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# Influence of Temperature and Light Intensity on Absorption, Translocation, and Phytotoxicity of Fenoxaprop-ethyl and Imazamethabenz-methyl in *Avena fatua*

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**Abstract.** The absorption and translocation of fenoxaprop-ethyl and imazamethabenz-methyl were investigated in wild oat (*Avena fatua* L.) plants grown under different temperature and light intensity conditions by using $^{14}C$ tracer techniques. The phytotoxicity of both herbicides, applied as individual droplets, was also determined under similar environments. The absorption of fenoxaprop-ethyl and imazamethabenz-methyl was increased by high temperature (30/20°C) and to a lesser extent by 70% shading; low temperature (10/5°C) had limited effect on the absorption. The basipetal translocation of fenoxaprop-ethyl was not affected by high temperature, and the increase in imazamethabenz-methyl translocation at high temperature was likely the result of the increased absorption. Low temperature decreased total translocation and translocation efficiency in both fenoxaprop-ethyl and imazamethabenz-methyl. Low light intensity tended to reduce the efficiency of basipetal translocation of both herbicides. Fenoxaprop-ethyl phytotoxicity was reduced by high temperature but not by low temperature. Temperature had little effect on imazamethabenz-methyl effectiveness. Under 70% shading, the phytotoxicity of both herbicides was enhanced.

**Key Words.** Environmental Stress—Drought—Shading—Wild oat

Changes in the effectiveness of postemergent herbicides under differing environments may be related to environment-induced variations in herbicide deposition, absorption, translocation, metabolism, and/or action at the target(s). The foliar absorption of most graminicides was greater under higher temperature conditions (Grafstorm and Nalewaja 1988, Kells et al. 1984, Sharma et al. 1976, Wills 1984, Wills and McWhorter 1983). The influence of temperature on herbicide translocation and phytotoxicity varied (Blair et al. 1983, Coupland 1986, Devine et al. 1983, Grafstorm and Nalewaja 1988, Kells et al. 1984, Klevorn and Wyse 1984, Morrison 1983, Nalewaja and Woznica 1988, Smeda and Putnam 1990, Wills 1984, Wills and McWhorter 1983). There have been limited studies on the effects of light intensity on herbicide performance and underlying physiologic processes. Low light intensity could result in either reduced herbicidal activity (Blair et al. 1983, Chandrasena and Sagar 1986, Price and Ipor 1992) or enhanced activity (Coupland 1986, Farahbakhsh et al. 1988). Limited studies suggested that herbicide translocation was usually reduced under shading or low light conditions (Coupland 1989b, Kells et al. 1984, Olson and Nalewaja 1982, Price and Ipor 1992), although exceptions exist (Coupland 1989a).

Our previous studies of *Avena fatua* with spray application indicated that high temperature decreased the phytotoxicity of fenoxaprop-ethyl (hereafter referred to as fenoxaprop) but not that of imazamethabenz-methyl (hereafter referred to as imazamethabenz); and low temperature could reduce the performance of both herbicides (Xie et al. 1994a). The phytotoxicity of fenoxaprop and imazamethabenz was increased under 70% shading conditions (Xie et al. 1994b). An association of environment-induced changes in herbicide spray deposition has been reported with the above efficacy changes (Xie et al. 1995). The objective of this study was to determine the influence of temperature and light intensity on foliar absorption and basipetal translocation of fenoxaprop and imazamethabenz in *A. fatua.* Such an understanding may allow for development of appropriate ways for efficient weed control under such stresses. In addition, the phytotoxicity of those two herbicides applied as individual

**Abbreviation:** S.E.D., standard errors of difference.

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droplets was also examined at various temperature and light regimes.

