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Effects of Tillage and Rainfall on Atrazine Residue Levels in Soil[1]

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Abstract. **A field study was conducted in 1987 to 1991 to determine the effect of tillage and rainfall on distribution of atrazine in soil. Soil samples (10-cm increments to 50 cm) and crop residue samples were taken at regular intervals after application each year and analyzed for atrazine. Crop residue and living vegetation on no-till plots intercepted 60 to 70% of the applied atrazine; 3 to 16% of the atrazine remained in crop residue 1 to 2 wk later. The amount of atrazine recovered in soil, 1 to 2 wk posttreatment, ranged from 22 to 59 and 47 to 73% of the amount applied for no-till and conventional till, respectively. An average of 2.6 times more atrazine was recovered in the surface 10 cm of soil under conventional till than under no-till for all samplings and years. Total amounts of atrazine in the sampled profile (0- to 50-cm depth) were also generally lower under no-till than conventional till. More leaching below 10 cm occurred under no-till than conventional till, particularly in 1988 and 1990 when rain fell soon after application. Variation in soil atrazine levels among years was related to timing and amount of the first and subsequent rainfall after application. Nomenclature: Atrazine, 6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine.**
Additional index words: **No-till, conventional till, degradation, dissipation, half-life.**

INTRODUCTION

Tillage practice and yearly variations in rainfall patterns can significantly affect the distribution of pesticides in soil. Conservation tillage practices and no-till in particular leave large amounts of crop residue on the soil surface. In addition, volunteer vegetation (weeds) or cover crops can combine with crop residue to nearly cover the soil surface at the time of pesticide application. Depending on amount and type of crop residue or vegetation, 15 to 80% of applied pesticide may be intercepted (1, 2, 6, 8, 13, 19). Amounts intercepted also vary among different pesticides and formulations. Pesticides are usually washed from crop residue to the soil by rainfall, but the amount reaching soil is dependent on rainfall amount and timing after application (13, 17). The amount of pesticide that washes from crop residue also is dependent on type of residue. Pesticides are more easily washed from dead plant tissue, such as crop residue and residues from the previous year, compared to living or freshly harvested vegetation (18). Water infiltration and agrochemical leaching can occur at higher rates under no-till than conventional till (4, 10, 11). Macropores, which are generally more numerous and well developed under no-till than conventional till, appear to be primarily responsible for the increased rate of water infiltration and agrochemical transport (3, 5, 12, 16). However, amount of leaching under no-till is related to timing, amount, and intensity of initial rains following agrochemical application (5, 17, 18). A small initial rain will significantly reduce amount of pesticides leached by subsequent larger rains presumably by increasing soil-pesticide interactions which reduce the amount of pesticide available for leaching (17). More atrazine was leached by high- compared to low-intensity rains (5, 18) and the sooner a rain occurs after application, the more likely is pesticide leaching (11).

Field studies to evaluate effects of tillage on pesticide dissipation in soil are limited and inconsistent. Higher soil concentrations of atrazine were found under conventional till than no-till down to 80 cm, but only one sampling, 5 mo after application, was made (7). Another study found that soil concentration of three herbicides over 2 yr was higher under conventional till than no-till, but only the surface 15 cm of soil was analyzed (6). In yet another 2 yr study, concentration of several herbicides was higher under no-till than conventional till 8 wk after application in one year, with little difference between tillages 11 wk after application in a second year (10). Clearly, long-term field studies are needed to determine the effect of tillage on pesticide distribution in soil.

The objective of this study was to determine the interrelationships between tillage practice and rainfall patterns on distribution and dissipation of atrazine in soil under field conditions over several years.

MATERIALS AND METHODS

This research was conducted at the USDA Beltsville Agricultural Research Center, Beltsville, MD. The research site has been previously described (11). In brief, a 1.4-ha field that had been in conventional-till corn production since 1981 was, in 1986, divided into two no-till and two conventional-till plots. The soil is a Hatboro silt loam (fine-loamy, mixed, nonacidic, mesic Typic Fluvaquents). Surface soil (0 to 10 cm) pH was 6 to 6.5, decreasing to 4.8 to 5 in the subsoil. Organic carbon contents of this surface soil averaged 0.9% in no-till and 0.7% in conventional till in 1988. In 1991, organic carbon contents at depths of 0 to 1.5, 1.5 to 3, 3 to 5, 5 to 10, and 10 to 20 cm were: for no-till, 2.4, 1.4, 0.9, 0.7, and 0.7%; and for conventional till, 0.7, 0.7, 0.7, 0.7, and 0.7%, respectively. The organic carbon content of the 0- to 10-cm depth in 1991 was 1.1% for no-till and 0.7% for conventional till. Additional soil properties are given in Table 1.

