Field History and Dissipation of Atrazine and Metolachlor in Colorado

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ABSTRACT

Farmers in eastern Colorado have commented that atrazine does not provide the length of weed control that they expected in fields that have received multiple applications of the herbicide. Multiple laboratory studies suggest that atrazine dissipates more rapidly in soils with a history of atrazine use compared with soils that had not been treated with the herbicide and this could be related to the above observation. Field and laboratory studies were conducted to determine the rate of dissipation of atrazine and metolachlor in fields in Colorado. The published half-lives of atrazine and metolachlor are 60 and 56 d, respectively. In the field studies, the half-lives of atrazine and metolachlor in the top 15 cm of the soil ranged between 3.5 and 7.2 d and 17.9 and 18.8 d, respectively. In laboratory studies, the half-life of atrazine varied from 1.4 to 19.8 d with the shortest half-life occurring in soils which had been treated with atrazine for at least 5 yr. The longest half-life was in a soil that had never received atrazine. The half-life of metolachlor in these same soils varied from 10.6 to 28.2 d. There was no apparent relationship between the half-life of metolachlor and the half-life of atrazine in the laboratory studies. These results confirm farmers' observation of the shorter residual activity of atrazine in Colorado fields receiving atrazine over multiple years.

ATRAZINE [2-chloro-4-(ethylamino)-6-isopropylamino)-*s*-triazine] is a soil-applied herbicide for controlling many broadleaf and certain grass weeds in corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and sugarcane (*Saccharum officinarum* L.). In 2003 68% of the corn in the United States was treated with atrazine at an average rate of 1.1 kg ha^{-1} (NASS, 2004). In Colorado, approximately 400 000 ha of corn are planted annually and 44% of this area receives atrazine (NASS, 2004). Farmers expect full season weed control from an atrazine application. The reported half-life of atrazine in the field is 60 d (Wauchope et al., 1992; Wackett et al., 2002). However, farmers in eastern Colorado reported recently that atrazine was not giving the residual control expected (D. Anderson, personal communication, 2005). There could be several reasons for this lack of control including selection of tolerant or resistant weed biotypes, leaching below the seed zone, or enhanced degradation.

Two soil factors that may affect the rate of atrazine degradation are soil pH and organic matter (OM). Atrazine is a weak base, pKa 1.7, and adsorbs less as soil pH increases (Goetz et al., 1989; Clay and Koskinen, 1990). Soil pH has a greater effect on the rate of degradation than OM or other soil properties (Obien and Green, 1969; Holford et al., 1989) with a decrease in the rate of degradation as the pH increases (Best and Weber, 1974; Hitbold and Buchanan, 1977; Ferris et al., 1989). However, in soils with a history of atrazine use, atrazine degraded faster in soils with a pH $>$ 6.5 compared with soils with a pH $<$ 6.0. (Houot et al., 2000). This effect was probably due to the bioavailability of the herbicide to soil microbes. In these studies, atrazine degradation rate was not correlated to microbial biomass (Houot et al., 2000).

In the mid 1990s, soil bacteria were isolated that were able to mineralize atrazine (Mandelbaum et al., 1995; Radosevich et al., 1995). Following this discovery, the genes that code for enzymes capable of metabolizing atrazine were isolated and sequenced (De Souza et al., 1995; Boundy-Mills et al., 1997; Sadowsky et al., 1998). Homologs of these genes have been detected in atrazine-degrading bacteria isolated from around the world (De Souza et al., 1998).

Enhanced atrazine degradation in laboratory studies on soil from fields that had received multiple atrazine applications has been reported in Argentina, Belgium, Canada, France, Australia, and the United States (Barriuso and Houot, 1996; Ostrofsky et al., 1997; Pussemier et al., 1997; Vanderheyden et al., 1997; Yassir et al., 1999; Houot et al., 2000; Hang et al., 2003; Popov et al., 2005; Zablotowicz et al., 2006). Enhanced degradation was correlated with years of atrazine use and soil pH (Barriuso and Houot, 1996; Pussemier et al., 1997; Vanderheyden et al., 1997; Yassir et al., 1999; Houot et al., 2000; Hang et al., 2003; Zablotowicz et al., 2006).

