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Response of Oats to Atrazine[1]

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ABSTRACT

The popularity of atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine], a persistent corn (*Zea mays* L.) herbicide, has caused problems for oats (*Avena sativa* L.) grown in rotation with corn. Despite frequent inquiries about the response of oats to atrazine, very little testing for cultivar differences to atrazine has been conducted. Therefore, the objective of this study was to evaluate the response of current oat genotypes to atrazine.

Twenty oat genotypes were evaluated for response to atrazine for 2 years. Five atrazine treatments, 0, 1.12, 2.24, 3.36, and 4.48 kg/ha, were applied postemergence to corn land during each of the years prior to growing the oats. Atrazine damage to oats grown in 1976 was light because of wet conditions during the last half of 1975, while damage to oats grown in 1977 was more severe because of dry conditions during the last half of 1976.

Grain and straw yield responses of the genotypes were evaluated on the combined data from the 2 years of testing with a regression procedure. Tolerant genotypes were expected to have a high mean and a regression coefficient less negative than −1.0, while intolerant genotypes were expected to have a low mean and a regression coefficient more negative than −1.0. There was significant genetic variability for grain yield response to atrazine. Froker, Lang, Mackinaw, X2078-1, and X1839-1 were more tolerant of atrazine than Dal, Lyon, Otee, and Allen. There also was significant variability for straw yield response to atrazine, but grain and straw yield responses (regression coefficients) were not significantly correlated. Straw yield response to atrazine was closely associated with plant height.

The influence of atrazine on kernel quality was evaluated in a subset of eight genotypes. Groat protein percentage was increased by higher levels of residual atrazine, but groat protein yields were reduced because of the grain yield reductions. Groat percentage and 100-seed weight were not reduced in 1976 when atrazine damage was light, but both were reduced in 1977 when damage was severe.

Although there was significant genetic variability for response to atrazine among the 20 genotypes tested, the variability probably is not sufficient to warrant intercrossing them in an effort to develop genotypes with improved tolerance. A thorough search of the World Oat Collection for more tolerant genotypes is recommended.

Additional index words: Grain yield, Straw yield, Protein, Regression, *Avena sativa* L.

ATRAZINE [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine] has been used extensively as a selective herbicide on corn (*Zea mays* L.) in much of the United States. Its long-time use exemplifies its effectiveness in controlling broadleaf and grassy weeds, particularly quackgrass [*Agropyron repens* (L.) Beauv.]. Atrazine persists in the soil for varying periods of time, depending upon soil properties and climatic effects, especially rainfall (Birk and Roadhouse, 1964; Burnside et al., 1969; Rodgers, 1968). Residual effects have injured succeeding crops such as oats (*Avena sativa* L.), which are considered susceptible to the chemical (Buchholtz, 1965).

Oat workers in the Midwest have been questioned frequently about genetic variability for response to atrazine since the early days of its use. However, for a variety of reasons, very little work has been done on the response of oats to atrazine. The most comprehensive work was published by Smith and Buchholtz (1964), who reported significant differences among 20 oat genotypes for dry shoot weight. They evaluated grain yield of the most tolerant and intolerant genotypes in large field plots containing residual atrazine and corroborated the dry shoot weight results.

The oat genotypes used by Smith and Buchholtz (1964) are no longer used today. Furthermore, these workers measured grain yield only to corroborate extremes in dry shoot weight. The research reported herein was conducted to evaluate genetic variability among 20 current oat genotypes for grain and straw yield response to atrazine. In addition, the effect of atrazine on groat percentage, groat protein percentage, and groat protein yield was evaluated in a subset of eight genotypes.

MATERIALS AND METHODS

Genotypes

The oat genotypes consisted of 14 cultivars and six experimental selections representing a wide range of variability in plant height and heading date (Table 1). All of the genotypes were adapted to Wisconsin growing conditions.

Table 1. Description of oat genotypes.

