Foliar Washoff and Runoff Losses of Lactofen, Norflurazon, and Fluometuron under Simulated Rainfall

Krishna N. Reddy,* Martin A. Locke, and Charles T. Bryson

Southern Weed Science Laboratory, Agricultural Research Service, U.S. Department of Agriculture, P.O. Box 350, Stoneville, Mississippi 38776

Lactofen [(±)-2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate] washoff from velvetleaf (*Abutilon theophrasti* Medic.) and common cocklebur (*Xanthium strumarium* L.) foliage was investigated. Plants were sprayed with lactofen at 0.4 kg of ai ha^{-1} and subjected to 2.5 cm of rainfall in 20 min at 1 and 24 h after application (HAA). At 1 HAA, in both species, over 97% of lactofen was washed off from foliage. At 24 HAA, lactofen washoff ranged from 51% to 82% in both species. Runoff losses of lactofen, norflurazon [4-chloro-5-(methylamino)-2-[3-(trifluoromethyl)phenyl]-3(2*H*)-pyridazinone], and fluometuron [*N,N*-dimethyl-*N*′-[3-(trifluoromethyl)phenyl]urea] on a Bosket sandy loam soil in 2.24 m × 1.22 m × 0.25 m fiberglass runoff trays with 1.1% slope were also studied. A rainfall of 2.5 cm in 20 min at 24 HAA generated 0.8 cm of runoff and contained 3.2% of applied lactofen. However, lactofen loss in runoff was reduced by 94% with a cover crop of Italian ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.). Norflurazon and fluometuron losses in runoff from no-crop residue trays were 4.4% and 0.8%, respectively, when a rainfall of 3.8 cm in 30 min was applied at 24 HAA. No runoff was observed in cover-crop residue trays. More than one-third of the total loss of all herbicides occurred in the first liter of runoff.

Keywords: *Herbicides; lactofen; norflurazon; fluometuron; runoff; foliar washoff; water quality; plant residue; cover crop; sediment*

INTRODUCTION

Crop losses due to weeds, insects, and plant pathogens are enormous, and without effective pest control strategies, crop production is unprofitable. Use of synthetic chemicals for pest control is increasing in both developed and some less well developed countries. In terms of usage, herbicides top the list of pesticides. In 1991, the total pesticide usage on 10 major crops in the United States was 217 000 000 kg of active ingredient (ai), of which 183 000 000 kg (84%) was herbicides (Antognini, 1993). Herbicides provide cost-effective, timely weed control and help farmers to be highly productive and remain economically viable. Herbicides will probably remain an integral part of modern agriculture since there are no cost-effective weed control alternatives on the horizon that are likely to completely replace herbicides (Duke, 1992).

Off-target movement of herbicides from agricultural lands and its impact on the environment is a growing public concern. Increasing awareness of potential problems associated with herbicide use has provided impetus for studying alternative practices that reduce herbicide use. Increasing crop residue can impede surface water flow, thereby reducing movement of herbicide in runoff (Brown et al., 1985; Beke et al., 1989; Wauchope et al., 1990). No-tillage is one management practice that can increase crop residue over conventional tillage systems (Sadeghi and Isensee, 1992; Burwell and Kramer, 1983). Raising a cover crop during fallow periods can also reduce runoff of pesticide and soil erosion.

In any management system, rainfall can reduce the efficacy of pesticides by washing the material off of the plant foliage when applied to foliage (Bryson, 1987; Reddy and Singh, 1992) or by decreasing the availability of pesticide for target weed uptake by causing pesticide runoff and leaching when applied to soil. Rainfall also causes movement of soil-applied pesticides in runoff and by leaching (Baldwin et al., 1975; White et al., 1976; Asmussen et al., 1977; Wauchope, 1978, 1987b; Wauchope and Leonard, 1980; Burwell and Kramer, 1983; Lichtenstein and Liang, 1987; Hubbard et al., 1989; Buttle, 1990; Wauchope et al., 1990). However, in some cases, moderate rainfall immediately after application of certain soil-applied herbicides is beneficial for herbicide incorporation into the upper soil zone. The elapsed time between pesticide application and a rainfall event can be critical to pesticide washoff, runoff, or leaching losses.