## Materials and Methods

### *General Procedure*

All experiments were conducted in growth chambers. A genetically uniform line of *A. fatua,* Crop Science 40, was used. The seeds were pregerminated on moist filter paper for 3 days at room temperature. Plants used for radioactive study were grown in 6.7-cm diameter styrofoam cups (fitted with one drainage hole) filled with silica sand. Each cup contained one plant and was placed into a second styrofoam cup without drainage holes. The plants were watered daily with 10–20 mL of ¼ strength Hoagland's nutrition solution (Hoagland and Arnon 1939). For the phytotoxicity study, the plants were grown in 7.5-cm diameter plastic pots filled with loamy sand soil (dark brown Chernozemic, pH 7.6, 36 ppm $NO_3$-N, 30 ppm P, > 300 ppm K), with one plant/pot. Sixty mg/pot of a 20:20:20 (N, P, K) water-soluble fertilizer was given at the one-leaf stage.

Four environmental regimes were established as follows (Xie et al. 1994c). (1) the non-stressed (standard) regime was 20/15°C, full light (400 $\mu E/m^2/s$) with a 16-h photoperiod, daily watering. (2) the low temperature regime employed: standard conditions except that within 9 days before herbicide application the temperature was decreased gradually to 10/5°C and increased gradually within 14 days after the application to 15/10°C, with plants experiencing 10/5°C for 7 days immediately before and 7 days after the application if applicable. (3) the high temperature regime employed standard conditions except that the temperature was 30/20°C throughout the experiment. (4) the shading regime used standard conditions except that plants were grown under 70% shading (120 $\mu E/m^2/s$) by covering the plants with white fabric throughout the experiment. The seedlings designated for low temperature and shading regimes were planted 4 and 2 days, respectively, ahead of those designated for standard and high temperature regimes so that all plants had three leaves when the herbicides were applied.

### *Radioactive Herbicide Study*

At the three-leaf stage, *A. fatua* plants were treated with [$^{14}$C]fenoxaprop and [$^{14}$C]imazamethabenz. The detailed procedure has been described previously (Xie et al. 1996). Briefly, the working solution contained 11.25 $\mu Ci\ mL^{-1}$ of radioactivity and 1,500 $\mu g\ mL^{-1}$ (fenoxaprop) or 3,000 $\mu g\ mL^{-1}$ (imazamethabenz) of the herbicides. Two 2-$\mu$L drops of the working solution were applied to the adaxial midsection of the second lamina using a micropipette. The plants were harvested 48 and 96 h following $^{14}$C application and were divided into four parts: treated second lamina, tillers, the remainder of the foliage, and roots. $^{14}$C quantification was done with a liquid scintillation analyzer. The results were expressed as a percentage of the applied dose since the recovered radioactivity of both herbicides was more than 90% of applied radioactivity. At each time interval five plants per treatment were harvested; an individual plant constituted one replication. The experiment was repeated once, and all data were pooled for analysis since there was no significant interaction between experiments. Standard errors of difference (S.E.D.) within same time interval were given to show the variance. Means stated as significantly different ($p = 0.05$ or $p = 0.01$) were based on the orthogonal contrasts between the nonstressed regime and other environmental regimes within same time interval.

### *Phytotoxicity Study*

When *A. fatua* plants were at the three-leaf stage, a commercial emulsifiable concentrate formulation of fenoxaprop (1 $\mu g\ \mu L^{-1}$) or a commercial suspension concentrate formulation of imazamethabenz (2 $\mu g\ \mu L^{-1}$) was applied with a micropipette to the adaxial midsection of the first and second laminae with a 1-$\mu$L droplet size. The dose for fenoxaprop varied with environmental factors. In the experiment involving various temperatures, the fenoxaprop dose was 40 $\mu$g/plant; and in the experiment involving various light intensities, the dose was 20 $\mu$g/plant. In all phytotoxicity experiments, the dose for imazamethabenz was 30 $\mu$g/plant.

The plants were harvested 3 weeks after herbicide application, and shoot dry weight was determined. There were six replications per treatment. The experiment was repeated once, and all data were pooled for analysis since there was no significant interaction between experiments. S.E.D. were given to show the variance. Means stated as significantly different ($p = 0.05$ or $p = 0.01$) were based on the orthogonal contrasts between the nonstressed regime and other environmental regimes.