Each year, about 2 wk before planting, the conventional-till plots were plowed and harrowed, leaving a bare soil surface. The

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Table 1. Composition and physical properties of Hatboro silt loam under no-till and conventional till[a].

Depth	Sand	Silt	Clay	Bulk density
cm		%		g cm^{-3}
No-till:				
0–10	37	46	17	1.5
10–20	37	45	18	1.6
20–30	35	43	22	1.6
30–40	36	38	26	1.6
40–50	39	36	25	1.7
Conventional:				
0–10	35	49	16	1.5
10–20	34	50	16	1.6
20–30	31	49	20	1.6
30–40	31	45	24	1.7
40–50	37	41	22	1.7

[a]All values mean of 15 samples.

soil surface in the no-till plots was almost completely covered by a combination of crop residue from the previous year and living vegetation. In the fall, after harvest, crop residue was left in the field for both no-till and conventional till and no cover crop was planted.

Corn was planted May 27, May 3, June 27, June 6, and May 8 for 1987 to 1991, respectively, and pesticide application was made 1 d later each year. Atrazine, paraquat (1,1′-dimethyl-4,4′-bipyridynium ion), and permethrin [3-phenoxybenzyl (1RS)-cis,trans-(2,2-dichlorovinyl)-2,2-dimethyl-cyclopropanecarboxylate] were applied in a single tank mix at 1.34, 0.34, and 0.09 kg ha^{-1}, respectively. Pesticides were applied using a tractor-mounted sprayer delivering 280 L ha^{-1} water at 210 kPa with TeeJet 730385[3] flat-fan nozzles. Atrazine, paraquat, and permethrin were applied as the wettable powder, soluble concentrate, and emulsifiable concentrate, respectively. Planting, using a two-row no-till planter, and spraying operations were conducted identically across all plots.

Sampling. Before pesticide application, 15 petri dishes (each containing about 25 g of soil from an untreated adjacent field) were randomly placed in each plot. In the no-till plots, a disk of crop residue and vegetation, cut with a sharpened pipe of the same diameter as the petri dish, was placed on the surface of the soil. All petri dishes were covered immediately after application and returned to the laboratory. Crop residue and soil were placed into separate extraction bottles and analyzed.

Soil samples (starting in 1987) were obtained manually by driving soil sampling tubes (4.1 cm i.d. by 1.5 m long) 10 to 100 cm deep. Some samplings in 1987 and 1988 were taken only to 10 cm because of limited rainfall and some to 100 cm to determine the extent of atrazine transport. Samples in 1990 and 1991 were all to 30- or 50-cm depths. The sampling tubes were retrieved using a chain hoist attached to a mobile metal framework wheeled between corn rows to each sampling site. Eight to 10 soil cores were taken from each plot for 1987 and 1988 and 15 cores per plot for 1990 and 1991. In the no-till plots, all crop residue representative of a uniform surface area was taken just before the soil sampling in 1988, 1990, and 1991. Each hole was backfilled with surface soil taken from an untreated control field. The soil cores were removed from the tubes, sectioned into 10-cm-depth increments, placed in tared glass bottles and taken to the laboratory. The samples were weighed in the bottles to preserve soil moisture content and frozen for later processing and analysis. Crop residue samples were frozen also. Several days before analysis, the frozen soil samples were allowed to thaw in a coldroom, and then were mixed. A mixing technique (15) was used that uniformly blends samples with moisture contents that vary from near air dryness to near saturation. Gravimetric water content was determined on a subsample of the mixed soil.