Knowledge of herbicide foliar washoff and runoff loss is essential information for environmental modeling, for optimizing weed management, and in developing alternate production practices (Cooper and Lipe, 1992). Full-scale field experiments are difficult and time-consuming, but simulated rainfall applied to small trays or trays of soil can provide useful runoff data (Wauchope, 1987a,b). Likewise, a simulated rainfall applied to plants treated with herbicides can provide information on vulnerability of herbicides to foliar washoff (Bryson, 1987; Reddy and Singh, 1992).

Norflurazon and fluometuron are used extensively for weed control in cotton and many other crops. Norflurazon and fluometuron are applied to the surface of the soil and sometimes incorporated. Fluometuron is sometimes applied to plant foliage. Lactofen is mostly applied to plant foliage in both cotton and soybean production (Weed Science Society of America, 1989). Chemical properties of these herbicides are shown in Table 1. Information on the effect of crop residue on runoff of lactofen, norflurazon, and fluometuron in a typical cotton soil in the Mississippi delta has not been

* Author to whom correspondence should be addressed.

Table 1. Chemical Properties of Herbicides and Their Method of Application[a]

herbicide	water solubility, mg L^{-1}	soil sorption, K_{oc}	field half-life, days	application method
lactofen	0.1	10000	3	postemergence
fluometuron	110.0	100	85	preplant incorporated preemergence postemergence
norflurazon	28.0	700	30	preplant incorporated preemergence

[a] From Weed Science Society of America (1989) and Wauchope et al. (1992).

reported. The objectives of this research were to (1) study the extent of foliar washoff of lactofen in two weed species and (2) quantify runoff loss of lactofen, norflurazon, and fluometuron in the presence or absence of cover crop or crop residue.

MATERIALS AND METHODS

Runoff Trays. Runoff trays used in the studies were described previously by Wauchope (1987a,b). Briefly, fiberglass trays were 224 cm long, 122 cm wide, and 25 cm deep with impermeable bottoms. One end of the tray provided a lip over which runoff water flowed into a sloped-floor trough containing a drain tube at the lower end. The trays were supported on concrete block pedestals of 40 cm height and were adjusted to 1.1% slope.

The soil used in the study was a Bosket sandy loam (fine-loamy, mixed, thermic Mollic Hapludalfs: 43% sand, 48% silt, 9% clay, 1.51% organic matter, pH 5.45). Trays were filled with soil to 23 cm depth, and the soil surface was leveled by raking. Four trays were planted with Italian ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.) in 1:1 mixture, and four trays were kept bare.

Rainfall Simulator. A rainfall simulator modeled after the one described by Meyer and Harmon (1979) reproduced droplet size, fall velocity, and kinetic characteristics similar to those of natural rainstorms. This rainfall simulator has been described previously (Wauchope, 1987a,b; Bryson, 1987).

Lactofen Foliar Washoff Study. Velvetleaf (*Abutilon theophrasti* Medic.) and common cocklebur (*Xanthium strumarium* L.) plants were grown in 10 cm diameter by 9 cm deep plastic pots containing Bosket sandy loam soil and Jiffy mix (Jiffy Products of America Inc., Batavia, IL; 1:1 v/v). After emergence, common cocklebur and velvetleaf plants were thinned to one and two per pot, respectively. Plants were grown in the greenhouse at a 35/27 °C mean day/night temperature and natural light with a 14 h photoperiod. Plants were watered and fertilized as needed. A commercial formulation of lactofen at 0.4 kg of ai ha^{-1} plus 0.6% AgriDex (Helena Chemical Co., Memphis, TN) as surfactant was applied to uniform plants at the 4–6-leaf stage. Lactofen was applied using an indoor spray table with an air pressure spray system in 187 L ha^{-1} at 138 kPa using TeeJet 8002E (Spraying Systems Co., Wheaton, IL) nozzles. Foliar washoff was evaluated by applying 2.5 cm of rainfall at 7.5 cm h^{-1} intensity. The rainfall simulator was set to deliver droplets at 2.0 m height, and the actual amount of rainfall was measured at the plant level with rain gauges. Rainfall was applied 1 and 24 h after application (HAA) of lactofen. A treatment with no rainfall was included as a control to determine the herbicide load on plants. Treatments were replicated six to seven times.