Genotype	Heading date†	Plant height†	Pedigree
		cm	
Allen	21 June	92	Complex Purdue cross involving Clintford and Clintland
Dal	29 June	101	Trispernia/Belar/2/Beedee
Froker	29 June	108	P.E.P. 34-39-1-2/X643-33
Goodland	27 June	97	Trispernia/Belar/2/2*Goodfield/3/Garland
Holden	25 June	98	Clintland/X421-5-2
Lang	21 June	93	Tyler/Orbit
Lodi	30 June	114	X215-1/X421-5-2
Lyon	25 June	113	Lodi/Portage
Mackinaw	1 July	110	Mich. 56-22-1424/Mich. 56-24-1524
Marathon	28 June	102	Holden/X1289-1
Otee	23 June	96	Albion Newton/2/Minhafer/3/Jaycee
Stout	23 June	85	Complex Purdue cross involving Clintland 64 and Milford
Spear	24 June	98	Neal/Clintland 64
Wright	27 June	108	Trispernia/Belar/3*Beedee
X1839-1	30 June	119	X1144-2/2*Lodi
X1986-1	28 June	99	X1274-2/X1178-1
X2078-1	26 June	103	Froker/X1274-2
X2221-1	25 June	93	X1289-1/Orbit
X2459-2	26 June	94	Jaycee/X1289-1
X2851-2	25 June	100	X1137-5/X1656-4
Mean	26 June	101	

† Means are from the yield nurseries grown at Madison, Wis., in 1974, 1975, and 1976.

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Field Procedures

A field experiment was conducted at Arlington, Wis., on a Plano silt loam soil (Typic Argiudoll, fine-silty, mixed, mesic) with 3.5 to 4.0% organic matter, a cation exchange capacity of 20.0 meq/100 g, and a pH of 6.3. Five actual ingredient atrazine treatments, 0, 1.12, 2.24, 3.36, and 4.48 kg/ha, were applied post-emergence to corn land during each of the years prior to growing the oats. The atrazine was applied on 28 May 1975 and 9 June 1976, while the oats were planted on 7 to 8 Apr. 1976 and 12 to 13 Apr. 1977. In both 1975 and 1976, the corn was harvested as silage and the experimental plot area was fall-plowed with a moldboard plow.

The experimental design was a split plot with five replicates. Five atrazine treatments and 20 oat genotypes were assigned randomly to the whole plots and subplots, respectively. A subplot consisted of four rows, each 3.1 m long and spaced 30.5 cm apart. Subplots were seeded at a rate of 25 seeds/30 cm of row (90 kg/ha).

Leaf damage ratings were made approximately 5 weeks after emergence using a 1 to 9 scale; with 1 being no damage and 9 being complete leaf necrosis and death of all plants in a plot. Plant height was measured just prior to harvest as the distance from the soil surface to the tips of the main panicles. Plants in a plot were harvested by cutting 2.44 m from each of the two center rows. The cutting height was approximately 5 cm above the soil surface. Harvested plants were dried for 1 week at 38 C, weighed to determine dry matter yield (grain + straw), and threshed to determine grain yield, straw yield, and harvest index (grain yield/dry matter yield).

Eight of the 20 genotypes were selected to study the effect of residual atrazine on groat percentage, groat protein percentage, groat protein yield, and 100-kernel weight. Dal, Froker, 'Lodi', Lyon, Otee, X1839-1. X2078-1, and X2221-2 were chosen because they represented a wide range in genetic variability for groat protein percentage and for response to atrazine. After determining the weight of 100 random kernels, a weighed sample of kernels was dehulled with an impact dehuller and the groat percentage was determined. The groats then were ground and total N was determined by the USDA Oat Quality Laboratory, Madison, Wis., by the Udy Dye-Binding technique. Groat protein percentage was determined by multiplying %N by 6.25. Groat protein yield in kg/ha was determined by the following equation:

$$\text{Groat protein yield (kg/ha)} = \text{grain yield (kg/ha)} \times \text{groat percentage} \times \text{groat protein percentage}.$$

Statistical Procedures

Data from the field experiment were analyzed as a split plot, with atrazine treatments as whole plots and oat genotypes as subplots. Atrazine treatments and oat genotypes were considered to be fixed effects.