Another widely used herbicide in Colorado is metolachlor [2-chloro-*N*-(6-ethyl-o-tolyl)-*N*-(2-methoxy-1-methylethyl)acetamide]. It is a common practice for farmers to apply a tank mixture of atrazine and metolachlor to corn. In 2003 25% of the corn in the United States was treated with metolachlor at an average rate of 1.5 kg ha^{-1} (NASS, 2004). In Colorado, approximately 12% of the corn received metolachlor in 2003 (NASS, 2004).

The reported half-life of metolachlor is 56 d (Wauchope et al., 1992). The rate of dissipation of metolachlor has also been correlated with history of use. The half-life of metolachlor decreased from 18 to 2.5 d in a field in India that had received four consecutive treatments of the herbicide over 18 mo (Sanyal and Kulshrestha, 1999). Although there have been no complaints in Colorado of loss of control after metolachlor application, it is important to know if the dissipation rate of metolachlor is related to its use history or the history of atrazine use.

Although it has been documented that extended use of atrazine can select for microbial populations that can

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Abbreviations: DAT, days after treatment.

rapidly degrade the herbicide, there are very few studies which have measured the rate of dissipation of atrazine in commercial fields. Laboratory studies use relatively small amounts of disturbed soil under constant temperature and moisture conditions whereas in the field the soil is undisturbed with potentially wide fluctuations in temperature and moisture (Beulke et al., 2005). In addition, most studies on atrazine degradation in the field have been done on small plots under controlled conditions of application rate, sampling intervals, etc. In commercial fields, the herbicides are applied by the farmer over a large, variable area. However, the impact of enhanced atrazine degradation is at the farmer level. Thus, it is important to understand if enhanced atrazine degradation actually occurs in commercial fields. The objective of this study was (1) to determine the field persistence of atrazine in commercial fields that had received multiple applications of atrazine, (2) to determine if there was a correlation between history of atrazine use and rate of atrazine dissipation, and (3) to compare the persistence of atrazine with that of metolachlor in these soils.

MATERIALS AND METHODS

Field Dissipation of Atrazine and Metolachlor

The rate of dissipation of atrazine and metolachlor in commercial fields was determined between 2003 and 2005. All of the fields were located near Yuma, CO and had been planted to corn and treated with atrazine for at least 5 yr and were in corn at the time of sampling. Field A was 57 ha and was sampled in 2003 and 2004, and included a Haxtun loamy sand, Albinas loam, and Ascalon fine sandy loam. Field B was 57 ha and was sampled in 2004 and 2005, and included a Julesburg loamy sand, Haxton loamy sand, and Rago loam. Field C was 53 ha and was sampled in 2005 and included a Haxtun loamy sand, Manter loamy sand, and Julesburg loamy sand. The objective of this part of the research was to measure the rate of dissipation of atrazine and metolachlor under commercial conditions. Hence, the sampling of soil from each of the fields varied depending on what herbicides the farmers applied, the irrigation schedule for each field, and how many sites the farmers would allow us to have in each field.

Herbicide Treatment

Field A: This field was under conventional tillage and received between 560 and 650 mm of supplemental irrigation annually. The field was treated by the farmer on 21 Apr. 2003 with a combination of atrazine plus acetochlor (Fulltime, Dow Agrosciences, Greenfield, IN) at a rate of 1.12 kg ha^{-1} of atrazine and 1.68 kg ha^{-1} of acetochlor. The field was irrigated immediately after spraying with 2.5 cm of water applied over 2 d. The field was treated by the farmer on 5 May 2004 with a combination of atrazine, metolachlor, and mesotrione [2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione] (Lumax, Syngenta, Greensboro, NC) at a rate of 0.84 kg ha^{-1} atrazine, 2.25 kg ha^{-1} metolachlor, and 0.225 kg ha^{-1} mesotrione. The field was irrigated immediately after spraying with 2.5 cm of water applied over 2 d.