Lactofen Extraction from Plants. Immediately after rainfall application, plants were excised at the soil surface and placed in a 1 L glass bottle. Methylene chloride (200 mL) was added to the bottle and thoroughly shaken for 1 min. Plants were taken out of the bottle and rinsed with methylene chloride, and the rinsate was combined with the extract in the bottle. The extracts were stored at 0–2 °C and were processed within 1 week. Methylene chloride extracts were filtered (Whatman No. 1) into a round-bottom evaporatory flask and evaporated to dryness at 40 °C on a rotary evaporator. Lactofen residue was dissolved in 4 mL of methanol and analyzed by HPLC. Total recovery of lactofen from extraction to analysis was 84%.

Lactofen Runoff Study. Lactofen (with 0.6% AgriDex as surfactant) spray solutions were prepared just before spraying and were applied to both cover-crop and no-cover-crop trays. Italian ryegrass and crimson clover were about 15–20 cm tall with complete ground coverage at spraying. There were four trays with cover crop and four trays with no cover crop. A tractor-mounted sprayer equipped with Teejet 8004E-SS nozzles was used in spraying at a spray volume of 187 L ha^{-1} and 214 kPa. Three 9 cm Petri dishes were placed in a row diagonally on the surface of each tray to collect spray to determine the actual amount of herbicide applied. Rainfall (2.5 cm applied at an intensity of 7.2–7.3 cm h^{-1}) was applied 24 h after herbicide application. Rainfall was applied to one tray at a time, and runoff (both water and sediment) was collected in 1 L fractions. Glass collection bottles were weighed before and after runoff collection. Runoff samples were stored at 0–2 °C, and samples were processed within 2–8 weeks.

Lactofen Runoff Analysis. Petri dishes used to collect lactofen spray were rinsed with 25 mL of methanol followed by 25 mL of methylene chloride. The rinsates were combined and evaporated to dryness at 40 °C on a rotary evaporator, and the residue was dissolved in 8 mL of methanol for HPLC analysis. Lactofen and sediment were determined from every runoff fraction. Total sediment was determined by weighing the residue remaining in the beaker after oven-drying a 200 mL aliquot of well-shaken runoff, poured rapidly into a weighed beaker. For lactofen analysis, 400 mL of well-shaken runoff (both water and sediment) was poured into a beaker and weighed. Runoff sample was transferred to a 1 L separatory funnel, 40 mL of 1 N HCl added and shaken, 200 mL of methanol added and shaken, and 150 mL of methylene chloride added and shaken, and then the sample was allowed to stand for phase separation. After phase separation, the lower phase was collected. The extraction was repeated twice with 75 mL of methylene chloride, and the lower phases from three extracts were combined. Combined extracts were filtered using a fritted glass funnel apparatus with microfiber filter paper Whatman GF/F (Whatman LabSales, Hillsboro, OR). Sediment in the combined extract was removed by prefilter using Whatman No. 1 filter paper. Methylene chloride extracts were evaporated to dryness at 40 °C on a rotary evaporator. Lactofen residue was dissolved in 4 mL of methanol for HPLC analysis. Lactofen recovery was checked using runoff samples spiked with 5 μg of lactofen and ranged from 75% to 89%.

Norflurazon and Fluometuron Runoff Study. Norflurazon and fluometuron were applied together using a tractor-mounted sprayer as described in the lactofen study. Ten days before herbicide application, the cover crops (ryegrass and crimson clover) in runoff trays were desiccated with paraquat. There were four trays with cover-crop residue and four trays with no crop residue. The spray was collected in Petri dishes as described in the lactofen runoff study to determine the actual amount of herbicide applied. Rainfall was applied 24 h after herbicide application (3.8 cm at 7.4–7.6 cm h^{-1} intensity). All other experimental conditions were as described in the lactofen runoff study. Runoff samples were analyzed within 2–3 weeks.

Norflurazon and Fluometuron Runoff Analysis. Petri dishes used to collect norflurazon and fluometuron spray were rinsed with 10 mL of methanol and analyzed by HPLC. Norflurazon, fluometuron, and sediment were determined in every runoff fraction. Total sediment was determined as described in the lactofen runoff study. For norflurazon and fluometuron analysis, about 20 g of well-shaken runoff was rapidly poured into a 25 mL glass centrifuge tube. The runoff was centrifuged at 5900*g* for 15 min. The herbicides in the supernatant were analyzed by HPLC with no further sample purification. The recovery ranged from 83% to 98% for norflurazon and from 80% to 94% for fluometuron.