Extraction and analysis. A 25-g subsample of the mixed soil was extracted by shaking (wrist-action) for 1 h with 100 ml of methanol:water (4:1 by vol), filtered, and the filtrate reduced to ca. 15 ml in a rotary evaporator. The entire crop residue and 0 d after treatment (DAT) soil samples were extracted as above. Atrazine was extracted from the aqueous filtrate by solid-phase adsorption using C_{18} cartridges[4], eluted from the cartridge with ethyl acetate, and analyzed by gas-liquid chromatography using a nitrogen-phosphorus detector. The recovery efficiency for atrazine was 85% with a detection limit of 1 µg kg^{-1}. The analytical procedure is described in detail elsewhere (11).

[3]Spraying Systems Co., North Ave., Wheaton, IL 60188.
[4]Waters, Millipore Corp., Milford, MA 01757.

RESULTS AND DISCUSSION

The concentration of atrazine in the soil profile under no-till and conventional-till practices is shown in Tables 2 and 3. Values represent the mean of all samples taken from duplicate plots of each tillage treatment. Thus, each value is the mean of 16 to 20 samples for 1987 and 1988 and 30 samples for 1990 to 1992. Although sampling depth varied from year to year, only concentrations to the 50-cm depth are presented in Tables 2 and 3 because pesticide residue levels below 50 cm in the soil horizon were all < 10 g ha^{-1} for both treatments.

Data for 1989 are not presented because we considered results to be unreliable. Atrazine was not applied until June 28 because high rainfall in May and June (210 mm and 124 mm, respectively) prevented access to the field. Poor germination due to late planting and wet soil necessitated replanting the corn 2 wk after atrazine application; only two soil samplings were then made. Soil residues were very low and because of the unexpected events, we felt that the results could not be compared to other years.

Distribution and dissipation. Atrazine recovered immediately after application (0 DAT) ranged from 85 to 92% of the theoretical amount applied. The 0 DAT values for no-till represent the sum of atrazine recovered in soil plus crop residue. Atrazine recovered in the first soil cores taken after application (8, 13, or 14 DAT) always contained the highest concentration and represented 22 to 59 and 47 to 73% of atrazine applied to the surface of the no-till and conventional-till plots, respectively. Addition

Table 2. Atrazine[a] residues in soil as a function of time after application and tillage practice[b].

Soil depth	Atrazine residue at days after application[c]							
	1987				1988			
	0[d]	13	48	91	0[d]	13	41	71
cm	g ha^{-1}							
No-till:								
0–10	1139 ± 152	337 ± 74	80 ± 12	47 ± 10	1220 ± 256	247 ± 41	95 ± 19	61 ± 6
10–20	—	—	59 ± 27	—	—	103 ± 30	41 ± 11	—
20–30	—	—	36 ± 18	—	—	58 ± 18	31 ± 6	—
30–40	—	—	11 ± 3	—	—	—	33 ± 10	—
40–50	—	—	9 ± 2	—	—	—	14 ± 3	—
Total	1139	337	195	47	1220	408	214	61
Conventional:								
0–10	1175 ± 178	510 ± 94	178 ± 36	121 ± 21	1248 ± 197	858 ± 97	237 ± 74	205 ± 21
10–20	—	—	28 ± 5	—	—	45 ± 12	45 ± 9	—
20–30	—	—	21 ± 3	—	—	10 ± 2	10 ± 2	—
30–40	—	—	23 ± 8	—	—	—	7 ± 2	—
40–50	—	—	15 ± 2	—	—	—	8 ± 2	—
Total	1175	510	265	121	1248	913	307	205

[a]Initial application = 1340 g ha^{-1}.

[b]Mean and standard error of mean based on 20 samples.

[c]— Not sampled.

[d]Based on surface samples taken immediately after application; for no-till values represents sum of atrazine recovered from soil plus vegetation.

of the atrazine remaining on the crop residue under no-till at the first sampling for 1988, 1990, and 1991 increased the recovery to 36, 75, and 35%.

