Point and nonpoint source leaching of atrazine from a corn field: Effects on tile drainage water quality

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[1]Agriculture Canada Research Station, P.O. Box 20280, Fredericton, NB, Canada E3B 4Z7; [2]Environment Canada, Environmental Conservation Branch, P.O. Box 23005, Universite de Moncton Campus, Moncton, NB, Canada E1A 6S8; and [3]Department of Civil Engineering, University of New Brunswick, P.O. Box 4400, Fredericton, NB, Canada E3B 5A3. *Received 14 March 1995; accepted 22 September 1995.*

Milburn, P., Leger, D.A., O'Neill, H., MacQuarrie, K. and Richards, J.E. 1995. **Point and nonpoint source leaching of atrazine from a corn field: Effects on tile drainage water quality**. Can. Agric. Eng. 37:269-277. Atrazine concentrations in tile drainage waters emanating from a continuously cropped, commercial corn field (silt to clay loam) were monitored for 30 consecutive months, March 1989 to September 1991. Water samples were collected approximately every two weeks from three independent tile drainage plots within the field. Excluding the effects of an accidental spill, atrazine concentrations in the tile water ranged from 0.1 to 29 µg/L. Concentrations declined with time after application to approximately 0.1 µg/L prior to planting the following spring. In June 1990, approximately 60 g of active ingredient were accidently discharged in one of the plots followed by a 71 mm rainfall (in 12 h) several days later. Subsequent auto-sampling of the drainage waters every 4 hours revealed atrazine + deethylatrazine concentrations to 150 µg/L. Concentrations decreased to less than the maximum acceptable concentration for drinking water (MAC) within six days of the initiation of tile flow. As a result of this storm, about 18 g of atrazine leached from the soil into the tile drainage water. This was in contrast to simulation results for a uniform porosity soil that indicated no atrazine would be transported to drain depth. Atrazine + deethylatrazine concentrations declined to <1.0 µg/L by May 1991, similar to concentrations in the other plots where atrazine was properly applied. Documented case histories of this nature are helpful in assessing the degree and duration of hazard resulting from accidental release of atrazine in a field crop setting.

Keywords: atrazine, deethylatrazine, leaching, tile drainage, corn production, accidental spill, water quality, preferential flow.

Les concentrations d'atrazine dans l'eau de drains souterrains installés dans des champs (limon à loam argileux) en maïs continu ont été mesurées durant 30 mois consécutifs, de mars 1989 à septembre 1991. Les échantillons d'eau on été prélevés, à toutes les deux semaines environ, au bout des drains de trois parcelles indépendantes. Si on exclut les effets d'un déversement accidentel, les concentrations d'atrazine dans les eaux de drainage ont atteint des valeurs allant de 0.1 à 29 µg/L. Les concentrations ont diminué progressivement jusqu'à atteindre 0.1 µg/L, au printemps suivant, avant le semis. En Juin 1990, 60 g d'ingrédient actif ont été déversés accidentellement sur une des parcelles. Une pluie de 71 mm (en 12 h) est survenue plusieurs jours plu tard. A la suite de déversement, les concentrations d'atrazine et de deethylatrazine, dans les échantillons prélevés des drains à toutes les 4 heures avec un échantillonneur automatique, ont atteint 150 µg/L. Dans les 6 jours qui ont suivi le début de l'écoulement des drains, les concentrations se sont abaissées sous la concentration maximale acceptable (CMA) pour l'eau potable. A cause de cette pluie, 18 g d'atrazine ont été transportés du sol jusque dans l'eau de drainage. Cela contrastait avec les simulation des résultats pour un sol de porosité uniforme qui prédisaient que l'atrazine ne serait pas transportée jusqu'aux drains. Les concentrations d'atrazine et de deethylatrazine ont diminué jusqu'à moins de 1.0 µg/L, en mai 1991, ce qui est similaire aux concentrations mesurées sur les autres parcelles où l'application avait été faite adéquatement. Le suivi et l'analyse d'histoires de cas de cette espèce sont utiles pour évaluer la gravité et la durée des dangers qui résultant de déversements accidentels d'atrazine.

INTRODUCTION

Atrazine is a commonly used herbicide in corn production. It is also one of the pesticides most frequently detected in groundwater, including tile drainage water (Goodrich et al. 1991; Hallberg 1989). The frequency of atrazine detection in groundwater and tile drainage water is the result of its widespread usage, moderate persistence, and mobility through the soil (McRae 1991; Jayachandran et al. 1994). Typical atrazine concentrations measured in selected tile drainage and groundwater studies in Canada and the United States are summarized in Table I.