A regression analysis procedure based on the model of Finlay and Wilkinson (1963) and Eberhart and Russell (1966) for evaluating the response of a genotype was performed on the combined data from the 2 years of testing grain yield and straw yield. These models characterize the response of a genotype by (i) the mean of the genotype across the treatments or experiments, (ii) a regression coefficient that measures response of the genotype to the treatments or experiments, and (iii) the sum of the squared deviations from regression for the genotype. For each genotype the mean yield across all atrazine levels (including the controls) was calculated. Regression coefficients were computed by regressing the genotype means from the residual atrazine levels onto the atrazine level means. Because increasing levels of residual atrazine reduced the level means for each trait, regression coefficients were negative. Regression coefficients were evaluated for significant difference from −1.0 with a t-test. Deviations from regression were calculated for each genotype. However, none of them were significant for either trait, and therefore, they are not presented or discussed.

With this modified regression procedure, a genotype with a tolerant response to atrazine residue would have a high mean yield and a regression coefficient less negative than −1.0. Conversely, a genotype with an intolerant response would have a low mean yield and a regression coefficient more negative than −1.0.

RESULTS AND DISCUSSION

Oat growth and production were reduced more substantially by residual atrazine in 1977 than in 1976 (Table 2). In comparison with the control, grain and straw yields in the highest level of residual atrazine were approximately 70% in 1976, while in 1977 they were approximately 33%. Yield reductions were smaller in 1976 because abundant rainfall during the latter half of 1975 leached much of the atrazine from the root zone by the time that the oats were planted in 1976. Conversely, substantial atrazine residue remained in the topsoil when the 1977 crop was planted because the latter half of 1976 was very dry.

The response of harvest index to increasing atrazine differed between years (Table 2). While harvest indexes were reduced by high levels of atrazine residue in 1977, the effect of atrazine was less pronounced in 1976. These differing trends may have been caused by differences in the extent of photosynthetic inhibition caused by atrazine, a known photosynthetic inhibitor (Imbamba and Moss, 1971; Moreland et al., 1959; Moss, 1968). Leaf damage was greater in 1977 (Table 2), suggesting that photosynthetic activity was reduced more than in 1976. Ultimately, grain yield was reduced more substantially than straw yield in 1977 because in the sequence of growth and development the kernel is the last morphological structure to be filled with carbohydrates. When photosynthate production is reduced, the last structure (sink) that is filled in a sequence may incur the greatest reduction.

Means, regression coefficients, and standard errors of regression for grain yield are presented in Table 3. Genotypes with grain yields higher than the 20-genotype mean had regression coefficients that were less negative than −1.0, while genotypes with grain yields below the mean had regression coefficients that were more negative than −1.0. The correlation between grain yields and regression coefficients of the 20 genotypes was significantly negative (−0.55*). Three of the five genotypes that were significantly higher yielding than the mean had regression coefficients that were significantly less negative than −1.0. The experimental selection X1986-1 was the only genotype among the top nine that had a regression coefficient more negative than −1.0. This genotype was high yielding in low levels of residual atrazine, but was relatively low yielding when atrazine carryover was extensive.

Except for the cultivar 'Goodland', lower yielding genotypes had regression coefficients that were more negative than −1.0 (Table 3). Although Goodland's regression coefficient was significantly less negative than −1.0, it had low yields in low levels of residual atrazine. In high levels of atrazine, Goodland was higher yielding than some genotypes, but it still was considerably lower yielding than X1839-1 and X2078-1. Consequently, its mean grain yield was significantly lower than the overall mean.

Although higher-yielding genotypes tended to have less leaf damage than lower yielding genotypes, there were several exceptions to this trend (Table 3). For example, Mackinaw suffered substantial leaf damage in both years of testing, but in spite of this, it maintained a sufficient level of photosynthetic activity to

Table 2. Whole plot means for the 20 oat genotypes grown in atrazine residue plots at Arlington, Wis., in 1976 and 1977.