On average, 2.6 times more atrazine was recovered in the top 10 cm of soil under conventional till than under no-till for all samplings and years (Tables 2 and 3). Amounts were always highest for the first sampling and then decreased with time and depth. The amount of atrazine recovered in the profile (0 to 30 or 0 to 50 cm) was also higher under conventional till than no-till, except for the 8 DAT sampling in 1990, but differences in the total amounts recovered were not as large as in the surface soil. The thick vegetative and crop residue cover in the no-till plots intercepted 60 to 70% of the applied atrazine (Table 4). This level of atrazine interception is similar to interception rates reported for other pesticides (6, 14, 19). Most of the atrazine intercepted by the crop residue was eventually washed off to soil, but only slowly because of the delay between application and the first rain (12 h in 1988 to 4 d in 1990) and incomplete washoff of the pesticide. A similar study showed that only 30 to 60% of the atrazine applied to corn residue was washed off in the first rain (13). In our study, 2.6 to 16% of the applied atrazine remained on crop residue in the no-till plots 8 to 13 d after application (Table 4).

A second factor affecting soil concentration was leaching. There was a general trend for atrazine concentration to be higher in the 10- to 30- or 10- to 50-cm depth below no-till than for the comparable depth in conventional till. Differences between tillage treatments generally disappeared or become smaller after the first sampling. The highest concentrations in the 10- to 30-cm depths, recorded 8 and 13 DAT for 1990 and 1988, respectively, were associated with unusual rainfall (Tables 2 and 3). In 1988, a 45-mm, 2-d duration rain that began 12 h after application leached much of the applied atrazine through the soil profile in the no-till plots but only into the surface soil in the conventional-till plots. Total recovery at 13 DAT was 33 and 73% of the applied atrazine under no-till and conventional till, respectively. In addition, very little, 2.6%, of the applied atrazine remained on crop residue 13 DAT in 1988 compared to 13 and 16% for the first samplings of 1991 and 1990, respectively, further indicating the extent of washoff from the first rainfall. Leaching studies on the same plots indicated that 9 and 1% of the applied atrazine was leached to shallow groundwater (1 m) under no-till and conventional till, respectively, 6 d after application in 1988 (9, 11). In 1990, a 27-mm, 30-min duration rain occurred 4 DAT and was responsible for the very high soil residue levels for the 8 DAT sampling, especially under no-till. Again, as in 1988, there was significant leaching below 10 cm under no-till, while the atrazine concentration below 10 cm under conventional till was nearly identical to the amounts found for the first sampling in 1988 and 1990. It is unknown whether differences in sampling times (8 and 13 DAT for 1990 and 1988, respectively) or the higher amount of rain in 1988 compared to 1990 accounts for the higher atrazine concentrations for each depth in 1990 than 1988.

Much of the leaching of pesticides (and other solutes) under no-till is thought to occur via preferential transport through macropores, a process that can bypass much of the soil matrix (3, 5). Under this process, water from rain or irrigation will preferentially flow through macropores and rapidly transport some of the surface-applied atrazine below the root zone. The process is rapid so only a small amount of transported atrazine may adsorb to the surrounding soil matrix as it passes through the root zone. Our data support this concept; i.e., the increased

Table 3. Atrazine[a] residues in soil as a function of time after application and tillage practice[b].

Soil depth	Atrazine residue at days after application[c]				
	1990				
	0[d]	8	29	84	157
cm	g ha^{-1}				
No-till:					
0–10	1193 ± 161	441 ± 79	114 ± 19	46 ± 6	6 ± 1
10–20	—	167 ± 31	37 ± 6	30 ± 5	3 ± 1
20–30	—	96 ± 19	18 ± 2	16 ± 5	3 ± 2
30–40	—	—	16 ± 3	—	3 ± 1
40–50	—	—	12 ± 3	—	5 ± 2
Total	1193	704	197	92	20
Conventional:					
0–10	1224 ± 212	572 ± 56	319 ± 41	70 ± 14	15 ± 5
10–20	—	43 ± 6	36 ± 8	16 ± 3	3 ± 1
20–30	—	27 ± 5	22 ± 3	6 ± 2	2 ± 1
30–40	—	—	10 ± 2	—	<1
40–50	—	—	13 ± 2	—	<1
Total	1224	642	400	92	20
	1991				
	0[d]	14	29	54	85
	g ha^{-1}				
No-till:					
0–10	1233 ± 222	157 ± 21	96 ± 16	31 ± 6	19 ± 3
10–20	—	45 ± 8	25 ± 5	17 ± 5	12 ± 21
20–30	—	31 ± 10	15 ± 3	10 ± 3	7 ± 2
30–40	—	25 ± 11	13 ± 3	8 ± 2	7 ± 2
40–50	—	15 ± 3	10 ± 2	9 ± 3	7 ± 2
Total	1233	273	159	75	52
Conventional:					
0–10	1207 ± 178	522 ± 57	240 ± 86	94 ± 11	54 ± 12
10–20	—	26 ± 11	23 ± 5	20 ± 2	22 ± 3
20–30	—	16 ± 3	8 ± 2	8 ± 2	6 ± 2
30–40	—	7 ± 2	5 ± 2	5 ± 2	3 ± 2
40–50	—	12 ± 3	5 ± 2	3 ± 2	7 ± 2
Total	1207	583	281	130	92