Field B: This field was under conventional tillage and received between 560 and 650 mm of supplemental irrigation annually. The field was treated by the farmer on 17 May 2004 with a combination of atrazine plus dimethenamid (G-Max Lite, BASF, Research Triangle Park, NC) at a rate of 1 kg ha^{-1} of atrazine and 0.79 kg ha^{-1} of dimethenamid. The field was irrigated immediately after herbicide application with 2.5 cm of water applied over 2 d. The field was treated by the farmer on 29 May 2005 with a combination of atrazine plus metolachlor plus glyphosate (Expert, Syngenta, Greensboro, NC) at a rate of 1.5 kg ha^{-1} of atrazine, 1.2 kg ha^{-1} of S-metolachlor, and 0.7 kg ae ha^{-1} of glyphosate. The field was irrigated 24 h after herbicide application with 2.5 cm of water applied over 2 d.

Field C: This field was under strip-tillage with a 25-cm tilled strip over each row, and received 650 mm of supplemental irrigation during the growing season. The rows were on 76.2-cm centers. The field was treated by the farmer on 17 May 2005 with a combination of atrazine, metolachlor, and mesotrione (Lumax, Syngenta, Greensboro, NC) at a rate of 0.84 kg ha^{-1} atrazine, 2.25 kg ha^{-1} metolachlor, and 0.225 kg ha^{-1} mesotrione. The field was irrigated 24 h after spraying with 2.5 cm of water applied over 2 d.

Soil Sampling

Field A: Ten plots (3 by 12 m) were established across the field and four cores from the top 30 cm of field-moist soil were taken at random in each plot with a soil sampler that was 1.9 cm in diameter and 30 cm long. The cores were divided into 0- to 15-cm and 15- to 30-cm sections and the cores from the two horizons were combined to create two samples from each site for each time point. In 2003 samples were taken at 0, 14, 28, 42, and 56 d after treatment (DAT). In 2004, samples from the same ten plots were taken at 7, 13, 22, and 30 DAT.

Field B: Two plots (3 by 12 m) were established in the field and samples were taken as described previously. In 2004, samples were taken at 3, 7, 21, 35, and 50 DAT. In 2005, samples were taken from the same plots at 3, 10, 18, 31, and 45 DAT.

Field C: Six plots (3 by 12 m) were established across the field and samples were taken as described previously. Samples were taken 3, 23, 27, 40, and 54 DAT. Soil samples from all three fields were stored at −20 C until analyzed.

Herbicide Extraction

Ten g of soil were placed into a 50-mL centrifuge tube with a Teflon-lined cap, and 10 mL of water and 10 mL of water-saturated toluene was added. The tube was shaken horizontally for 2 h on a reciprocating shaker. The samples were removed from the shaker and centrifuged for 20 min at 2000 × *g*. Two mL of the toluene phase were transferred to a 2-mL volumetric to which 10 μL of a 0.1 mg mL^{-1} butylate internal standard solution was added. Quality control samples were included with each run and showed that the extraction efficiency for atrazine and metolachlor was 93 to 99%.

The herbicide concentrations in the toluene phase were analyzed using a gas chromatograph equipped with a mass spectrometer (Shimadzu GC-17A and GC–MS QO 5050A, Shimadzu Scientific Instruments, Columbia, MD) and monitoring the masses for butylate (m/z 146), atrazine (m/z 200), and metolachlor (m/z 162). A RTX-5 30-m by 0.25-mm column (Restek, Bellefonte, PA) was used with a flow of helium at 1 mL min^{-1}. The injection temperature was 250°C and the detector temperature was 280°C. The program for detecting atrazine and metolachlor was as follows: initial oven temperature was 130°C (hold 1 min), which was ramped at 20°C min^{-1} to 250°C and then held at 250°C for 1.5 min with a run time of 10 min. Under these conditions the retention times of butylate, atrazine, and metolachlor were 4.2, 6.1, and 7.4 min,

respectively. The detection limit was 5 μg kg^{-1} of soil for each herbicide.

The amount of water in each sample was determined by drying a sample at 105°C and determining the weight before and after drying. The amount of herbicide extracted from the soil was adjusted to the dry weight of soil.