## Results

### *Effect of Temperature and Light Intensity on Fenoxaprop*

The absorption of [$^{14}$C]fenoxaprop in *A. fatua* was not significantly affected by various environmental conditions when the plants were harvested 48 h after herbicide application, whereas by 96 h after the application fenoxaprop absorption was increased by high temperature ($p < 0.01$) and low light intensity ($p < 0.05$) (Table 1). Basipetal translocation of this herbicide out of the treated lamina, based on either applied $^{14}$C or absorbed $^{14}$C, was reduced by low temperature. High temperature had no significant effect on fenoxaprop translocation. Forty-eight h after application, the translocation efficiency (on the basis of absorbed $^{14}$C) was reduced under 70% shading ($p < 0.05$). But the total basipetal translocation (based on applied dose) of fenoxaprop was increased under the shading ($p < 0.05$) measured 96 h after application.

Regardless of environmental regimes, more than 91% of absorbed fenoxaprop remained in the treated lamina (Table 2). Compared with the nonstressed treatment, all stressful environments resulted in less $^{14}$C distribution into the tillers. Under low temperature conditions, $^{14}$C distribution in other foliage tissues besides the treated lamina was also reduced. Except for the distribution in the tillers, the distribution of [$^{14}$C]fenoxaprop in *A. fatua* tissues was not affected by high temperature. Under low light intensity, $^{14}$C distribution into the roots was reduced, especially 48 h after the application; but there was more $^{14}$C contained in the foliage tissues other than the treated lamina and tillers ($p < 0.01$) at the 96-h interval.

Compared with its effect under 20/15°C (nonstressed) conditions, the phytotoxicity of fenoxaprop to *A. fatua,* applied at 40 $\mu$g/plant as individual droplets, was not affected by low temperature but was decreased ($p < 0.01$) by high temperature (Table 3). At 20 $\mu$g/plant, fenoxaprop phytotoxicity was enhanced ($p < 0.01$) by 70% shading treatment (Table 4).

**Table 1.** Influence of temperature and light intensity on absorption and basipetal translocation (% of applied) of $^{14}C$ following foliar application of [$^{14}C$]fenoxaprop and [$^{14}C$]imazamethabenz to *A. fatua*

| Herbicide | Time (h) | Non stressed | Low temperature | High temperature | Shading | S.E.D. ($df$ = 36) |
|---|---|---|---|---|---|---|
| Absorption | | | (% of applied) | | | |
| Fenoxaprop | 48 | 48.0 | 49.7 | 61.0 | 59.6 | 4.7 |
| | 96 | 59.0 | 65.3 | 85.5 | 72.8 | 4.9 |
| Imazamethabenz | 48 | 19.6 | 13.8 | 36.1 | 23.3 | 2.5 |
| | 96 | 25.1 | 23.5 | 41.6 | 30.0 | 1.8 |
| Basipetal translocation | | | | | | |
| Fenoxaprop | 48 | 2.9 (6.0)[a] | 2.1 (4.2) | 2.9 (5.4) | 2.6 (4.2) | 0.31 |
| | 96 | 4.9 (8.7) | 3.9 (6.1) | 5.2 (6.6) | 6.7 (9.2) | 0.54 |
| Imazamethabenz | 48 | 1.2 (6.0) | 0.5 (4.2) | 1.9 (5.0) | 1.6 (6.8) | 0.20 |
| | 96 | 1.8 (7.2) | 1.1 (4.8) | 2.5 (6.1) | 1.6 (5.1) | 0.09 |

[a] Values in parentheses are the percentage of absorbed $^{14}C$.