The current maximum contaminant level (MCL) for atrazine in drinking water in the United states (US) is 3 µg/L; degradation products are not considered (Belluck at al. 1991). The corresponding interim maximum acceptable concentration (IMAC) in Canada was recently decreased from 60 µg/L (parent compound only) to 5 µg/L total (parent compound plus its N-dealkylated metabolites) (Personal Communication: David G. Green, Senior Engineering Consultant, Criteria Section, Environmental Health Directorate, Health Canada, Ottawa, ON). Deethylatrazine was determined to be the primary metabolite of atrazine in groundwater and soil (Adams and Thurman 1991).

There is currently no published information in Atlantic Canada on the extent of atrazine leaching as a result of recommended, on-farm application practices. The objective of this study was to determine the magnitude and duration of non-point source atrazine leaching from a commercial corn field in southern New Brunswick.

A related objective is to report leaching losses and associated observations resulting from an accidental point source

Table I: Atrazine in tile drainage or groundwater: results from selected studies

Investigator/ location	Study type and duration (years)	Soil type	Atrazine applied* (kg ai/ha)	Atrazine concentrations measured ! (μg/L)	Cumulative atrazine leached ! (g ai/ha)	Comments
Masse et al. 1994 Quebec	ground water; (3)	sand; loam	2.35	<1-10$_{r,a}$		continuous corn; groundwater to 3 m
Gaynor et al. 1992; Ontario	tile drainage;(3)	clay loam	1.86	6-16$_{r,aa,d}$	6.2-30.5$_{r,aa}$	continuous corn; 3 tillage treatments
Government of Nova Scotia 1990	private on-farm wells		NS	0.02-2.19$_{r}$		98 wells in Kings County
Jayachandran et al. 1994; Iowa	tile drainage;(2)	loam	1.68	1.3-5.1$_{r,g}$	5.4-9.8$_{r,g}$	no-till continuous corn; atrazine first year only
Kladivko et al. 1990; Indiana	tile drainage;(3)	silt loam	1.1	1-10$_{r}$	0.1-0.6$^{+}_{aa}$	continuous corn; variable tile spacings
Kross et al. 1990; Iowa	private on-farm wells		NS	1.14$_{a,t}$ 7.71$_{m,t}$		State wide survey; 690 sites
Muir and Baker 1976; Quebec	tile drainage;(2)	sandy loam	2.8	0.06-10.82$_{r}$	2.1$_{f}$	continuous corn
Rudolph and Goss 1993; Ontario	private on-farm wells		NS	0.69$_{a}$		1204 wells
Von Stryk and Bolton 1977; Ontario	tile drainage;(4)	clay loam	1.2	0.3-3.5$_{r}$	2.7-8.7$_{r,aa}$	continuous and rotation corn; fertilized and unfertilized.

* ai = active ingredient; NS= not specified

! a = average; aa = average annual; d = atrazine + deethylatrazine; f = April to December, 1974 only; g = growing season, about May 1 to August 30; m = maximum; r = range; t = atrazine + deethylatrazine + deisopropylatrazine.

\+ 1985-86 crop year only.

atrazine spill that occurred on one of the plots during the study. This point source release provided a unique opportunity to observe pesticide fate and transport in a field setting and to compare these observations with theoretical estimates of atrazine travel times in the soil-water system.

METHODS AND MATERIALS

The study was conducted on a commercial dairy farm where systematic subsurface (tile) drainage outflows and concomitant atrazine concentrations were measured year round for three years of continuous corn production. Nitrate leaching at this site over the same cropping period was previously reported by Milburn and Richards (1994).

Briefly, three one-hectare plots were established within the field, each with an identical drainage system and separate outlet (Fig. 1). Drain depth and spacing were 0.8 m and 12 m, respectively. The topography was undulating, with slopes from two to four percent. The soil was classified as an imperfectly drained Petitcodiac silt loam to gravelly clay loam lodgement till (MacMillan and Chalifour 1980). Prefabricated 25 mm Parshall flumes equipped with Omnidata WL1 Datapod stage recorders (Omnidata International, Inc., Logan, UT) were used to record hourly tile discharge rates. Details on the site, location, soil, tile drainage system configuration, plot layout, corn production practices, cumulative seasonal and annual tile drainage flow, annual nitrate leaching, flow measurement technique, and associated equipment were provided elsewhere (Milburn and Richards 1994).