[a]Initial application = 1340 g ha^{-1}.

[b]Mean and standard error of mean based on 30 samples.

[c]— Not sampled.

[d]Based on surface samples taken immediately after application; for no-till values represents sum of atrazine recovered from soil plus vegetation.

amount of atrazine recovered in the 10- to 50-cm depth under no-till compared to conventional till is not large enough to account for the difference in the mass of atrazine found in the surface 10 cm of soil between the two tillage systems. This is most likely what happened in 1988 when much of the applied atrazine leached through the sampled profile under no-till but remained in the surface soil under conventional till because recent tillage had destroyed the macropores. While it is clear from the soil and groundwater data (11) that increased leaching occurred under no-till, it is not clear if leaching was solely responsible for the differences in total atrazine content between tillage plots. Calculations based on measured atrazine in shallow groundwater (11) and more recent unpublished data indicate that < 2% of the applied atrazine reached 1- to 3-m-deep groundwater in 1987, 1990, and 1991.

Degradation may also explain lower atrazine concentrations seen under no-till. The surface soil (0 to 1.5 cm) under no-till plots contained nearly four times more organic carbon than the same soil depth under conventional till. Since microbial population densities generally increase with increasing organic carbon, it seems likely that degradation may occur more rapidly in the surface several cm of soil under no-till than under conventional till. However, half-life estimations, based on soil residue data only (Tables 2 and 3) and assuming that dissipation was first-order, ranged from 26 to 35 d. These half-life estimations suggest that dissipation and or degradation rates in soil were not different between no-till and conventional till. However, since soil residue determinations were made on 10 cm increments of soil, the question of degradation within the organic carbon-rich surface few cm of soil under no-till has not been resolved by this study.

Table 4. Atrazine recovered on crop residue as a function of days after application[a].

Year	DAT	Recovery
	d	%
1987	0	56.2 ± 7.2
1988	0	69.5 ± 12.8
	13	2.6 ± 3.5
	41	0.8 ± 0.5
1990	0	58.5 ± 11.4
	8	16.0 ± 4.6
	29	4.8 ± 3.0
	84	0.1 ± 0.1
1991	0	58.8 ± 7.7
	14	13.2 ± 5.7
	29	4.1 ± 2.2
	54	0.5 ± 0.4

[a]Amount recovered expressed as % of applied. Mean ± standard error of mean of 10–15 samples.

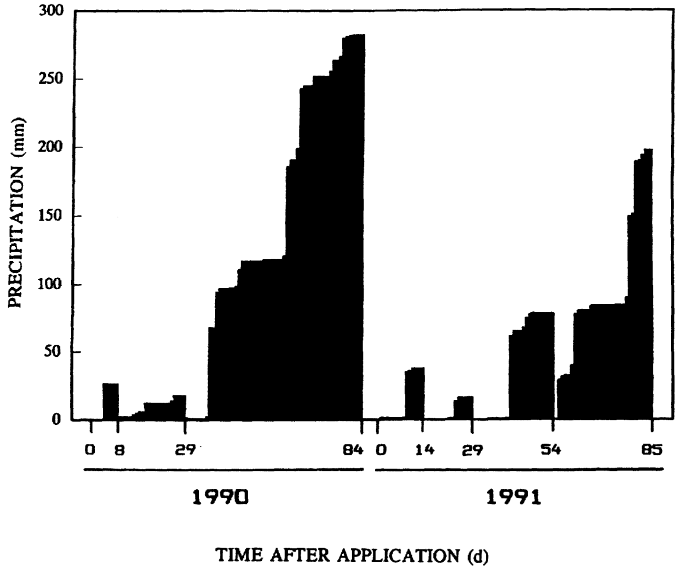

Figure 2. Total rainfall between soil samplings for 1990 and 1991. Numbers indicate days after application that soil samples were taken and histograms show cumulative rainfall between each soil sampling after application. Atrazine was applied at 0 time each year.