Laboratory Dissipation of Atrazine and Metolachlor

Soil Collection

Soils were collected on 25 Mar. 2004. Surface residue was removed and a 30- by 30- by 15-cm-deep volume of field-moist soil was placed in plastic bags and stored at 4°C until further analysis. Four soils (D through G) were collected from a farm near Haxtun, CO in the northeastern portion of the state. Two soils (H, I) were collected at the Irrigation Research Farm at Yuma, CO. Soil samples were also taken from Field A, B, and C (A through C).

Soils in eastern Colorado are typically lighter soils with low organic matter and high sand content. The soils from Fields A through C were identified above. Soils D through H were identified as follows: (D) Lliff loam; (E) Platner loam; (F) Rago loam; (G) Rosebud Escabosa loam; (H) and (I) Ascolon sandy loam.

The water holding capacity (−33 kPa) of each soil was determined via pressure plate analysis (Klute and Dirksen, 1986). Soil texture (sand, silt, clay), pH, cation exchange capacity, and other properties were determined for each sample by a commercial soil analysis laboratory (MDS Harris, Lincoln, NE). Total soil carbon was determined by combustion (Nelson and Somers, 1982). Inorganic C was measured using a modified pressure calcimeter (Sherrod et al., 2002). Soil organic C was calculated as total C from dry combustion minus inorganic C. (Nelson and Somers, 1982; Sherrod et al., 2002). The herbicide use history, soil texture, organic matter, and water holding capacity are shown in Table 1.

Herbicide Dissipation in the Laboratory

The initial amount of water in each soil was determined and then 600 g of soil was weighed and water added to bring the soil to −33 kPa. The water contained both atrazine and metolachlor to bring the final concentration of each herbicide to 1 mg kg^{-1} of dry soil. This rate of herbicide is equivalent to an application rate of 1 kg ha^{-1} (Tasli et al., 1996). The soils were mixed by sieving and then 100-g aliquots were placed in each of five 250-mL jars with Teflon-lined caps. Three of the jars of each soil were incubated at 26°C and the other two jars were incubated at 4°C. Ten-g samples of soil were removed 1, 2, 4, 8, 16, and 32 DAT and extracted as described previously. The amount of atrazine and metolachlor in each sample was analyzed as described previously. The amount of water in each sample was determined by drying at 105°C and the amount of herbicide extracted from the soil was adjusted to the dry weight of soil. The experiment was conducted twice.

Statistical Analysis

Dissipation of atrazine and metolachlor was fitted to Eq. [1] (Systat, 2004):

$$Y = Ae^{-kt} \quad [1]$$

where A is the amount of herbicide in soil at the first sampling time (mg kg^{-1}); k is the first-order rate constant (d^{-1}); and t is time (d). Half-life ($T_{1/2}$) values for atrazine and metolachlor dissipation were calculated from Eq. [2]:

$$T_{1/2} = \ln 2/k \quad [2]$$

The half-lives of atrazine and metolachlor in the laboratory studies were subjected to analysis of variance (Systat, 1997). Treatment means were separated at the 5% level of significance using Fisher's protected least significant difference test.

RESULTS AND DISCUSSION

Field Dissipation

Atrazine dissipated rapidly from the top 15 cm of soil in Fields A through C in each year (Fig. 1A). The rate of dissipation of metolachlor was slower than atrazine (Fig. 1B). The calculated half-life of atrazine in Fields A through C ranged from 3.5 to 7.2 d whereas the half-life of metolachlor in these same fields ranged from 17.8 to 18.8 d (Table 2).

The rate of dissipation of atrazine and metolachlor was more rapid than expected based on the reported values in the literature, although the rate of atrazine dissipation was similar to that reported by Krutz et al. (2006b) who found that the half-life of atrazine in Mississippi in plots that were under continuous corn was 9

Table 1. Herbicide history and characteristics of soils in study.