**Table 2.** Influence of temperature and light intensity on distribution of $^{14}C$ in plant parts (% of applied) following foliar application of [$^{14}C$]fenoxaprop to *A. fatua*

| Time (h) | Plant part | Non stressed | Low temperature | High temperature | Shading | S.E.D. ($df$ = 36) |
|---|---|---|---|---|---|---|
| | | | (% of applied) | | | |
| 48 | Treated lamina | 45.1 (94)[a] | 47.6 (96) | 58.1 (95) | 57.1 (96) | 4.7 |
| | Tillers | 0.4 (0.9) | 0.2 (0.5) | 0.3 (0.4) | 0.3 (0.4) | 0.06 |
| | Remainder of foliage | 1.7 (3.6) | 1.2 (2.4) | 2.0 (3.2) | 1.9 (3.1) | 0.24 |
| | Roots | 0.8 (1.6) | 0.7 (1.4) | 0.7 (1.1) | 0.4 (0.7) | 0.07 |
| 96 | Treated lamina | 54.1 (92) | 61.4 (94) | 80.3 (94) | 66.1 (91) | 5.0 |
| | Tillers | 0.8 (1.4) | 0.6 (0.9) | 0.6 (0.7) | 0.4 (0.6) | 0.07 |
| | Remainder of foliage | 3.0 (5.1) | 2.1 (3.2) | 3.3 (3.9) | 5.3 (7.3) | 0.42 |
| | Roots | 1.2 (1.9) | 1.2 (1.9) | 1.2 (1.5) | 0.9 (1.3) | 0.16 |

[a] Values in parentheses are the percentage of absorbed $^{14}C$.

**Table 3.** Effect of temperature on the phytotoxicity of fenoxaprop (40 μg/plant) and imazamethabenz (30 μg/plant) applied as individual droplets to *A. fatua*

| Temperature (°C) | Shoot dry weight (% of control) | |
|---|---|---|
| | Fenoxaprop | Imazamethabenz |
| 10/5 | 34 | 25 |
| 20/15 | 48 | 31 |
| 30/20 | 96 | 26 |
| S.E.D. ($df$ = 33) | 7 | 4 |

**Table 4.** Effect of light intensity on the phytotoxicity of fenoxaprop (20 μg/plant) and imazamethabenz (30 μg/plant) applied as individual droplets to *A. fatua*

| Light intensity (μE $m^{-2}$ $s^{-1}$) | Shoot dry weight (% of control) | |
|---|---|---|
| | Fenoxaprop | Imazamethabenz |
| 400 | 64 | 28 |
| 120 | 24 | 16 |
| S.E.D. ($df$ = 22) | 7 | 2 |

### *Effect of Temperature and Light Intensity on Imazamethabenz*

[$^{14}C$]Imazamethabenz absorption into *A. fatua* foliage was increased by high temperature ($p < 0.01$) and under low light intensity was also increased ($p < 0.05$) 96 h after herbicide application (Table 1). Low temperature decreased the herbicide absorption ($p < 0.05$) only at the 48-h interval. Basipetal translocation of [$^{14}C$] imazamethabenz, based on either applied $^{14}C$ or absorbed $^{14}C$, was reduced ($p < 0.01$) by low temperature. At high temperature, although the total basipetal translocation was greater ($p < 0.01$), the translocation efficiency was not significantly changed. 70% shading had limited effect on the total herbicide translocation, whereas the translocation efficiency was reduced ($p < 0.05$) under the shading at the 96-h interval.

By 96 h after [$^{14}C$]imazamethabenz application, more than 93% of absorbed herbicide still remained in the

**Table 5.** Influence of temperature and light intensity on distribution of $^{14}C$ in plant parts (% of applied) following foliar application of [$^{14}C$]imazamethabenz to *A. fatua*