All field operations, including herbicide application, were performed by the farmer/land owner using commercial farm equipment. The meteorological station nearest the experimental site for which 30-year climatic normals were available was the Environment Canada Station located at Sussex, 25 km to the west. Precipitation data from Sussex were used as an estimate of rainfall at the experimental site

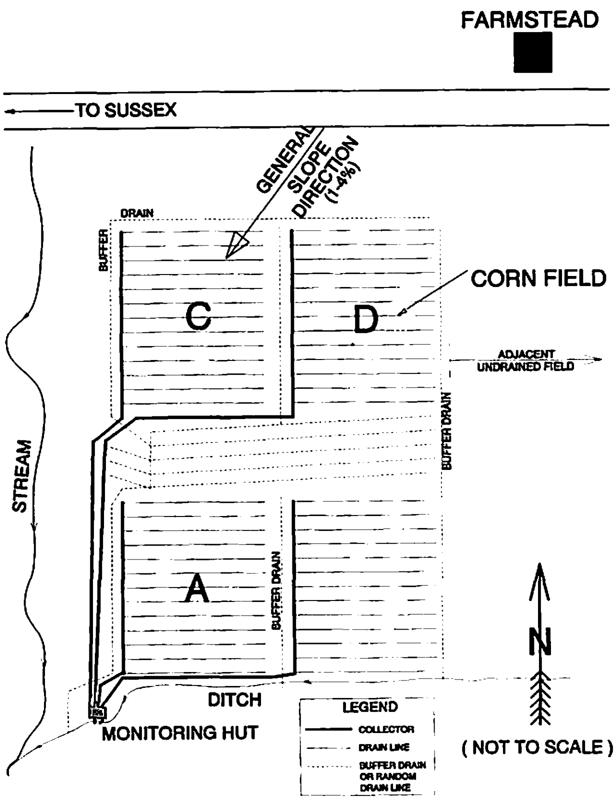


Fig. 1. Schematic of experimental site (after Milburn and Richards 1994).

Tile water sample collection and analysis

Tile discharge rate and associated atrazine concentrations were monitored in all three plots from March 1989 to September 1991. Analysis for the primary metabolite deethylatrazine (DEA) began in January 1990 and continued until September 1991. Tile water samples were collected manually approximately every two weeks during the growing season and every 3 to 4 weeks during winter months. Water samples were collected in 1 L amber glass bottles and preserved at pH 9 with sodium hydroxide (1 N).

To obtain additional information on fluctuation of atrazine and deethylatrazine concentrations within tile drainage events, water samples were collected from plot D every 4 hours for a 4-week period following application in 1990. In 1991, similar 4-h sampling and additional manual sampling were imposed on plot D for specific periods prior to and following herbicide application. An ISCO Model 3200 automatic waste water sampler (ISCO, Lincoln, NE) equipped with 300 mL glass bottles was employed to collect the 4-h samples. Upon retrieval samples were preserved at pH 9 as described above.

Field quality control (QC) consisted of submitting blanks, spikes, and replicate samples to the laboratory. Blanks consisted of Millipore$_{TM}$ (Millipore Corporation, Bedford, MA) water. Spikes consisted of either Millipore$_{TM}$ or natural water to which was added 100 µL of a spiking solution containing atrazine (2.5 mg/L), deethylatrazine (2.5 mg/L), metribuzine (2.5 mg/L) and simazine (4.0 mg/L) in methanol. Sequential duplicate or triplicate samples were also collected during the study. All field QC samples were preserved at pH 9 and comprised approximately 20% of all the samples submitted.

Atrazine analysis was performed according to a method developed by Environment Canada, Atlantic Region, Moncton, NB. Briefly, the samples were first filtered (0.45 µm filters) and then poured through an XAD-4 resin column pre-washed with ethyl acetate, methanol, and water. The column was then eluted with 3 x 50 mL of ethyl acetate, allowing the first 50 mL to pass through the residues on the filter. The excess water was removed from the ethyl acetate before drying over sodium sulphate. The solution was concentrated to 3 mL with a rotovap and was analyzed with a Hewlett Packard gas chromatograph-mass selective detector (GC-MSD) using a DB-1 open tubular column. Quantitation was effected against a standard subjected to the clean-up steps. The laboratory also processed blanks and spikes as part of their internal QC protocol. Detection limits for atrazine and deethylatrazine varied depending on sample cleanliness, sample and final extract volumes, extraction efficiencies, and instrument performance. For both chemicals the lowest limit of quantitation reported was 0.001 and 0.01 µg/L for the 1 L and 300 mL samples, respectively.

Atrazine use and leaching

Prior to planting of corn in 1989, atrazine had not been applied to the soil. The field was tile drained in August, 1988 and moldboard plowed in November 1988. Before tile drainage improvement, the site was cropped to grass, as natural drainage conditions permitted.

Corn was planted in 1989, 1990, and 1991. Atrazine was applied by the farmer each year as a post-emergent spray (1.5 kg/ha active ingredient) in accordance with Atlantic region recommendations (Advisory Committees on Cereal, Protein, Corn and Forage Crops 1989). A Century (Century Implements, Winnipeg, MB) field sprayer equipped with an 800 L tank and an 8.3 m spray boom was used. The farmer calibrated the sprayer each spring using a recommended procedure; field spraying and associated calibration activities were completed at a forward speed of 6 km/h. Dates of planting, post emergent atrazine application, and harvest are summarized in Table II.