HPLC Analysis. The HPLC system consisted of a Waters Maxima controller, a Waters UV detector Model 490, a Waters fluorescence detector Model 470, two Waters pumps Model 510,

Table 2. Lactofen Load and Foliar Washoff from Velvetleaf and Common Cocklebur Foliage

weed species	rainfall, HAA[a]	lactofen load on canopy, μg/plant(s) no rain[b]	rain[b]	t test[c]	foliar washoff,[d] %
velvetleaf	1	253.9 (42.7)	4.5 (0.7)	*	98.2
	24	94.3 (17.0)	46.4 (8.5)	*	50.8
common cocklebur	1	329.7 (76.4)	10.1 (1.3)	*	96.9
	24	160.2 (21.5)	28.5 (6.5)	*	82.2

[a] HAA, hours after application of lactofen. [b] Standard error in parentheses. [c] *, significant at 5% level as determined by t test. [d] Percent of lactofen washed off by rain as compared to the no-rain control.

and a Waters WISP Model 710B automatic sampler (Waters Corp., Milford, MA). Lactofen separation was performed on an Alltima reversed-phase C_{18} column (Alltech Associates Inc., Deerfield, IL) with the initial mobile phase of water (adjusted to pH 3.0 with phosphoric acid)/acetonitrile (50:50) at a flow rate of 1 mL min^{-1}. The mobile phase was programmed to a gradient of 10% water and 90% acetonitrile over 22 min. An injection volume of 10−60 μL and a detection wavelength of 296 nm were used.

Norflurazon and fluometuron separation was performed on an Econosil reversed-phase C_{18} column (Alltech Associates) with the initial mobile phase of water/acetonitrile (55:45) at a flow rate of 1 mL min^{-1}. The mobile phase was programmed to a gradient of 20% water and 80% acetonitrile over 24 min. An injection volume of 50−200 μL was used. Fluometuron and norflurazon were monitored at emission wavelengths of 329 and 398 nm, respectively, after an excitation at 294 nm.

Statistical Analysis. Data were subjected to a t test (Cochran) using SAS software (SAS Institute Inc., Cary, NC), and means were separated at the 5% level of significance.

RESULTS AND DISCUSSION

Lactofen Foliar Washoff Study. Lactofen concentration on foliage was 253.9 μg plant^{-1} for velvetleaf and 329.7 μg plant^{-1} for common cocklebur at 1 HAA (Table 2). The difference in the amounts deposited on the foliage of the two species was mainly due to the difference in the plant size. Apparently the common cocklebur plants were bigger than the velvetleaf plants. A rainfall of 2.5 cm at 1 HAA removed over 97% of lactofen from the foliage as compared to no-rain control in both species. At 24 HAA, lactofen concentration on foliage of both species was lower than at 1 HAA, possibly due to volatilization, photodegradation, or plant uptake and metabolism of lactofen. A rainfall of 2.5 cm at 24 HAA removed 51% of lactofen as compared to no-rain control from velvetleaf foliage and 82% from common cocklebur foliage. These results are similar to the range reported for other pesticides. For example, a rainfall of 2.4−11.1 cm applied 2 HAA washed off 46−55% of permethrin (Willis et al., 1986, 1992), 62% of malathion (Willis et al., 1992), 62% of EPN, and 88% of methyl parathion (McDowell et al., 1984) from plant foliage.

Rainfall application within 1 HAA simulated conditions under which the maximum amount of lactofen would be susceptible to washoff. Rainfall after 24 HAA simulated a field condition when herbicide application occurs on a dry day but a rainstorm is encountered the following day. These two simulated conditions would give information on the extent of lactofen washoff from foliage. In the event of high-intensity rainfall occurring within hours after application, lactofen would washoff from foliage and be available for runoff. In the event of rainfall occurring 24 h after lactofen application (such an event is not uncommon under field conditions), any herbicide remaining on plant foliage would be vulnerable to washoff.