| Time (h) | Plant part | Non stressed | Low temperature | High temperature | Shading | S.E.D. ($df$ = 36) |
|---|---|---|---|---|---|---|
| | | | (% of applied) | | | |
| 48 | Treated lamina | 18.3 (93)[a] | 13.2 (96) | 34.3 (95) | 21.7 (93) | 2.4 |
| | Tillers | 0.2 (0.8) | 0.1 (0.6) | 0.2 (0.4) | 0.1 (0.3) | 0.02 |
| | Remainder of foliage | 0.7 (3.7) | 0.2 (1.5) | 1.1 (3.0) | 1.2 (5.2) | 0.15 |
| | Roots | 0.4 (1.8) | 0.3 (1.8) | 0.6 (1.7) | 0.3 (1.4) | 0.06 |
| 96 | Treated lamina | 23.4 (93) | 22.4 (95) | 39.1 (94) | 28.4 (95) | 1.8 |
| | Tillers | 0.2 (0.9) | 0.2 (0.8) | 0.3 (0.7) | 0.1 (0.4) | 0.03 |
| | Remainder of foliage | 1.0 (3.8) | 0.5 (2.0) | 1.5 (3.6) | 1.0 (3.4) | 0.07 |
| | Roots | 0.6 (2.3) | 0.4 (1.9) | 0.7 (1.7) | 0.4 (1.4) | 0.04 |

[a] Values in parentheses are the percentage of absorbed $^{14}C$.

treated lamina irrespective of environmental conditions (Table 5). The distribution of $^{14}C$ in various plant parts was decreased by low temperature. With the exception of tillers, there was more radioactivity found in all tissues under the high temperature regime. The amount of the herbicide remaining in the treated lamina was higher ($p < 0.05$) under low light intensity, whereas the tillers contained less $^{14}C$ ($p < 0.01$) under such conditions. At the 96-h interval, the roots of shaded plants also contained less radioactivity ($p < 0.01$).

Applied at 30 μg/plant as individual droplets, imazamethabenz phytotoxicity in *A. fatua* was similar under various temperature regimes (Table 3). Its phytotoxicity was enhanced ($p < 0.01$) when the plants were grown under 70% shading conditions (Table 4).

## Discussion

### *Temperature Effect*

This study demonstrates that in *A. fatua,* high temperature stress had an adverse effect on the phytotoxicity of fenoxaprop applied as individual droplets, similar to that reported previously when the herbicide was applied as a spray (Xie et al. 1994a). Toxicity of other ACCase-inhibiting graminicides such as diclofop-methyl (Chow 1978, Donn and Bieringer 1980) and fluazifop-butyl (Coupland 1986, Smeda and Putnam 1990) has been found to be susceptible to high temperature stresses. The leaves of high temperature-grown *A. fatua* contained more epicuticular wax than those grown at lower temperatures (Xie et al. 1994a), which apparently had no adverse effect on fenoxaprop absorption. It has been shown that the plant cuticle may not be a significant barrier for foliar penetration of the ester herbicide formulation because of the high lipophilicity of such formulation (Kloppenburg and Hall 1990, Price 1982, Whitehouse et al. 1982). In this study, the basipetal translocation of fenoxaprop was not affected, whereas the absorption was enhanced under high temperature conditions (Table 1), suggesting that high temperature-reduced activity in fenoxaprop could not be associated with the reduction in the herbicide absorption and translocation. A similar conclusion was reached for imazaquin (Malefyt and Quakenbush 1991). It appears unlikely that the adverse high temperature effect could be alleviated greatly by adding surfactant into spray solution of commercially formulated fenoxaprop (unpublished data). In addition, high temperature stresses could enhance metabolic degradation as occurred with fluazifop-butyl (Coupland 1986). Possible involvement of fenoxaprop metabolism could not be excluded even though a reduction in the spray deposition was found at the high temperature regime (Xie et al. 1995).