Rainfall characteristics. Differences in the soil atrazine content in the 0- to 10-cm depth for similar sampling times between years can largely be accounted for by differences in timing, amount, and intensity of rainfall. Initial rainfall patterns for 1987, 1990, and 1991 are reasonably comparable, 4 to 9 d between treatment and the first significant rainfall (Figures 1 and 2). Nearly equal amounts of atrazine were found in the 0- to 10-cm depth of conventional-till plots for the 13 and 14 DAT sampling in 1987 and 1991, respectively, while the no-till in 1987 contained twice as much atrazine as the no-till in 1991. Total rainfall by 2 wk posttreatment was nearly identical both years, but differences in amount and intensity of the first major rainfall [1 h, 14 mm, 4 DAT (1987) and 0.45 h, 33 mm, 9 DAT (1991)] affected the washoff and leaching under no-till differently. The low intensity 1987 rain probably removed much of the atrazine from crop residue and into the surface soil. In comparison, the larger, higher intensity rainfall in 1991 probably transported more of the atrazine past the surface soil than in 1987. These field observations agree well with two laboratory rainfall simulation studies which examined initial storm effects on atrazine leaching through no-till soil (17, 18).

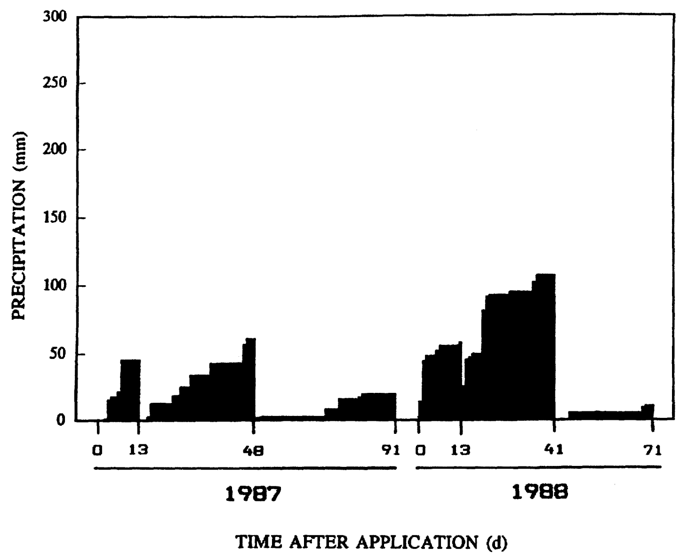

Figure 1. Total rainfall between soil samplings for 1987 and 1988. Numbers indicate days after application that soil samples were taken and histograms show cumulative rainfall between each soil sampling after application. Atrazine was applied at 0 time each year.

Atrazine recovered in surface soil 48 and 91 DAT in 1987 was consistently higher than for the comparable 54 and 85 DAT samplings in 1991, for both tillage systems. Rainfall amounts and intensities were both higher (Figures 1 and 2) in 1991 than at comparable samplings in 1987, which would likely cause more leaching and account for lower atrazine residues in 1991. However, rainfall received by both the 29 DAT and 84 and 85 DAT samples was nearly identical in 1990 and 1991, probably explaining why residual atrazine levels were also similar both years.

Evidence of extensive atrazine leaching under no-till in 2 yr of the study coincides with significant rainfall soon after application. The implication is that unless a major rain occurs soon after pesticide application, no-till practices will effectively reduce the amount of atrazine in the surface 50 cm of soil compared to conventional-till practices. What is not clear from this study is if the reduced amount of atrazine under no-till is due only to greater leaching through the soil or if increased dissipation may have occurred under no-till, especially in the organic matter-rich surface layer of soil. Future research needs to address this subject.