Estimates of atrazine loss in drainage water were calculated seasonally (growing season, fall, winter, spring) and annually for each plot. Atrazine concentrations were averaged for each season and plot and multiplied by the cumulative drainage total for that season and plot as reported by Milburn and Richards (1994). Annual loss was the sum of the seasonal losses. Because the auto sampler operated only on plot D for selected periods during the 1990 and 1991 growing seasons, there were many more datum points contributing to seasonal average concentrations in plot D during these times than for the remaining plots and seasons. The number of datum points contributing to each average atrazine calculation is provided in the summary of results (Table III).

Atrazine spill

During routine atrazine application on June 27, 1990, the sprayer was damaged when the tractor became stuck in a

Table II: Atrazine application, planting and harvesting dates

Year	Corn variety	Planting date†	.... Atrazine*........... Date applied	Rate (kg/ha)	Harvested as	Harvest date!
1989	Euros LG3 (Hyland)	May 19	June 6	1.5	whole plant silage	Sept. 15-30
1990	Euros LG3 (Hyland)	June 5	June 27	1.5	high moisture ear corn	Nov. 1-15
1991	3195 (Hyland)	May 26	June 16	1.5	high moisture ear corn	Nov. 1-15

† Row spacing 760 mm; planting populations were 65 000 seeds/ha in 1989 and 1990, and 72 000 seeds/ha in 1991.

* Aatrex, 480 g/L, Ciba-Geigy Can/Ag Division, Mississauga, Ontario.

! Normal harvest dates in southern NB (Personal Communication 1993: Walter Brown, Agriculturist, NB Dept. of Agriculture, Sussex, NB).

Table III: Atrazine loss in the drainage water by plot and season

Crop year*	Season**	Avg. seasonal atrazine conc.! (μg/L)			Seasonal drainage!! (mm)			Atrazine loss per plot (g/ha)		
		A	C	D	A	C	D	A	C	D
1989-90	growing season	0.97 (6)	0.02 (10)	2.64 (10)	24	27	67	0.2	0.0	1.7
	fall	4.57 (4)	7.62 (4)	3.80 (5)	85	105	123	3.9	8.0	4.7
	winter	0.53 (5)	1.24 (5)	0.64 (5)	145	251	280	0.8	3.1	1.8
	spring	2.26 (2)	3.55 (2)	2.70 (2)	157	252	247	3.5	8.9	6.7
							Total	8.3	20.1	14.9
1990-91	growing season	0.32 (9)	0.30 (9)	8.01 (166)	158	212	228	0.5	0.6	18.2
	fall	0.75 (5)	2.22 (4)	1.75 (5)	185	267	268	1.4	5.9	4.7
	winter	0.46 (2)	0.38 (4)	0.88 (2)	219	242	334	1.0	0.9	2.9
	spring	0.47 (3)	0.28 (4)	1.49 (15)	217	221	273	1.0	0.6	4.1
							Total	3.9	8.0	29.9
1991-92	growing season	0.28 (3)	0.22 (3)	0.47 (41)	37	73	79	0.1	0.2	0.4
	fall	0.24 (1)	1.11 (1)	0.81 (2)	220	235	269	0.5	2.7	2.2
							Total	0.6	2.9	2.6

* Mid May to mid May the following year.

** Growing season = May 15 - Sept. 15; fall = Sept. 16 - Dec. 14; winter = Dec. 15 - March 14; spring = March 15 - May 14.

! Arithmetic mean of concentration points collected in the corresponding season; number of data points below in brackets; includes 4-h data points for plot D in growing seasons 1990 and 1991.

!! Totals from Milburn and Richards (1994).

Table IV: Summary of initial conditions, boundary conditions, and input parameters to the CHEMFLO model

van Genuchten (1980) parameters: $n = 1.4$; $a = 1 \times 10^{-2}$, 5×10^{-3}
Saturated hydraulic conductivity, $K_{sat} = 38, 76$ mm/h
Dispersivity: 10 mm
Degradation rate: 0.0 h^{-1} (ie. no decay)
Water/soil partition coefficient: 0.0 (ie. no sorption)
Soil bulk density: 1.5 Mg/m^3
Initial condition at x = 0:
-800 mm pressure head
Boundary condition imposed at time 0:00 h:
rainfall rate at soil surface = 8.8 mm/h for 8 h (70 mm total); 0.0 mm/h for next 8 h
potential at lower surface (800 mm) = -20mm

localized wet spot; the spray boom contacted the ground and the delivery hose to the spray boom broke. In the confusion, atrazine continued to be discharged from the severed delivery hose for an estimated 15 to 30 seconds before the machine operator disengaged the sprayer. This incident occurred in plot D (Fig. 1). The exact location is not known. The spill was not reported to the authors for several months and there was no knowledge of a spill when we decided to use an automatic sampler on July 2, 1990 in plot D. Our capture of a major drainage event (71 mm precipitation over 12 h recorded at Sussex on July 24; 15 mm on July 25) several days after initiation of high-frequency sampling was therefore fortuitous.

