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RUNOFF FROM FESCUE PLOTS TREATED WITH TRIMEC

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ABSTRACT. *Runoff of herbicides can promote adverse impacts in receiving waters. The objective of this study was to assess the effects of rainfall delay, herbicide application rate, rainfall intensity, and pre-application rainfall on runoff of TRIMEC (a combination of 2,4-D, dicamba, and mecoprop), a herbicide that is commonly used in central Kentucky. The levels of rainfall delay were 0, 2, and 4 d following application; and the levels of herbicide application rate were 0, 0.5, 1 and 2 times the recommended rate. Simulated rainfall was applied at intensities of 64, 102, and 140 mm* h^{-1}*; and the depths of water applied prior to TRIMEC application were 0, 13, and 25 mm. Flow-weighted composite runoff samples were analyzed by gas chromatography. Maximum concentrations in runoff for treatment combinations studied were: 2,4-D, 45.5* $\mu g\ L^{-1}$*; dicamba, 1.59* $\mu g\ L^{-1}$*; and mecoprop, 212* $\mu g\ L^{-1}$*. The rainfall delay affected both 2,4-D and dicamba concentrations but not mecoprop concentration, suggesting that its foliar half-life might be longer than suggested. As anticipated, runoff concentrations of all TRIMEC constituents were significantly (*$p < 0.05$*) affected by herbicide application rate. Rainfall intensity affected only the concentration of mecoprop, with concentrations at the highest intensity being significantly (*$p < 0.05$*) greater than those at the two lower concentrations. Pre-application rainfall had no significant effects on runoff concentrations. Mass transport averaged 1.51, 0.38, and 14.8% of amounts applied for 2,4-D, dicamba, and mecoprop, respectively, reflecting differences in degradation rates, wash-off characteristics and other factors. Mass transport was in no case significantly affected by the treatments. The findings of this study suggest that when TRIMEC is applied at the recommended rate under comparable soil, vegetation and weather conditions, the potential for 2,4-D to exceed the maximum contaminant level of 70* $\mu g\ L^{-1}$ *in runoff is low.*

Keywords. *Herbicide, Runoff, Turf.*

Pesticides, upon being transported off-site in runoff, can have detrimental effects on humans and wildlife. In general, pesticides have the potential to harm people, deplete bird populations, eliminate nontarget organisms, or promote nonpest species to pest status. Methods for minimizing the potential hazards of pesticides lost in runoff are necessary to avoid such consequences of pesticide uses. Effective pollution prevention methods must be based on understanding the dynamics of fate and transport for the particular pesticide being considered.

Most early studies of pesticide loss in runoff waters involved application to row-cropped fields. Wauchope (1978) conducted a very thorough review of studies that had been reported prior to 1977. Those and subsequent studies have provided significant information on the interactions between pesticide properties, management practices, and runoff losses. Pesticide properties recognized as important with regard to the fate of a herbicide in the environment include ionizability, water solubility, volatility, soil adsorption, and persistence. Baker and Mickelson (1994) considered soil adsorption and persistence to be the two key properties among this list. Management practices that have been investigated from the standpoint of pesticide losses have included application rate, method, and timing relative to the occurrence of high rainfall. Wauchope (1978) noted that the highest runoff losses almost always occurred during the first storm following application, which has since been corroborated by Baker and Mickelson (1994).

In contrast to studies involving pesticide application to agricultural areas, there have been relatively few studies of pesticide transport after application to turfgrass, with many of those reported within the last decade. Research to date suggests considerable differences between the two settings in terms of pesticide transport dynamics. One of these differences concerns runoff production. It is well known that turf systems will generally produce less runoff than low-cover systems (e.g., row-crops during early growth stages), because turf systems can be expected to experience reduced surface sealing, have greater interception capacity, and (in the case of conventional tillage) have a more highly developed soil structure and macropore system. Runoff from turf systems can be so low that it can be difficult to measure significant amounts when natural rainfall is used to produce the runoff. For example, Morton et al. (1988) investigated nutrient losses from turfgrass [a mixture of 90% Kentucky bluegrass (*Poa pratensis* L.) and 10% red fescue (*Festuca rubra* L.) plots and observed only two runoff events due to natural rainfall during the two-year

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study. Evans et al. (1998) used simulated rainfall (64 mm in 1.5 h) to generate runoff from turf [tall fescue (*Festuca arundinacea* Schreb.)], finding that the proportion of rainfall translated into runoff was less than 1% for some plots used in the study (although the proportion was higher for most plots).