Year of oat growth	Atrazine treatment of the previous year	Grain yield	Straw yield	Leaf damage	Plant height	Harvest index
		kg/ha	kg/ha	1-9	cm	
1976	0	3,373 a*	3,280 a	1.0 a	86 a	0.508 b
	1.12	3,359 a	3,179 a	1.2 a	86 a	0.515 a
	2.24	3,155 b	3,036 b	1.5 b	84 b	0.511 ab
	3.36	2,608 c	2,430 c	3.5 c	80 c	0.515 a
	4.48	2,298 d	2,230 d	3.9 d	78 d	0.505 b
1977	0	3,309 a	3,539 a	1.0 a	94 a	0.483 a
	1.12	3,183 b	3,468 a	1.0 a	92 b	0.480 a
	2.24	2,774 c	3,008 b	2.4 b	90 c	0.480 a
	3.36	1,723 d	2,067 c	5.1 c	85 d	0.449 b
	4.48	1,028 e	1,288 d	7.1 d	82 e	0.430 c

* Within years and columns, means not followed by a common letter are significantly different at the 5% level according to Duncan's New Multiple Range Test.

Table 3. Means, regressions, and standard errors of regression for grain yield and leaf damage means for 20 oat genotypes grown in residual atrazine at Arlington, Wis., in 1976 and 1977.

Genotype	Grain yield: Mean	Grain yield: Regression coefficient	Grain yield: Standard error of regression	Leaf damage†: Mean
	kg/ha			1-9
X2078-1	3,147**	−0.89*	0.042	3.7*
Lang	2,963**	−0.90	0.049	4.1
Mackinaw	2,941**	−0.91	0.067	4.6*
Froker	2,935**	−0.88*	0.041	3.9*
X1839-1	2,901*	−0.65**	0.032	3.9*
Marathon	2,828	−0.76**	0.049	4.3
X1986-1	2,782	−1.18**	0.019	3.8*
X2221-2	2,724	−0.91	0.055	4.1
Lodi	2,720	−0.90	0.076	4.4
20 genotype mean	2,677	−1.00		4.2
Spear	2,615	−1.07	0.052	4.0
X2459-2	2,599	−1.17**	0.068	4.4
Stout	2,598	−1.09	0.051	3.9*
Otee	2,587	−1.22**	0.022	4.1
Holden	2,584	−1.13*	0.053	4.4
Wright	2,497	−1.08	0.094	4.2
Dal	2,474*	−1.12	0.041	4.5*
Lyon	2,468*	−1.20	0.113	4.6*
X2851-2	2,430**	−1.07	0.044	4.2
Goodland	2,362**	−0.89**	0.020	4.2
Allen	2,343**	−1.08	0.051	4.1

*,** Significantly different from the mean at the 5 and 1% levels of probability, respectively. † Each leaf damage score is the mean of damage from the highest three levels of residual atrazine in each of the 2 years of testing.

produce high grain yields. 'Stout' was the other genotype that did not perform as expected. Although it had significantly less than average leaf damage, its grain yield was 10% lower than the mean. The correlation of means for grain yield and leaf damage was negative but nonsignificant (−0.37), indicating that these two traits were not sufficiently associated for leaf damage to be considered a reliable indicator of genotypic grain yield response to atrazine.

There was significant genetic variability for straw yield response to atrazine (Table 4). Unlike the association between means and regressions for grain yield, the association between means and regressions for straw yield was nonsignificant ($r = 0.25$). Only one of the six genotypes with a mean straw yield significantly greater than the 20-genotype mean had a regression coefficient significantly less negative than −1.0, while none of the six genotypes with straw yields significantly lower than the mean had a regression coefficient that was significantly different from −1.0. In fact, four of the six genotypes with significantly low straw yields had coefficients that were 4 to 11% less negative than −1.0, and Mackinaw (in the high yielding group) had a regression coefficient (−1.19) that was significantly more negative than −1.0. Mean straw yield also was not associated with mean leaf damage ($r = 0.06$), indicating that leaf damage should not be considered an indicator for genotypic straw yield response to atrazine.

A trait that was closely associated with straw yield in residual atrazine was plant height (Tables 4 and 5). Regression coefficients for plant height, computed but not presented in this paper, also were positively associated with straw yield coefficients (Table 5), indicating that these two traits responded similarly to increasing levels of atrazine. The taller types also were later maturing (Table 1). Although maturity was not measured in the atrazine experiments, the correlation between heading date (Table 1) and straw yield

Table 4. Means, regressions, and standard errors of regression for straw yield and means for plant height for 20 oat genotypes grown in residual atrazine at Arlington, Wis., in 1976 and 1977.