Soil	Atrazine history	Sand	Silt	Clay	Organic matter	Water holding capacity (−33 kPa)	pH
					%		
A (Field A)	Continuous corn, atrazine, and an acetanalide applied for at least 5 yr†	60.0	21.2	18.7	0.6	9.4	7.6
B (Field B)	Continuous corn, atrazine, and an acetanilide applied for at least 5 yr‡	63.1	20.6	16.3	1.2	10.1	6.3
C (Field C)	Continous corn, atrazine and metolachlor applied for at least 5 yr	88.8	7.5	3.7	1.2	7.9	7.1
D	Continuous corn, atrazine applied for 3 yr	42.5	25.0	32.5	2.0	25.5	7.4
E	Sunflower, atrazine applied once 30 mo before collection	40.0	20.0	40.0	1.8	22.9	5.4
F	Grain sorghum, atrazine applied three out of four previous years	35.0	23.1	41.8	1.7	24.6	5.7
G	Grass waterway, no herbicides applied for at least the previous 5 yr	35.7	33.1	31.2	5.6	34.2	7.1
H	Continuous corn, atrazine, and an acetanilide applied for 3 yr	62.5	18.1	19.4	1.5	16.9	5.6
I	Sunflower, three previous years had received atrazine and acetochlor	71.3	15.0	13.7	1.3	9.4	6.6

† Acetanilides included acetochlorand metolachlor.
‡ Acetanilides included dimethenamid and metolachlor.

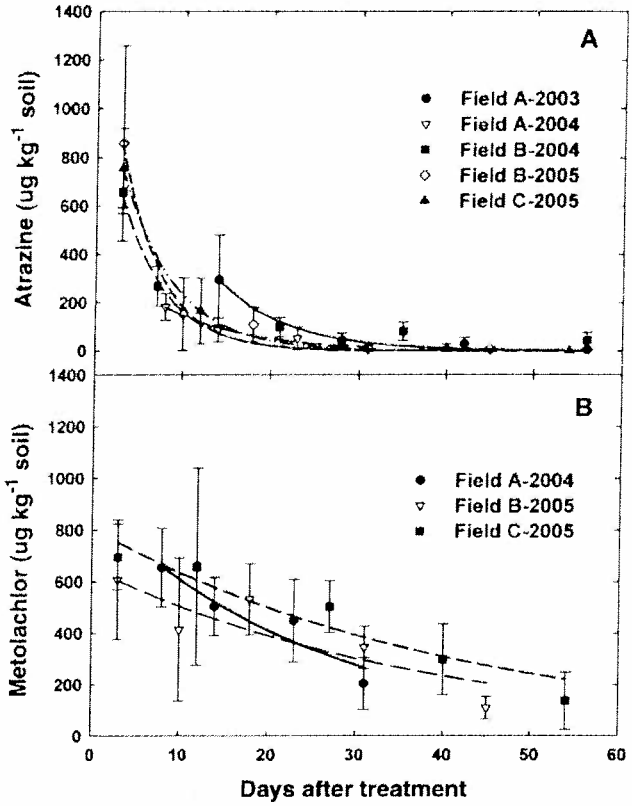

Fig. 1. Dissipation of atrazine and metolachlor in three fields in eastern Colorado from 2003 through 2005. Data are fitted to equation $Y = Ae^{-kt}$ where A is the amount of herbicide in soil at the first sampling time (mg kg^{-1}); k is the first-order rate constant (d^{-1}); and t is time (d).

to 10 d compared to 17 d in plots that had never received atrazine.

The rate of metolachlor dissipation was slightly longer than that observed by Mueller et al. (1999), who reported that the half-life of metolachlor in the top 15 cm of soil was 13.7 d in Kentucky, Mississippi, and Tennessee. In contrast, Sanyal and Kulshrestha (1999) reported that in India the half-life of metolachlor decreased from 18 to 2.5 d after four applications over 8 mo (Sanyal and Kulshrestha, 1999). In these studies, metolachlor was applied only once or, at most, twice during a calendar year in these fields.

Table 2. Degradation rate constants (k) and half-lives ($T_{1/2}$) for atrazine and metolachlor in three fields in eastern Colorado.