Table 3. Lactofen Load and Losses in Runoff from Cover-Crop and No-Cover-Crop Trays

variable	no cover crop[a]	cover crop[a]	t test[b]
lactofen applied			
mg tray^{-1}	102.6 (6.0)	115.6 (6.6)	ns
g ha^{-1}	375.5 (21.8)	422.9 (24.3)	ns
rainfall			
amount, cm	2.5	2.5	ns
intensity, cm h^{-1}	7.3 (0.1)	7.2 (0.2)	ns
runoff volume			
L tray^{-1}	22.3 (1.2)	3.8 (0.1)	*
cm	0.8 (0.04)	0.1 (0.01)	*
as % of rainfall	32.6 (1.7)	5.6 (0.2)	*
sediment loss			
kg ha^{-1}	310.8 (67.0)	5.5 (0.3)	*
lactofen lost in runoff			
mg tray^{-1}	3.1 (1.2)	0.2 (0.06)	*
as % of applied	3.2 (1.2)	0.2 (0.05)	*
lost in first L of runoff			
mg L^{-1}	1.2 (0.5)	0.1 (0.02)	ns
as % of applied	1.2 (0.6)	0.1 (0.02)	ns
as % of total loss	31.1 (6.4)	33.1 (2.3)	ns

[a] Standard error in parentheses. [b] ns, nonsignificant; *, significant at 5% level as determined by t test.

Lactofen Runoff Study. Initial soil moisture (0−5 cm depth) was about 26% in both bare and cover-crop trays. Runoff from bare trays began earlier than from cover-crop trays. Typically, runoff would start about 2 min after the onset of rainfall in bare trays and after about 10 min in cover-crop trays. Runoff ended about 3 and 7 min after rain stopped in bare and cover-crop trays, respectively. Runoff from bare trays was 22.3 L tray^{-1} as compared to 3.8 L tray^{-1} in cover crop trays (Table 3), which means 32.6% of rainfall applied was lost as runoff in bare trays as compared to 5.6% of rainfall applied in cover-crop trays. Cover crop reduced runoff by 83% compared to no-cover-crop trays.

Sediment loss in runoff was 57 times greater from the bare trays than from cover-crop trays, which amounted to a 98% reduction in sediment loss by cover crop (Table 3). Total sediment loss from bare trays was 311 kg ha^{-1}, which was similar to the sediment loss (410 kg ha^{-1}) observed by White et al. (1976) on a 0.34 ha watershed. Sediment load in runoff fractions ranged from 2.42 to 4.43 g L^{-1} in bare trays as compared to 0.27−0.40 g L^{-1} in cover-crop trays (Figure 1).

In bare trays 3.2% of applied lactofen was lost in runoff compared to 0.2% of applied from cover-crop trays (Table 3). This is a 94% reduction in lactofen loss due to cover crop. The first liter of runoff had the highest concentration of lactofen regardless of cover crop. Lactofen concentration in the first liter of runoff from bare trays was higher (1.2 mg L^{-1}) as compared to that from cover-crop trays (0.1 mg L^{-1}) (Table 3). However, the fractional loss of lactofen in the first liter of runoff was about the same in both bare (31% of total loss) and cover-crop (33% of total loss) trays. Lactofen concentration in subsequent runoff samples from bare trays decreased exponentially (Figure 1). These results are similar to that observed in 2,4-D (White et al., 1976), atrazine (Wauchope, 1987b), and cyanazine (Wauchope et al., 1990). An exponential decrease in lactofen concentration can be attributed to lactofen leaching below the soil surface due to continuous rainfall; consequently, less chemical would be available for runoff. These results suggest that most lactofen losses occur during the first few runoff events following application.

Under field conditions, ground cover with canopy can vary within and between fields. Canopy cover may vary from 0% to 100% depending upon weed species, density,

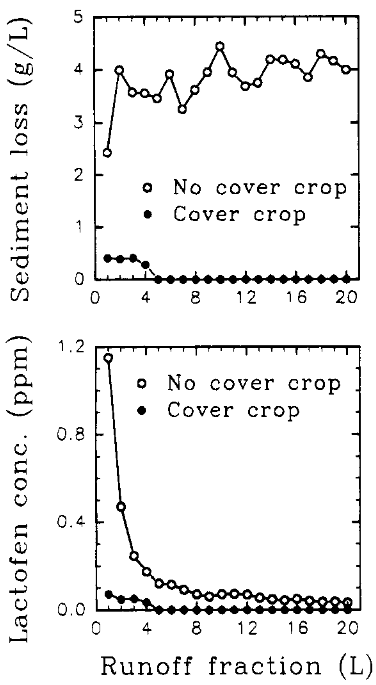

Figure 1. Sediment loss and lactofen concentration in runoff from cover-crop and no-cover-crop trays.