Genotype	Straw yield: Mean	Straw yield: Regression coefficient	Straw yield: Standard error of regression	Plant height: Mean
	kg/ha			cm
X1839-1	3,389**	−0.98	0.088	102**
Mackinaw	3,262**	−1.19*	0.082	97**
Lodi	3,026**	−1.14	0.133	101**
Marathon	2,996**	−0.99	0.105	86
Wright	2,979*	−1.18	0.116	97**
Froker	2,969*	−0.76**	0.087	90**
X2078-1	2,904	−0.86*	0.061	88**
Dal	2,855	−1.32**	0.093	88**
20 genotype mean	2,750	1.00		86
Otee	2,745	−1.32**	0.099	81**
Goodland	2,706	−0.74**	0.046	79**
Lang	2,589	−0.68**	0.066	78**
X1986-1	2,588	−1.08	0.063	80**
Lyon	2,576	−1.27	0.142	95**
X2221-2	2,565	−0.85	0.114	78**
Spear	2,531*	−0.89	0.100	83**
Holden	2,500**	−0.91	0.061	87
Stout	2,464**	−0.96	0.068	71**
X2459-2	2,453**	−1.05	0.096	77**
X2851-2	2,445**	−0.93	0.115	81**
Allen	2,404**	−0.99	0.070	76**

*,** Significantly different from the mean at the 5 and 1% levels of probability, respectively.

Table 5. Correlations between traits based upon genotype means and genotype regression coefficients.

	Straw yield	Plant height
Grain yield	0.53*†	0.27
	0.37	−0.25
Straw yield		0.80**
		0.59**

* and ** Significant at the 5 and 1% levels of probability, respectively.
† Upper numbers are correlations of genotype means, while lower numbers are correlations of genotype regression coefficients.

Table 6. Whole plot means for the eight oat genotypes used to study the effects of atrazine on kernel quality.

Year of oat growth	Atrazine treatment of the previous year	Grain yield	Groat protein percentage	Groat percentage	100-seed wt.	Groat protein yield
	kg/ha	kg/ha			g	kg/ha
1976	0	3,398 a*	16.3 c	68.0 c	2.97 c	377 a
	2.24	3,125 b	16.7 b	68.3 c	3.04 c	363 a
	3.36	2,658 c	18.2 a	69.4 b	3.14 b	313 b
	4.48	2,311 d	18.1 a	70.3 a	3.23 a	293 c
1977	0	3,505 a	17.6 c	67.9 a	3.09 a	419 a
	2.24	2,909 b	18.9 b	67.3 ab	3.08 a	368 b
	3.36	1,692 c	20.0 a	67.2 ab	3.00 b	223 c
	4.48	1,187 d	20.0 a	66.4 b	3.00 b	155 d

* Within columns and years, means not followed by a common letter are significantly different at the 5% level according to Duncan's New Multiple Range Test.

among the control plots in 1976 and 1977 was highly significant ($r = 0.69^{**}$). The six genotypes with straw yields significantly greater than the overall mean were tall, intermediate to late maturing types, while the genotypes with significantly low straw yields were shorter, earlier types. These results indicate that in this set of 20 diverse genotypes, plant height and maturity were reliable indicators of straw yield response to atrazine, with taller, later types producing greater straw yields across all levels of atrazine. Not all tall genotypes were high straw yielders in high atrazine. For example, Mackinaw, which had the second highest mean straw yields, had higher straw yields than Froker and Lang in low levels of atrazine, but it did not maintain this advantage in higher levels of atrazine, as indicated by its regression coefficient (Table 5).

Despite the significant correlation between mean grain and straw yields, the nonsignificant correlation between regressions for these traits seems to be more conclusive evidence that grain and straw yield responses to increasing atrazine were not closely associated (Table 5). Means for grain and straw yield were associated because oat plants that tend to produce high grain yields usually produce high straw yields. This occurs because the high yields are attributable to high tillering or to heavy panicles (large number of spikelets per panicle and/or substantial weight per seed) requiring considerable culm tissue. Neither means nor regressions for grain yield and plant height were significantly associated (Table 5). Thus, in terms of response to atrazine, plant height and straw yield were significantly associated, but neither of these was closely associated with grain yield.

