by withholding water for 7 days before spraying and 10 more days of stress after spraying.

to a dark incubator set at 20°C with low RH (30%). Six h after these RH treatments, all plants were moved back to the original growth chamber set at 25/15°C until harvest. RH in the growth chamber was approximately 40% during the day and 65% at night. Plants were grown under either well watered or drought conditions. Imazamethabenz at 150 g ai ha^{-1}, fenoxaprop at 100 g ai ha^{-1}, diclofop at 400 g ai ha^{-1}, and flamprop at 125 g ai ha^{-1} were applied. The experiment was repeated once, and the data were pooled for analysis because there was no interaction between experiments.

Results and Discussion

Drought or High Temperature Alone

The phytotoxicity of fenoxaprop in wild oat was reduced greatly by drought alone, high temperature (30/20°C) alone, and the combined stress of drought and high temperature (Tables 1, 2, and 3). Among these three stressful environmental regimes, the adverse effect on fenoxaprop performance was as follows: drought plus high temperature > drought alone > high temperature alone. Increasing fenoxaprop application rate up to 400 g ai ha^{-1} could relieve completely the adverse high temperature effect on wild oat control but could only alleviate partially the combined effect of drought and high temperature stresses (Table 2). The additive effect of drought plus high temperature on fenoxaprop activity could be attributed to: (1) drought-reduced fenoxaprop absorption and translocation (Xie et al. 1996b); (2) reduced spray retention under high temperature (Xie et al. 1995); (3) possible drought-induced changes in cell membranes (Downey 1992); and (4) possible increase in herbicide detoxification at high temperature (Xie et al. 1996b).

When wild oat plants were grown under high temperature conditions, long term drought did not reduce significantly imazamethabenz phytotoxicity relative to high temperature alone (Table 1). However, the effectiveness of this herbicide under drought plus high temperature was less than its effectiveness under unstressed conditions (20/15°C plus adequate soil moisture) (Table 3). This effect may be related to the combination of slightly reduced imazamethabenz absorption and translocation under drought (Xie et al. 1996b), high temperature-reduced spray retention (Xie et al. 1995), and enhanced imazamethabenz detoxification under high temperature (Pillmoor 1985).

Drought reduced diclofop activity greatly in wild oat at both medium (20/15°C) and high temperatures (Table 3), which could be ascribed to drought-induced changes in cell membrane structures (Downey 1992). Even without drought stress, high temperatures still had an adverse effect on the performance of diclofop although such an effect was not as profound as that induced by drought (Table 3). Gillespie and Miller (1983) showed that high temperatures resulted in enhanced diclofop detoxification. High temperature alone did not affect flamprop

Table 2. Effect of drought on the phytotoxicity of fenoxaprop applied to wild oat plants grown at high temperature.[a]

Herbicide rate (g ai ha^{-1})	Shoot dry weight (%)[b]	
	Well watered	Drought[c]
Fenoxaprop		
100	81	99
200	63	72
400	17	62
LSD (0.05)	20	

[a] The plants were grown at a growth chamber set at 30/20°C during the entire experimental period.
[b] Shoot dry weight percentage is based on shoot dry weight of herbicide-treated plants over the weight of untreated plants grown in the same environmental regimen.
[c] Drought was imposed by withholding water for 7 days before spraying and 10 more days of stress after spraying.

Table 3. Effect of drought on the phytotoxicity of several graminicides applied to wild oat plants grown at two temperature regimes.[a]

Herbicide rate (g ai ha^{-1})	Shoot dry weight (%)[b]			
	20/15°C		30/20°C	
	Well watered	Drought[c]	Well watered	Drought
Imazamethabenz (200)	14	30	26	44
Fenoxaprop (100)	28	89	75	99
Diclofop (400)	39	95	74	99
Flamprop (125)	45	66	45	69
LSD (0.05)	20			

[a] The plants were grown at two growth chambers set at either 20/15°C or 30/20°C during the entire experimental period.
[b] Shoot dry weight percentage is based on shoot dry weight of herbicide-treated plants over the weight of untreated plants grown in the same environmental regimen.
[c] Drought was imposed by withholding water for 7 days before spraying and 10 more days of stress after spraying.

Table 4. Effect of drought on the phytotoxicity of imazamethabenz and fenoxaprop applied to wild oat plants grown at low temperature.[a]

Herbicide rate (g ai ha^{-1})	Shoot dry weight (%)[b]	
	Well watered	Drought[c]
Imazamethabenz (100)	43	50
Fenoxaprop (100)	56	80
LSD (0.05)	16	

[a] The plants were grown at a growth chamber in which the temperature was lowered gradually from 20/15°C to 15/10°C over a 9-day period and held at 10/5°C for 7 days immediately before spraying. After an additional 7 days at 10/5°C after spraying, the temperature was raised gradually over 7 days to 15/10°C until harvest.
[b] Shoot dry weight percentage is based on shoot dry weight of herbicide-treated plants over the weight of untreated plants grown in the same environmental regimen.
[c] Drought was imposed by withholding water for 15 days before spraying and 10 more days of stress after spraying.

phytotoxicity compared with that found at medium temperature; and drought stress similarly reduced flamprop phytotoxicity under the two temperature regimen (Table 3). The transport of flamprop-acid, the active form of flamprop, was reduced slightly under water stress; and flamprop phytotoxicity was greater at warmer temperature (25 vs 12°C) (Jeffcoat et al. 1977).