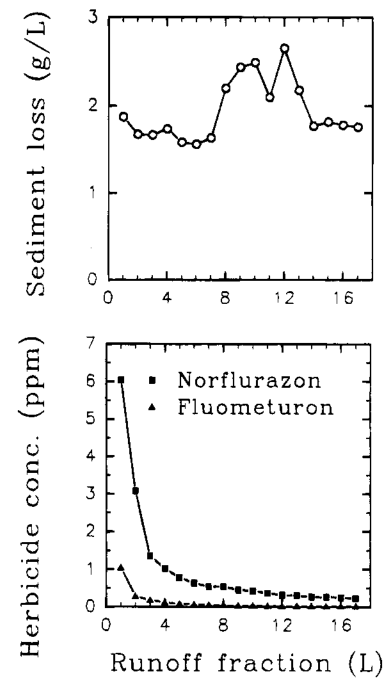

Figure 2. Sediment loss and norflurazon and fluometuron concentration in runoff from no-residue trays.

and growth. Since lactofen is a foliar-applied herbicide, it is difficult to quantify how much of a given spray falls on foliage or on soil surface. However, lactofen runoff can be quantified under 0% and 100% canopy coverage. Cover-crop trays had 100% canopy coverage, which simulated maximum interception of herbicide spray with little or none falling on the soil surface. The bare trays simulated the other extreme with the maximum lactofen spray contacting the soil surface. Typical lactofen application in the field will fall between these extremes in terms of canopy coverage, and lactofen runoff would likely be less than 3.2% of applied (Table 3).

Reduction in lactofen removed in runoff from cover-crop trays was mainly due to decreased runoff rather than unavailability of herbicide for runoff. Results of the washoff study suggest that a 2.5 cm rainfall event 24 HAA can wash off 51−82% of lactofen applied and be available for runoff (Table 2).

Norflurazon and Fluometuron Runoff Study. There was no runoff from crop-residue trays in spite of an increase in rainfall to 3.8 cm as compared to 2.5 cm in the lactofen runoff study. Runoff collected from bare trays was 19.2 L tray^{-1}, which was 18.4% of rainfall applied (Table 4). Runoff in this study was less compared to that in the lactofen runoff study because of the following: (a) although trays were watered 1 day before herbicide application, the initial soil moisture (0−5 cm depth) was about 15% in both bare and crop-residue trays as compared to 26% in lactofen study and (b) warmer temperatures (36 °C high, 21 °C low) characterized the norflurazon and fluometuron study compared to the lactofen study (20 °C high, 6 °C low). Sediment load in runoff fractions ranged from 1.56 to 2.65 g L^{-1} in bare trays (Figure 2).

In bare trays, 4.4% of applied norflurazon was lost in runoff, of which about 35% was lost in the first liter of runoff (Table 4). Only 0.8% of applied fluometuron was

Table 4. Norflurazon and Fluometuron Losses in Runoff from Crop-Residue and No-Crop-Residue Trays

	norflurazon[a]			fluometuron[a]		
variable	no crop residue	crop residue	t test[b]	no crop residue	crop residue	t test[b]
herbicide applied						
mg tray^{-1}	395.7 (47.1)	420.7 (3.3)	ns	266.2 (6.2)	275.0 (1.8)	ns
g ha^{-1}	1447.9 (17.3)	1539.5 (12.2)	ns	974.1 (22.8)	1006.4 (6.7)	ns
rainfall						
amount, cm	3.8	3.8	ns	3.8	3.8	ns
intensity, cm h^{-1}	7.6 (0.2)	7.4 (0.1)	ns	7.6 (0.2)	7.4 (0.1)	ns
runoff volume						
L tray^{-1}	19.2 (1.7)	0	*	19.2 (1.7)	0	*
cm	0.7 (0.1)	0	*	0.7 (0.1)	0	*
as % of rainfall	18.7 (1.6)	0	*	18.7 (1.6)	0	*
sediment loss						
kg ha^{-1}	138.8 (24.7)	0	*	138.8 (24.7)	0	*
herbicide lost in runoff						
mg tray^{-1}	16.8 (3.2)	0	*	2.1 (0.5)	0	*
as % of applied	4.4 (0.9)	0	*	0.8 (0.2)	0	*
lost in first L of runoff						
mg L^{-1}	6.0 (1.7)	0	*	1.0 (0.3)	0	*
as % of applied	1.6 (0.5)	0	*	0.4 (0.1)	0	*
as % of total loss	34.6 (4.7)	0	*	49.5 (4.3)	0	*