Knowing the boom width (8.3 m), forward speed (6 km/h), approximate duration of the accidental atrazine discharge (15-30 s), and the amount of active ingredient applied per hectare (1.5 kg), we calculated that about 40 to 80 g a.i. were discharged during the accident. The flux of atrazine and deethylatrazine in the tile drainage water immediately following the spill was calculated by multiplying the concentration of the tile water sample (collected every 4 h) by the tile flow volume of the preceding 4-h period and summing for the period of interest.

The numerical model CHEMFLO (Nofziger et al. 1989) was used to investigate theoretical atrazine travel times for the accidental spill described above. CHEMFLO is a one dimensional, unsaturated flow and solute transport model. Water movement is modeled using an implicit finite-difference solution to the Richards (1931) equation. Chemical transport is modeled using a numerical solution of the convection-dispersion equation. Although the model was not intended to simulate tile drained soils or dual-porosity transport, we utilized CHEMFLO to provide an initial estimate of atrazine and water movement from the crop root zone under near saturated conditions. The calculated results were then compared with measured results to assess the concept of uniform-porosity transport at the field site. A moisture characteristic curve from a local lodgement till soil similar in composition and texture to the soil at the experimental site (Saltspring loam; Holstrum 1986) was approximated in the simulation. The van Genuchten (1980) water content functions used in the model and the soil moisture characteristic of the Saltspring soil are shown in Fig. 2. A summary of model inputs is provided in Table IV.

RESULTS AND DISCUSSION

Atrazine leaching from recommended applications

Concentrations of atrazine and deethylatrazine (DEA) in the tile drainage water and corresponding tile discharge rate of each of the three drainage plots over the years 1989-1991 are presented in Fig. 3; 4-h concentration data associated with the 1990 spill in plot D are not included.

Concentrations prior to application on June 6, 1989 (day 157) were less than 0.04 µg/L in plots A and C and less than 0.40 µg/L in plot D. The slightly higher spring concentration in plot D may be caused by input from the field immediately east of plot D (Fig. 1), which was in corn in 1988 and extended about 2 metres into plot D. Carryover of atrazine applied to the corn field in 1988 was probably influencing the samples collected from plot D in the spring of 1989, similar to the spring atrazine concentrations of < 1.0 µg/L in all plots in the spring of 1990 and 1991 (Fig. 3). Three days following atrazine application in 1989, an increase in atrazine concentration was observed in plots A and D only (day 160, June 9; Fig. 3), in the absence of any substantial tile discharge. Concentrations two weeks later in all plots were about 1 µg/L or less.

The greatest atrazine concentration simultaneously observed in all plots over the course of the study was on day 316 (November 16, 1989) when drainage discharge was high. Concentrations ranged from 16 to 29 µg/L, declining to 1 µg/L or less by December 11. The second maxima occurred on day 95 (April 5, 1990), again during substantial leaching or drain discharge; total concentrations(atrazine + deethylatrazine) ranged from 7 to 17 µg/L. Maximum concentrations of the same order of magnitude were recorded by Kladivko et

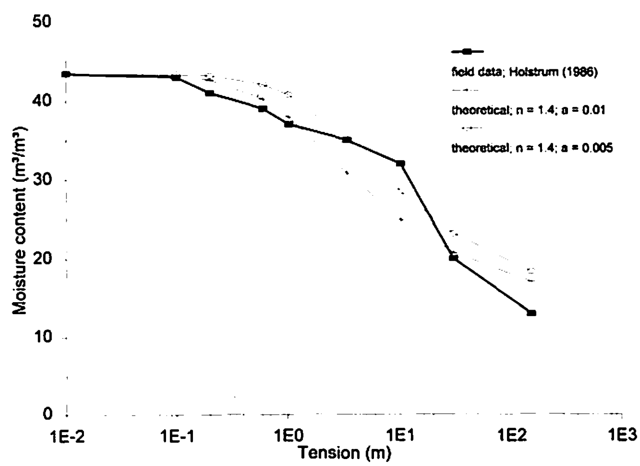


Fig. 2. Soil moisture characteristic of the Saltspring soil compared to the van Genuchten (1980) water content functions used in the CHEMFLO model.