Field	Sites†	Year	Herbicide	r^2	k‡	$T_{1/2}$§
					d^{-1}	d
Field A	10	2003	Atrazine	0.76	0.125 (0.030)	5.5
		2004	Atrazine	0.80	0.096 (0.019)	7.2
			Metolachlor	0.87	0.038 (0.008)	18.4
Field B	2	2004	Atrazine	0.80	0.198 (0.050)	3.5
		2005	Atrazine	0.80	0.190 (0.055)	3.7
			Metolachlor	0.87	0.039 (0.008)	17.9
Field C	6	2005	Atrazine	0.80	0.134 (0.028)	5.2
			Metolachlor	0.82	0.037 (0.005)	18.8

† Number of sites tested within each field.
‡ Decay constant with standard error in parentheses.
§ Half-life of each herbicide was calculated based on the initial concentration measured in each field and using the equation $T_{1/2} = \ln(2)/k$.

The dissipation of atrazine and metolachlor from the top 15 cm of soil in these fields could be due to multiple factors including leaching, microbial degradation, or chemical degradation. Atrazine has been shown to degrade by both chemical and biological means (Saxena et al., 1987; Liu et al., 1991; Miller et al., 1997) although microbial breakdown is considered the primary mechanism. Degradation of metolachlor is primarily microbially mediated (Liu et al., 1991; Miller et al., 1997; Staddon et al., 2001). Leaching could also account for part of the rapid loss of atrazine. The amount of atrazine and metolachlor at the 15- to 30-cm depth was measured in this study, and more than 90% of both herbicides that were extracted were in the top 15 cm of the soil columns (data not shown). These results agree with other field studies in Australia, France, Portugal, and the United States which found that over 80% of atrazine remained within the top 30 cm of the soil after 2 mo, with the majority of the herbicide remaining in the top 10 cm (Sorenson et al., 1994; Tasli et al., 1996; Stork, 1997; Azevedo et al., 2000). Hence, leaching was probably not a major factor in the dissipation of atrazine or metolachlor in these studies.

Laboratory Dissipation in Field Soil Samples

The results of the dissipation of atrazine and metolachlor in the laboratory incubation studies suggest that the dissipation of both herbicides is due to microbial activity. The half-life of atrazine soil from Fields A through C ranged from 1.5 to 1.9 d at 26°C. At 4°C, less than 5% of the atrazine dissipated after 32 d (data not shown). These results confirm the short half-life of atrazine that was observed in these fields.

The half-life of metolachlor in soil from Fields A through C in the laboratory ranged from 20.6 to 25.6 d at 26°C. At 4°C, there was no loss of metolachlor in any of the soils after 32 d (data not shown). Metolachlor dissipated more slowly in the laboratory study compared with the field, but it is not unusual for herbicides to dissipate more slowly in the laboratory compared with the field (Beulke et al., 2005). These results suggest that the dissipation of metolachlor in the field was primarily due to microbial degradation. However, metolachlor was also lost due to volatilization in the field. From 6.5 to 22% of applied metolachlor can volatilize from the soil surface and plant residues (Prueger et al., 1999; Rice et al., 2002). This would not be a factor in the laboratory studies and could partially account for the longer half-lives in the laboratory incubation studies compared with the field studies.

Relationship between Atrazine Use History and Dissipation

To determine if there is a relationship between years of atrazine use and the rate of dissipation of the herbicides, six soil samples were collected near the Yuma, CO area from fields with varying histories of atrazine use. The results suggest that there is a relationship between the years of atrazine use and the rate of atrazine dissipation (Table 3). The shortest half-life occurred in

Table 3. Laboratory study of persistence of atrazine and metolachlor in field soils from eastern Colorado (26°C, −33 kPa).

Field	Half life†	
	Atrazine	Metolachlor
	d	
A‡	1.9de	25.6ab
B	1.7de	20.6bc
C	1.5e	24.4abc
D	1.5de	26.0ab
E	7.9b	21.8bc
F	3.2c	14.0d
G	19.8a	10.7d
H	1.1e	25.8ab
I	2.0d	28.2a

† Half-life of each herbicide was calculated based on the initial herbicide level measured and the equation $T_{1/2} = \ln(2)/k$.

‡ Average half-life of three replications. Values followed by the same letter within a column are not different at $P = 0.05$.

soils (A through D, F, H) to which atrazine was applied the last 3 out of 4 yr, while the longest half-life was in a soil (G) that had not received any atrazine for at least 4 yr. Many others have also found accelerated atrazine degradation in soils collected from fields which had a history of repeated atrazine applications compared with soils collected from grassland or agricultural soils with no history of atrazine use (Vanderheyden et al., 1997; Yassir et al., 1999, Houot et al., 2000; Hang et al., 2003; Popov et al., 2005; Zablotowicz et al., 2006; Krutz et al., 2006b).