Turf systems also differ from low-cover agricultural systems in terms of sediment production. Eroded sediments are regarded as the dominant vehicle for transport of pesticides that are strongly adsorbed to soil particles (i.e., pesticides having high K_{OC} values). In comparison to row-cropped areas, however, turf systems typically generate very little sediment. Gross et al. (1994) found that, in comparison to row crops, tall fescue/Kentucky bluegrass plots produced low sediment yields. Edwards et al. (1996) measured average single-event sediment yields ranging from 2.7 to 9.2 kg ha^{-1} from four grazed pasture fields in Northwest Arkansas. Edwards and Daniel (1993) measured single-event sediment losses averaging only 0.3 kg ha^{-1} from well-managed tall fescue plots receiving simulated rainfall at 50 mm h^{-1}. Inherent differences between turf and row-cropped systems thus suggest that, for turf systems, pesticide loss from turf systems might be relatively low, but that research results from one setting are not directly applicable to the other.

The limited number of published studies on pesticide loss from turf tend to corroborate the anticipation of relatively (in comparison to row crops) low losses. Harrison et al. (1993) assessed losses of pesticides applied to turfgrass plots in runoff from natural rainfall supplemented with irrigation. Plots sloping from 9 to 14% were treated with several pesticides including 2,4-D and dicamba in simulating a seasonal care program typical for their area. The plots were seeded with three different turfgrass mixtures: CLASSIC [25% 'Merit' Kentucky bluegrass, 25% 'Julia' Kentucky bluegrass, 20% 'Shadow' chewings fescue (*Festuca rubra* ssp. commutata Gaud), and 30% 'Citation' perennial ryegrass (*Lolium perenne* L.)], CONTRACT [60% annual ryegrass (*Lolium multiflorum* Lam.), 20% common Kentucky bluegrass, and 20% creeping red fescue], and Kentucky bluegrass sod. Irrigation was used to wet the soil prior to each application of pesticide. The researchers initially used an irrigation rate of 75 mm h^{-1} but increased to 150 mm h^{-1} for 1 h to generate sufficient runoff. Maximum concentrations of 2,4-D and dicamba in runoff of 312 and 252 μg L^{-1} were measured although more than half the samples contained nondetectable concentrations.

Felton and Powell (1994) sampled a stream draining a 79 ha watershed in central Kentucky for several chemicals including the herbicide 2,4-D, which was applied as TRIMEC™ at a rate of 0.468 mL m^{-2} to a golf course draining into the stream. These researchers detected 2,4-D only during the spring in concentrations of 1.5 and 2.5 μg L^{-1}, which were well below the maximum contaminant level (MCL) of 70 μg L^{-1}.

TRIMEC (also marketed under the trade names Three-way, 33 Plus, and TrexSan), referred to in the study of Felton and Powell (1994), is widely used in the Central Kentucky area by home owners and lawn care professionals for broadleaf control. TRIMEC is a combination of 2,4-D, mecoprop, and dicamba. The compound 2,4-D, is a chlorinated phenoxy compound used as a systemic herbicide to control many types of broadleaf weeds. The molecular formula for 2,4-D amine is ($C_{10}H_{13}C_{12}NO_3$). Mecoprop, 2-[(4-chloro-o-tolyl)oxy]propionic acid, with a molecular formula of $C_{10}H_{11}ClO_3$, is a member of the selective, hormone-type phenoxy herbicides. Dicamba, 3,6-dichloro-o-anisic acid with a molecular formula of $C_8H_6Cl_2O_3$, is a member of the benzoic acid family of herbicides. The largest component of TRIMEC, 2,4-D (243 g L^{-1}) is the only constituent with a MCL, equal to 70 μg L^{-1} (U.S. Environmental Protection Agency, 1990). The LC_{50} (the median lethal concentration at which 50% mortality occurs) ranges from 1 to 100 mg L^{-1} in cutthroat trout, depending on the formulation used. The second largest constituent of TRIMEC, mecoprop (129 g L^{-1}) is relatively non-threatening. The smallest component of TRIMEC is dicamba (25 g L^{-1}) (Extension Toxicology Network, 1995). Dicamba is slightly toxic to fish, with 48-h LC_{50} values ranging from 35 mg L^{-1} for rainbow trout to 465 mg L^{-1} in carp. Selected properties of TRIMEC constituents are given in table 1.

While the studies of Harrison et al. (1993) and Felton and Powell (1994) suggest that runoff of TRIMEC components might not be a problem under typical conditions, the studies were not intended to assess the response of runoff losses to variables identified earlier as potentially significant. The objective of this study was to determine the influence of rainfall delay (period between application and simulated rainfall), herbicide application rate, simulated rainfall intensity, and pre-application rainfall on runoff of TRIMEC applied to tall fescue plots.