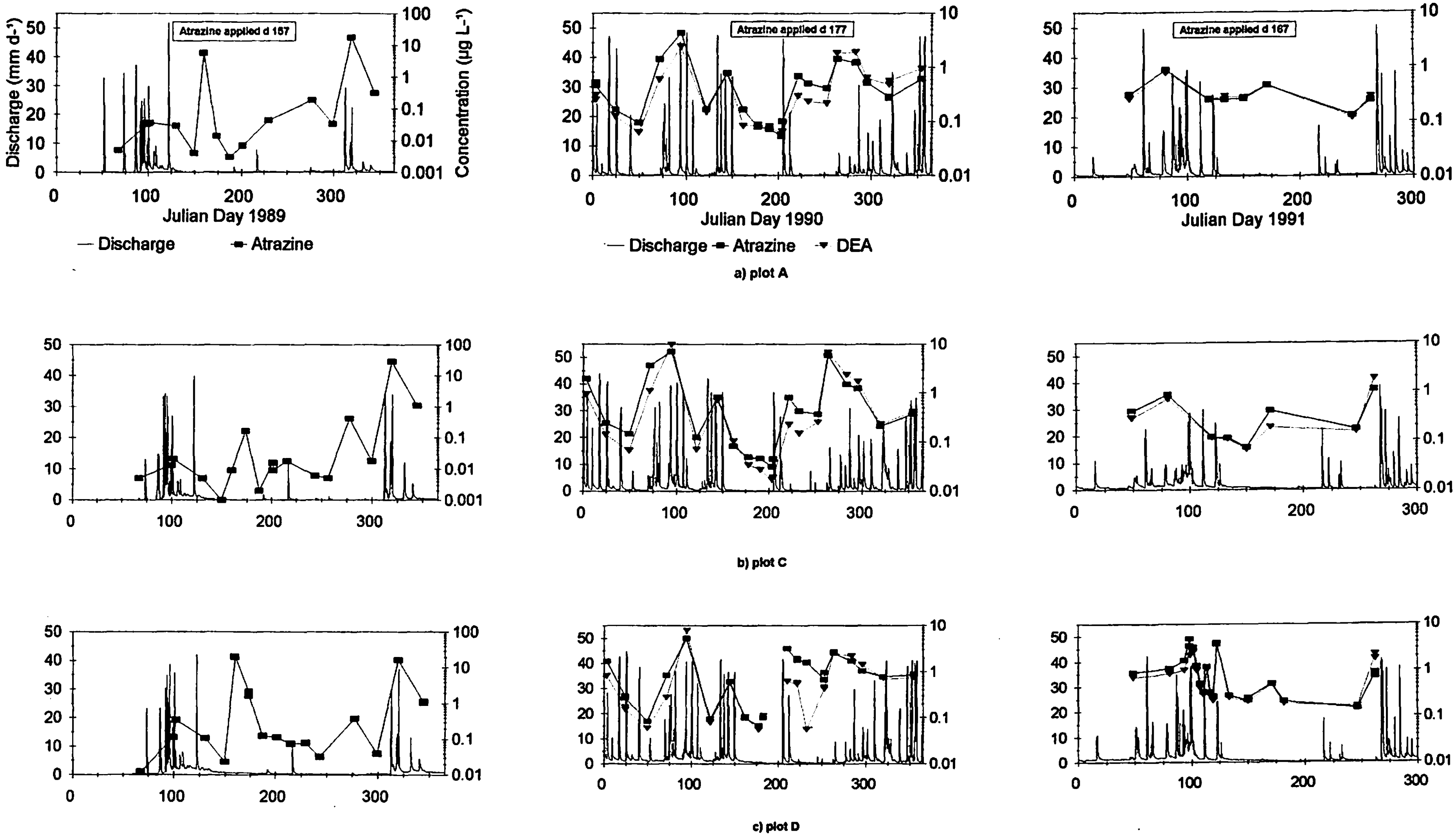


Fig. 3. Tile discharge hydrograph and concomitant atrazine and deethylatrazine (DEA) concentrations during 1989, 1990, and 1991: a) plot A; b) plot C; c) plot D.

al. (1991) and Gaynor et al. (1992) (Table I).

Total concentrations just prior to atrazine application in 1990 were about 0.2 µg/L. Maximum total concentrations following application ranged from 3.3 to 12.6 µg/L and were coincident with the onset of drainage discharge on day 263 (September 20).

In 1991 total concentrations prior to application (day 167; June 16) were similar to 1990, about 0.5 µg/L or less. In a study conducted near Ames, Iowa, total concentrations one year following application were slightly higher, between 1 and 3 µg/L (Jayachandran et al. 1994). The greater leaching volumes encountered in our study, resulting in a greater dilution of dissolved atrazine in the tile outflow, would partially explain the lower spring concentrations measured at our experimental site (Milburn and Richards 1994).