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LITERATURE CITED

1. Banks, P. A. and E. L. Robinson. 1982. The influence of straw mulch on the soil reception and persistence of metribuzin. Weed Sci. 30:164–168.
2. Banks, P. A. and E. L. Robinson. 1984. The fate of oryzalin applied to straw-mulched and nonmulched soils. Weed Sci. 32:269–272.
3. Czapar, G. F., R. Horton, and R. S. Fawcett. 1992. Herbicide and tracer movement in soil columns containing an artificial macropore. J. Environ. Qual. 21:110–115.
4. Dick, W. A., R. J. Roseberg, E. L. McCoy, W. M. Edwards, and F. Haghiri. 1989. Surface hydrologic response of soils to no-tillage. Soil Sci. Soc. Am. J. 53:1520–1526.
5. Edwards, W. M., M. J. Shipitalo, W. A. Dick, and L. B. Owens. 1992. Rainfall intensity affects transport of water and chemicals through macropores in no-till soil. Soil Sci. Soc. Am. J. 56:52–58.
6. Flint, J. L., W. W. Witt, J. R. Martin, and M. Barrett. 1989. Dissipation of imazaquin, imazethapyr, and chlorimuron in three soybean tillage systems. Pages 154–158 *in* Pesticides in Terrestrial and Aquatic Environments, 1990, D. L. Weigmann, ed. Virginia Water Resources Res. Ctr., Virginia Polytech. Inst. and State Univ., Blacksburg, VA.
7. Foy, C.L. and H. Hiranpradit. 1989. Movement of atrazine by water from application sites in conventional and no-tillage corn production. Pages 355–377 *in* Pesticides in Terrestrial and Aquatic Environments, 1990, D. L. Weigmann, ed. Virginia Water Resources Res. Ctr., Virginia Polytech. Inst. and State Univ., Blacksburg, VA.
8. Ghadiri, H., P. J. Shea, and G. A. Wicks. 1984. Interception and retention of atrazine by wheat (*Triticum aestivum* L.) stubble. Weed Sci. 32:24–27.
9. Gish, T. J., A. R. Isensee, R. G. Nash, and C. S. Helling. 1991. Impact of pesticides on shallow groundwater quality. Trans. Am. Soc. Agric. Eng. 34:1745–1753.
10. Hall, J. K., M. R. Murray, and N. L. Hartwig. 1989. Herbicide leaching and distribution in tilled and untilled soil. J. Environ. Qual. 18:439–445.
11. Isensee, A. R., R. G. Nash, and C. S. Helling. 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. J. Environ. Qual. 19:434–440.
12. Jones, R. E., Jr., P. A. Banks, and D. E. Radcliffe. 1990. Alachlor and metribuzin movement and dissipation in a soil profile as influenced by soil surface conditions. Weed Sci. 38:589–597.
13. Martin, C. D., J. L. Baker, D. C. Erbach, and H. P. Johnson. 1978. Washoff of herbicides applied to corn residue. Trans. Am. Soc. Agric. Eng. 33:1164–1168.
14. Mills, J. A., W. W. Witt, and M. Barrett. 1989. Effects of tillage on the efficacy and persistence of clomazone in soybean (*Glycine max*). Weed Sci. 37:217–222.
15. Nash, R. G. and M. L. Beall, Jr. 1990. Soil mixer for a wide range of water contents. Soil Sci. Soc. Am. J. 54:555–557.
16. Priebe, D. L. and A. M. Blackmer. 1989. Preferential movement of oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. J. Environ. Qual. 18:66–72.
17. Shipitalo, M. J., W. M. Edwards, W. A. Dick, and L. B. Owens. 1990. Initial storm effects on macropore transport of surface-applied chemicals in no-till soil. Soil Sci. Soc. Am. J. 54:1530–1536.
18. Sigua, G. C., A. R. Isensee, and A. M. Sadeghi. 1993. Influence of rainfall intensity and crop residue on leaching of atrazine in intact no-till soil cores. Soil Sci. 156:225–232.
19. Sorenson, B. A., P. J. Shea, and F. W. Roeth. 1991. Effects of tillage, application time and rate on metribuzin dissipation. Weed Res. 31:335–345.