In the two fields (E, I) that were in sunflower at the time the soil was collected, the half-lives were significantly different (Table 3). Atrazine dissipated more rapidly from soil I that had received three applications of atrazine over the previous 4 yr whereas soil E had had only one application of atrazine over the previous 30 mo.

There does not appear to be a clear relationship between metolachlor degradation and metolachlor use history. One of the shortest half-lives for metolachlor was in the soil (G) that was collected from the grass waterway. Presumably this soil had never been directly treated with the herbicide, although the waterway was next to a corn field that had been treated with herbicides. Staddon et al. (2001) found that the half-life of metolachlor was much shorter in a vegetative buffer compared with the half-life in an adjacent bare field. The authors concluded this could be due to the higher levels of organic matter and microbial activity in the vegetative buffer strip compared with the bare field. Seybold et al. (2001) found that the presence of switchgrass (*Panicum virgatum* L.) enhanced the degradation of metolachlor but not atrazine compared with bare soil. Krutz et al. (2006a) also found that metolachlor but not atrazine metabolism was more rapid in a vegetative buffer compared with cultivated soil. A similar phenomenon might explain why metolachlor but not atrazine had a short half-life in soil G.

The other fields, except for soil D, had a history of acetanilide applications, although it was not always metolachlor. Although there is one report of continuous metolachlor use leading to enhanced degradation of the herbicide (Sanyal and Kulshrestha, 1999), others have found no relationship between years of metolachlor use and rates of dissipation (Dowler et al., 1987; Harvey, 1987; Kotoula-Syka et al., 1997). These results suggest that under some circumstances, but not others, the use of an acetanilide may select for acetanilide-degrading bacteria. There was no relationship between the rate of metolachlor dissipation and atrazine dissipation ($R^2 = 0.22$), indicating that the microorganisms responsible for the rapid dissipation of atrazine do not metabolize metolachlor.

CONCLUSIONS

This study shows that atrazine has an extremely short half-life in fields in eastern Colorado that had received multiple applications of atrazine. In all of these fields the level of atrazine in the top 15 cm of soil was below 5 μg kg^{-1}, the detection limit of our extraction procedure, by 30 DAT. The concern that farmers have about not obtaining the length of weed control that they expect from atrazine is most likely due to rapid degradation of the herbicide. Metolachlor, on the other hand, does not appear to dissipate any more rapidly in these soils than has been reported in other studies. The laboratory experiments indicated a strong positive relationship between the rate of dissipation and years of atrazine use, and the rate of atrazine dissipation in the lab was faster than what was observed in the field. This phenomenon needs to be studied in other areas of the country to see if enhanced degradation of atrazine is common. Krutz et al. (2006b) have found this to be true in Mississippi, but it has yet to be documented in fields in other states.

The reason for the rapid dissipation of atrazine in these soils appears to be due to the presence of microorganisms that can metabolize the herbicide. Popov et al. (2005) found that in Australia atrazine degraded more rapidly in soils taken from croplands compared with natural grasslands, and this increase appeared to be due to an enrichment of a consortium of soil microorganisms in the soils that rapidly degraded atrazine. Smith et al. (2005) reported on a consortium of eight bacteria isolated from soil that rapidly degraded atrazine. Something similar may be occurring in these soils in Colorado. Further work needs to be done to attempt to isolate the soil microorganisms responsible for the enhanced atrazine degradation.

However, what, if anything, can farmers do to extend the soil residual activity of atrazine? One possibility is through manipulation of the soil nitrogen levels. Atrazine degradation is reduced in the presence of high inorganic nitrogen levels (Abdelhafid et al., 2000; Rhine et al., 2003). Sims (2006) also found that nitrogen starvation promotes the biodegradation of atrazine in soil. Research should be conducted to determine if there is a relationship between atrazine degradation in the field and the level and form of nitrogen in the soil.

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