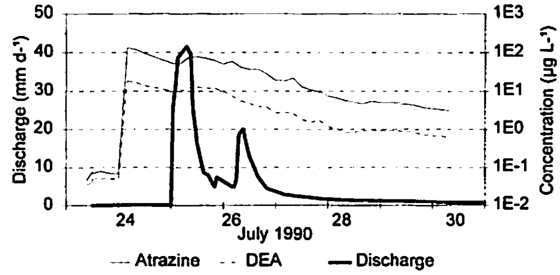
Cumulative atrazine leaching Annual atrazine losses in the drainage water ranged from 4 to 30 g/ha (Table III). Both the greatest seasonal and annual loss occurred in plot D during the 1990-91 crop year; 18 g/ha were leached during the growing season (May 15 - Sept. 15) and 30 g/ha over the entire crop year. We attribute this loss to a spill that occurred during herbicide application (previously mentioned), not to atrazine application according to crop recommendations. However, even when this plot year of data is included, annual atrazine losses are similar to those reported by Gaynor et al. (1992) (Table I). Their annual losses in tile drainage discharge ranged from 6 to 30 g/ha.

Excluding plot D in 1990-91, atrazine losses in tile drainage water during the growing season averaged 0.5 g/ha. This is lower than that reported by Jayachandran et al. (1994), where May to August losses were 5.4 and 9.8 g/ha during the year of atrazine application and 0.7 and 1.1 g/ha the year following atrazine application. The greater loss experienced by Jayachandran et al. (1994) during the growing season could be due to their study design, which included an earlier planting date, a slightly higher application rate, and atrazine application as a pre-emergent rather than a post emergent spray. All these factors would result in more atrazine in the soil over a longer period within the growing season compared to our study, and therefore increased opportunity for rainfall and subsequent leaching.

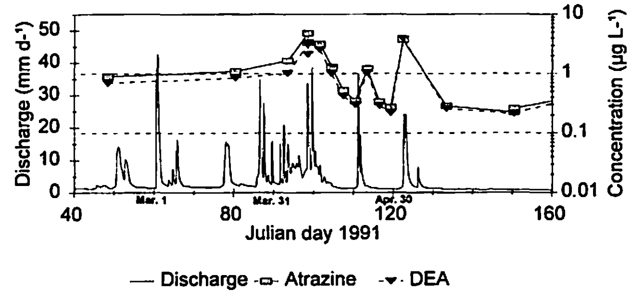
Atrazine spill

The drainage response of plot D to rainfall recorded at the Environment Canada meteorological station in Sussex as 71 mm between 16:00 h on July 24 and 8:00 h, July 25 and 15 mm on July 26 is shown in Fig. 4a. Also shown are atrazine and DEA concentrations of tile water samples collected every 4 h. Tile discharge increased abruptly at approximately 1:00 h on July 25, and peaked at about 9:00 h. Note that a similar tile discharge response occurred in all plots (day 206, 1990; Fig. 3) and that this was the first rainfall event that produced substantial tile discharge since atrazine application on day 177.

Early on July 24 during low tile discharge conditions (6 mm rainfall at Sussex), atrazine breakthrough occurred; maximum concentrations of atrazine and DEA were 133 µg/L and 18. 5 µg/L, respectively (Fig. 4a). These concentrations then generally declined with time through the rainfall events of July 24-26, though a slight increase in concentrations can be observed in both atrazine and DEA during the peak discharge period of July 25.



a) first event following spill



b) concentrations the following spring

Fig. 4. Atrazine leaching following a spill at plot D: a) tile drainage hydrograph and concomitant atrazine and DEA concentrations for the first major rainfall event following the spill; b) atrazine and DEA concentrations in the tile drainage water the next spring.

Total atrazine + DEA concentrations were consistently less than the current Canadian drinking water quality guideline of 5 µg/L by July 30, or within 6 days of the maximum breakthrough concentration. Over this period about 18 and 4 g of atrazine and DEA, respectively, were leached in 37 mm of drainage water. Assuming no contribution from the non-point source atrazine application, the total leaching loss (22 g) in this single event represents from 28 to 55% of the estimated initial atrazine released in the accidental spill. The remaining fraction may have sorbed onto soil particles, leached beyond tile depth, or degraded to compounds not monitored in this study.