Whole-plot means for the eight genotypes used to study the effect of atrazine on kernel quality are presented in Table 6. Groat protein percentage and groat protein yield responded similarly to atrazine residue in 1976 and 1977, while groat percentage and 100-seed weight responded differently during the 2 years. In both years, protein percentage increased significantly in greater atrazine residue. This response was not surprising in view of the inverse relationship between grain yield and protein percentage noted frequently in oats (Hutchinson and Martin, 1955; Brown et al., 1966; Briggle, 1971; Spilde et al., 1974; Sraon et al., 1975). The increases in protein percentage were greater in 1977 than in 1976 because grain yield reductions were greater in 1977.

Groat percentage and 100-seed weight increased in

Table 7. Grain and protein yields of four oat genotypes grown in residual atrazine at Arlington, Wis., in 1976 and 1977.

Genotype	Atrazine treatment of the previous year	Grain yield 1976	Grain yield 1977	Groat protein yield 1976	Groat protein yield 1977
	kg/ha				
X1839-1	0	3,181	3,563	353	405
	2.24	2,965	2,947	338	350
	3.36	2,903	2,102	359	264
	4.48	2,575	1,765	326	223
Froker	0	3,522	3,381	397	407
	2.24	3,236	3,257	376	390
	3.36	2,953	1,931	375	253
	4.48	2,606	1,493	327	194
Dal	0	3,162	3,326	359	402
	2.24	2,836	2,862	309	388
	3.36	2,151	1,371	281	201
	4.48	2,046	646	259	93
Lyon	0	3,481	3,406	379	423
	2.24	3,111	2,369	356	307
	3.36	2,387	938	293	121
	4.48	1,757	935	231	125
L.S.D. (0.05)		692	679	95	103

higher atrazine residue in 1976 when damage from atrazine was relatively light, but both decreased slightly in 1977 when leaf damage was greater and photosynthetic activity was inhibited more extensively. In 1976, plants damaged by atrazine recovered to some extent by compensating for reductions in components formed prior to average weight per seed through increases in this component. In 1977, damage to the photosynthetic system was too great to allow for a compensating effect in average weight per seed. These results indicate that kernel quality may not be reduced if atrazine damage is relatively light, but if atrazine damage is extensive it will be reduced. For example, none of the three kernel quality traits (protein percentage, groat percentage, and 100-seed weight) were reduced in the highest level of atrazine residue in 1976 when overall damage was not extensive, but groat percentage and 100-seed weight were reduced significantly in the highest level of atrazine in 1977 when damage was extensive.

Despite the increase in groat protein percentage in high atrazine, groat protein yields declined significantly each year because grain yields were reduced (Table 6). Genotypic responses for protein yield were similar to grain yield responses (Table 7). Froker and

X1839-1, which were tolerant to atrazine, produced more protein per hectare than the intolerant Dal and Lyon. Similar protein percentage and protein yield responses to simazine, an herbicide closely related to atrazine, have been reported in wheat (*Triticum aestivum* L.) by McNeal et al. (1969), Moyer and Paulsen (1977), and Ries et al. (1970).

The results of these experiments have shown that some oat genotypes are more tolerant of atrazine than others. Additional research could evaluate the inheritance of tolerance to atrazine, for the pedigrees listed in Table 1 indicate that tolerance to atrazine in oats may be reasonably heritable. For example, one of the parents of the tolerant genotype X2078-1 is Froker, which has tolerance. If studies indicated that tolerance to atrazine was heritable, then progress through breeding could be realized. However, there may not be enough genetic variability among the 20 genotypes tested in this study to warrant intercrossing them to develop more tolerant genotypes. Grain and straw yields of the most tolerant genotypes were reduced by more than 50% in the highest level of residual atrazine. Searching for more tolerant genotypes in sources such as the World Oat Collection and crossing promising genotypes that may be found with the tolerant genotypes in this study may be a more productive course of action.

Another factor to consider is the future of atrazine. Development of an equally effective replacement herbicide that has minimal carryover could decrease the use of atrazine, provided that the replacement herbicide is competitive economically.

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