[a] Standard error in parentheses. [b] ns, nonsignificant; *, significant at 5% level as determined by t test.

lost in runoff, of which about 50% was lost in the first liter of runoff from bare trays. The first liter of runoff had the highest concentrations of norflurazon (6.0 mg L^{-1}) and fluometuron (1.0 mg L^{-1}). This was followed by an exponential decrease in the concentration of both herbicides in subsequent runoff samples (Figure 2), similar to that observed in the lactofen study.

Limited runoff of fluometuron compared to norflurazon under similar conditions can be attributed to differences in chemical properties (Table 1). A greater portion of fluometuron (water solubility, 110 mg L^{-1}) compared to norflurazon (water solubility, 28 mg L^{-1}) may have leached rather than remain at the soil surface, thereby making less available for runoff. Furthermore, a greater amount of norflurazon (K_{oc}, 700) compared to fluometuron (K_{oc}, 100) may have sorbed to sediment and moved in runoff. The runoff loss of norflurazon (4.4% of applied at 3.8 cm of rainfall) from no-cover-crop trays was somewhat similar to that observed in the lactofen (water solubility, 0.1 mg L^{-1}; K_{oc}, 10,000) study, where 3.2% of applied lactofen was removed in runoff by 2.5 cm of rainfall.

In no-tillage systems, weeds are usually killed with herbicides prior to crop emergence. Cover crops grown during winter are also desiccated before crop planting in the following spring. Plant residue is generated in both conditions, but ground coverage by the plant residue may not be uniform. Plant residue coverage can vary from 0% to 100% depending upon weed or cover-crop growth. Since norflurazon and fluometuron are soil-applied herbicides, an attempt was made to quantify herbicide losses in runoff in the presence of crop residue. In the crop-residue trays, the soil surface was completely covered with residue, which is somewhat similar to a no-tillage system compared to bare trays (conventional tillage system). The absence of runoff in the crop-residue trays was mainly due to increased infiltration. These results suggest that in fields with about 1% slope and crop residue, the loss of norflurazon and fluometuron would be negligible even with 3.8 cm of rainfall at 7.5 cm h^{-1} intensity.

Conclusions. Lactofen is vulnerable to foliar washoff, particularly in the event of a rainstorm occurring within 1 HAA. Even 24 HAA, 2.5 cm of rainfall can remove a considerable amount of lactofen from foliage. Lactofen washed off from foliage is then available for runoff, in addition to any lactofen not intercepted by foliage. Of the total lactofen available, at most, 3.2% can move in runoff depending upon ground coverage by crop and weeds. The presence of a crop residue can greatly reduce movement of norflurazon and fluometuron in runoff. In fields with about 1% slope and no crop residue, a rainfall of 3.8 cm can move, at most, 4.4% of norflurazon and 0.8% of fluometuron in runoff. It appears that, of the two herbicides, fluometuron may be less vulnerable to move in runoff. Runoff losses observed in this study are within the range reported for fluometuron (1%) (Baldwin et al., 1975), cyanazine and sulfometuron-methyl (1−3%) (Wauchope et al., 1990), 2,4-D (1−10%) (White et al., 1976; Asmussen et al., 1977), atrazine (4−12%) (Wauchope, 1987b), and norflurazon (2%) (Southwick et al., 1993) under various conditions. In a review on pesticide losses in runoff from agricultural fields, Wauchope (1978) concluded that for most pesticides the total losses were less than 0.5% of the amounts applied with the exception of organochlorine insecticides, for which losses ranged from 1% to 5% of applied, depending on the conditions. Information from the present studies should be useful for developing alternative production practices based on a cover-crop, no-tillage system, which has the potential to reduce non-point source contamination.

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