Atrazine concentrations in the spring of 1991 showed little effect of the spill (Fig. 4b). They were < 1 µg/L by the time of application, similar to other plot-years. Transient concentrations > 1 µg/L during the spring melt were recorded, but they were of similar magnitude to those observed in all plots in the spring of 1990 (Fig. 3). It appears that the water quality effects of this spill within the root zone, a biochemically active environment of soil, organic matter, air and moisture, were relatively short lived. That is not to imply, however, that there were no negative effects on water quality arising from the spill. The concentration of atrazine residues in tile drainage effluent discharged to the receiving stream during the storm substantially exceeded freshwater aquatic life guidelines (2 μg/L; CCREM 1987). No data were collected to determine the extent of such impacts. However, in 1989, when natural stream flow was low, possible negative impacts of low concentrations of atrazine on planktonic drift populations of atrazine were observed near the tile discharge-stream confluence, but ambient environmental conditions were also felt to be contributing to measured results. Beyond 50 m downstream of the tile discharge-stream confluence, no impacts on planktonic drift populations were evident (Lakshminarayana et al. 1992).

A weakness of this aspect of the study is that there are no field data, other than the farmer's report, to confirm that the high concentrations observed in plot D in 1990 were the product of a spill rather than simply an improved data collection intensity. A similar intensity of water sampling, that would validate the leaching pattern of "properly" applied atrazine under similar rainfall conditions, was not employed in either of the other plots. We acknowledge that the greatest potential movement of surface applied pesticide occurs with the first water input subsequent to application (Gish et al. 1991), and that high concentrations similar to those in our study have been reported when atrazine was applied according to recommended practices. For example, when pesticide application was followed within 12 h by a 48 mm rainfall, Isenee et al (1990) measured atrazine concentrations to 200 μg/L in shallow groundwater. However, our interpretation remains that the results of plot D for the 1990-91 crop year were affected by an accidental spill.

Modeling results The extremely rapid arrival of atrazine in the tile discharge provides a vivid example of field-scale preferential transport. This can be demonstrated by comparing the observed results to those calculated by the CHEMFLO model. To simulate the spill several assumptions were made. These included: the solute (atrazine) was initially uniformly distributed in the top 150 mm of the soil profile; no degradation or sorption of atrazine occurred; the soil profile was near saturation (drained to equilibrium) prior to the 71 mm rainfall event of July 24; all of the 71 mm rainfall infiltrated the soil (ie. no runoff); and the spill occurred directly over a tile drain located at a depth of 0.8 m. These assumptions cause a more rapid transport of atrazine than would be expected in a natural uniform-porosity soil. For example, atrazine sorption could greatly retard the migration rate.

Despite these "worst case" assumptions, the modeling results indicate that following the 71 mm event, atrazine from the spill would still be restricted to a zone from 0.05 to 0.50 m below soil surface. Thus, no atrazine should appear in the tile discharge. Simulations were performed with several soil-moisture relationships and saturated conductivity values and this same conclusion was reached. Clearly these modeling results are not consistent with what happened at our experimental site (Fig. 4a). Other investigators have reported similar discrepancies between field and theoretical results (Beven and Germann 1982; Sposito et al. 1986). The most probable explanation for the discrepancy between the model and observed breakthrough would appear to be preferential transport through macro-pores, root holes, or fissures (Edwards et al. 1993).

SUMMARY AND CONCLUSIONS

To estimate atrazine leaching losses from farm-scale corn production practices in southern New Brunswick, we monitored the quantity and quality of tile drainage discharges from three large (1 ha) plots year round for three consecutive corn crops. For the conditions prevailing at our site we observed the following:

When applied as recommended, atrazine was present in tile drainage water in all plots in all seasons. Concentrations periodically exceeded the Canadian drinking water and freshwater aquatic life guidelines, (range of from < 0.1 to 29 μg/L), but were generally less than 1 μg/L by the time more atrazine was applied the next growing season.

Estimates of annual mass losses of atrazine in tile drainage water ranged from 4 to 30 g/ha, or from 0.3 to 2% of that applied annually. The greatest loss was attributed to an accidental atrazine spill in one of the plots.

The range of concentrations measured and estimates of mass losses in our study were within the range of those reported elsewhere in Canada and the United States.

Elevated concentrations of atrazine were detected in tile drainage water from one of the plots within hours of a 71 mm rainfall event, which was the first major rainfall following an accidental atrazine spill in this plot. Results from the simulation model CHEMFLO indicated that these measured field results could not be the product of uniform-porosity transport. Preferential flow was likely the dominant causal factor for the relatively quick travel time of atrazine to the drainage outlet.

We conclude that atrazine leaching similar to that documented in this study (excluding accidental spill effects) is likely to occur when it is applied as recommended to similar sites and soils in southern New Brunswick. Further research is required to determine the extent and nature of preferential flow processes in major soil types of Atlantic Canada, and its relative impact on pesticide transport.

ACKNOWLEDGMENT

The cooperation of the dairy farmer, Mr. Joerg Van Waldow of Corn Hill, NB is gratefully acknowledged. Appreciation is also expressed to the Atlantic Land Improvement Contractors Association for funding the installation of the drainage plots.

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