In the data presented in Table 3, all four herbicides were applied at approximately half the rate recommended for field use so that growth continued over a sufficient period to evaluate differences. At these application rates the magnitude of phytotoxicity reduction found under drought alone or drought plus high temperature conditions was as follows: fenoxaprop = diclofop > flamprop > imazamethabenz. At optimal temperatures, flamprop activity was less affected by drought than diclofop activity, as was also found by Wilcox et al. (1987). The present study clearly demonstrated that when wild oat plants are subjected to long term stressful conditions of drought, high temperature, and particularly a combination of the two, it may not be appropriate to apply fenoxaprop or diclofop.

When wild oat plants were grown under low temperature (10/5°C), drought had no significant effect on imazamethabenz activity but reduced fenoxaprop phytotoxicity significantly (Table 4). Thus, as long as drought stress prevails, wild oat control with fenoxaprop would be expected to be inadequate, regardless of the concurrent temperature conditions. Although the low temperature regime described resulted in slightly reduced fenoxaprop activity (Xie et al. 1994a) which could be related to the decrease in fenoxaprop translocation under low temperature (Xie et al. 1996a), this study (Table 4) did not reveal an additive effect of drought plus low temperature on fenoxaprop performance as was the case with drought plus high temperature (Table 3).

Table 5. Effect of drought on the phytotoxicity of several graminicides applied to wild oat plants grown at two RH regimens.[a]

Herbicide rate (g ai ha^{-1})	Shoot dry weight (%)[b]			
	Low RH		High RH	
	Well watered	Drought[c]	Well watered	Drought
Imazamethabenz (150)	40	53	32	43
Fenoxaprop (100)	67	105	63	94
Diclofop (400)	59	97	50	91
Flamprop (125)	23	35	17	33
LSD (0.05)	17			

[a] The plants were grown at two growth chambers set at 25/15°C before spraying. Immediately after spraying, half of the plants were moved to a dark incubator set at 20°C with low RH level (30%), and the other half of the plants were moved to a dark incubator at 20°C with high RH level (95%). Six h after these RH treatments, all the plants were moved back to original growth chamber set at 25/15°C until harvest.
[b] Shoot dry weight percentage is based on shoot dry weight of herbicide-treated plants over the weight of untreated plants grown in the same environmental regimen.
[c] Drought was imposed by withholding water for 7 days before spraying and 10 more days of stress after spraying.

Combined Effect of Soil Moisture and Humidity on Phytotoxicity

At 25/15°C, drought had limited effect on the phytotoxicity of imazamethabenz and flamprop in wild oat, whereas the same drought treatment reduced greatly the performance of fenoxaprop and diclofop (Table 5). Six hours of different RH treatments (30 vs 95%) imposed after the spraying had no significant impact on the phytotoxicity of all four herbicides examined regardless of soil moisture regimens.

Previous studies showed that high RH tended to enhance the performance of several graminicides, including asulam {methyl[(4-aminophenyl)sulfonyl]carbamate} and difenzoquat (1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium) (Morrison 1983), fluazifop {(±)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxypropanoic acid} (Coupland 1986), and sethoxydim {2-[-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} (Coupland 1987). Price (1983) suggested that high RH could be important for foliar uptake of herbicides when plants are under drought conditions. Based upon the experiments with ^{14}C-herbicides, it appeared that drought had no profound effect on the absorption of imazamethabenz (Xie et al. 1996b), fenoxaprop (Xie et al. 1996b), and diclofop (Akey and Morrison 1983), which may explain why high RH in the present study could not alleviate the adverse drought effect on the activity of fenoxaprop or diclofop. Still, at

95% RH our data showed a slightly enhanced wild oat control with all herbicides examined (Table 5). Furthermore, because of their lipophilic nature, the ester formulations of herbicides seem to be less affected by changes in RH than more polar formulations (Merritt 1984, Wills and McWhorter 1988). All of the graminicides we used are ester formulations.

In summary, drought-reduced phytotoxicity of fenoxaprop or diclofop in wild oat could apply and persist irrespective of concurrent temperature or humidity conditions. Among the four graminicides we applied, imazamethabenz and to a lesser extent flamprop were more tolerant to the long term stresses of drought or drought combined with high temperature than were fenoxaprop and diclofop. Drought had a greater adverse effect than high temperature alone on the performance of fenoxaprop or diclofop.

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