When applied as spray, fenoxaprop performance in *A. fatua* was sensitive to low temperature, although such an adverse effect was not as great as that at high temperature (Xie et al. 1994a). However, the present study showed that with droplet application, fenoxaprop activity was not affected by a similar low temperature treatment (Table 3). Although the portion of grassy plants in contact with the herbicides might affect the absorption, translocation, and effectiveness (Chandrasena and Sagar 1987, 1989, Walter et al. 1980), the reason underlying such a discrepancy is unknown. Although long term low temperature had little effect on fenoxaprop absorption (Table 1), such a regime resulted in less translocation into foliage and tillers, which might account for the reduced herbicide performance at low temperature (Xie et al. 1994a). In *A. fatua,* the translocation of flamprop and difenzoquat was also reduced at low temperatures (Jeffcoat et al. 1977, Sharma et al. 1976). Coupland (1989a) found that low temperature decreased the deesterification of fluazifop-butyl. Further study into fenoxaprop metabolism is needed since the possible decrease in fenoxaprop activa-

tion vs deesterification may decrease the amount available for phloem transport.

The results from this study were consistent with our previous study using spray application (Xie et al. 1994a) in which the phytotoxicity of imazamethabenz in *A. fatua* was not adversely affected by high temperature (Table 3). Under high temperature, imazamethabenz absorption was greatly increased, which was similar to the previous results (Malefyt and Quakenbush 1991, Pillmoor 1985). The increase in basipetal translocation at high temperature appeared to be directly related to the enhanced absorption rather than to the increased translocation efficiency. On the other hand, high temperature reduced spray deposition (Xie et al. 1995) as well as possibly increased metabolic degradation of imazamethabenz (Pillmoor 1985). With the formulation we used, therefore, the beneficial effects of high temperature on imazamethabenz absorption and accompanied translocation could offset the adverse effects of high temperature on spray deposition and/or herbicide metabolism, leading to similar imazamethabenz phytotoxicity in the plants grown under high temperature and normal temperature conditions.

In agreement with our previous results with spray application (Xie et al. 1994a), the present study showed that low temperature did not reduce imazamethabenz activity as long as it was imposed only for a few days around the application (Table 3). The absorption of this herbicide was decreased only initially under low temperature, and by 4 days after the application the absorption at low temperature was comparable to that at normal temperature (Table 1). Still, low temperature had an adverse effect on total basipetal translocation and translocation efficiency of imazamethabenz. The reduced imazamethabenz performance under the constant low temperature regime (Xie et al. 1994a) may be associated with such a reduction in herbicide translocation. The reduced rate of herbicide translocation at low temperature was thought to be the result of low temperature-grown plants having less active physiologic sinks than those grown under the warmer conditions (Coupland 1989b).

### *Light Intensity Effect*

For both fenoxaprop and imazamethabenz applied as individual droplets, the present study demonstrated that long term low light intensity (70% shading) resulted in greatly enhanced phytotoxicity in *A. fatua* (Table 4), which confirmed the previous report with spray application (Xie et al. 1994b). Although the initial absorption of both herbicides was not affected by high intensity, by 4 days after the application the absorption was increased by the shading (Table 1). The relatively low epicuticular wax content under the shading (Xie et al. 1994b) might be related to such an enhancement. The influence of light intensity on the basipetal translocation of fenoxaprop and imazamethabenz was minimal. The slight increase in total fenoxaprop translocation under the shading was the direct result of shading-enhanced absorption. Low light intensity tended to decrease the translocation efficiency via phloem of both herbicides. Fluazifop-butyl translocation via phloem was also reduced at low light intensities (Coupland 1989b, Kells et al. 1984). Nevertheless, shading-induced changes in herbicide absorption and translocation appeared to be secondary in importance in view of the magnitude of shading-enhanced phytotoxicity in both fenoxaprop and imazamethabenz. On the other hand, long term 70% shading could greatly increase the spray deposition of fenoxaprop and imazamethabenz (Xie et al. 1995), which was likely a major factor contributing to the enhancement in the herbicidal activity under the shading. Such a proposition is further supported by our previous study in which prespraying shading had a greater positive effect than postspraying shading on the phytotoxicity of both herbicides (Xie et al. 1994b). In addition, the total basipetal translocation of fenoxaprop, but not imazamethabenz, was increased under low light intensity. This may partly account for the previous results in which fenoxaprop was more responsive to postspraying shading than imaza-methabenz (Xie et al. 1994b).

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