METHODS

The experiment was conducted using plots constructed at the Maine Chance Research Farm of the University of Kentucky. The soil at the site was a Maury silt loam (fine, mixed, mesic *Typic Paleudalf*). Each plot measured 2.4 × 6.1 m and was surrounded on three sides by rustproof metal borders. An aluminum gutter was installed at the bottom of each plot to capture runoff. The runoff was then diverted to a collection tube (50 mm i.d. PVC pipe) that was sampled when desired. The plots had a 3% slope along the main axis and were level across the minor axis. The plots were seeded during the summer of 1995 with Kentucky-31 tall fescue and considered to have a cover of approximately 100% with a density of an average homeowner's lawn at the time of the experiment. A mean grass height of 100 to 150 mm was maintained by weekly mowing from early spring through the end of the experiment. The plots received approximately 25 mm irrigation per week during dry periods to promote growth and avoid summer dormancy.

Table 1. Characteristics of TRIMEC constituents (Knisel, 1993)

Chemical	Solubility (mg L^{-1})	Half-life Soil	Half-life Foliage	Washoff Fraction (%)	K_{oc}* (mL g^{-1})
		------(days)------			
2,4-D	8.0×10^5	10	9	45	20
Dicamba	4.0×10^5	14	9	65	2
Mecoprop	6.6×10^5	21	10	95	20

* Organic carbon partitioning coefficient.

The variables of interest (treatments) were rainfall delay, herbicide application rate, simulated rainfall intensity, and pre-application simulated rainfall. The levels of rainfall delay were zero, two, and four days following application. The levels of herbicide application rate were 0, 0.24, 0.48 (the manufacturer's recommended rate), and 0.96 mL m^{-2}. The levels of simulated rainfall were 64, 102, and 140 mm h^{-1}, applied until runoff had occurred for 0.5 h. Pre-application rainfall (applied prior to herbicide application) were 0, 13, and 25 mm.

Resource constraints did not permit a factorial experimental design, which would have enabled assessment of any interactions among treatments. Instead, the overall study was conducted as four separate experiments involving a total of 30 plots, with each experiment analyzed according to one-way analysis of variance (ANOVA) but with data from a "standard" treatment combination common to all separate experiments. The assignment of treatment levels to plots is given in table 2. The plot numbers in table 2 bear no relationship to the physical layout but are presented in this fashion for the sake of convenience.

The standard treatment combination, which was replicated three times, was defined as having a rainfall delay of 2 d, an herbicide application rate of 0.48 mL m^{-2}, simulated rainfall intensity of 102 mm h^{-1}, and no pre-application rainfall (table 2, plots 1-3). Effects of rainfall delay were assessed using the three standard combination plots (table 2, plots 1-3) and six additional plots (table 2, plots 4-9). The additional six plots had standard levels of all variables except rainfall delay; three plots had a rainfall delay of 0 d, and three had a rainfall delay of 4 d. In similar fashion, herbicide application rate effects were assessed using the three standard combination plots (table 2, plots 1-3) and nine additional plots (table 2, plots 10-18). The nine additional plots had standard levels of all variables except herbicide application rate; three of the nine received no TRIMEC, three received TRIMEC at 0.24 mL m^{-2}, and three at 0.96 mL m^{-2}. The same approach was used for assessing the effects of rainfall intensity (table 2, plots 1-3 and 19-24) and pre-application rainfall (table 2, plots 1-3 and 25-30). As indicated in table 2, there were three replications of each treatment combination, although not all possible treatment combinations were investigated.

Table 2. Assignment of treatments to plots*

	Level			
Plot	Rainfall Delay (d)	TRIMEC Application Rate (mL m^{-2})	Rainfall Intensity (mm h^{-1})	Pre-Application Rainfall (mm)
1	2	0.48	102	0
2	2	0.48	102	0
3	2	0.48	102	0
4	0	0.48	102	0
5	0	0.48	102	0
6	0	0.48	102	0
7	4	0.48	102	0
8	4	0.48	102	0
9	4	0.48	102	0
10	2	0.00	102	0
11	2	0.00	102	0
12	2	0.00	102	0
13	2	0.24	102	0
14	2	0.24	102	0
15	2	0.24	102	0
16	2	0.96	102	0
17	2	0.96	102	0
18	2	0.96	102	0
19	2	0.48	63	0
20	2	0.48	63	0
21	2	0.48	63	0
22	2	0.48	140	0
23	2	0.48	140	0
24	2	0.48	140	0
25	2	0.48	102	13
26	2	0.48	102	13
27	2	0.48	102	13
28	2	0.48	102	25
29	2	0.48	102	25
30	2	0.48	102	25

* The plot numbering scheme is presented for convenience and does not reflect the physical layout.

TRIMEC was applied using a back-mounted sprayer provided by the University of Kentucky Agronomy Department. The pre-application rainfall was simulated by a conventional hand-held sprinkler to apply the specified depths as determined using rainfall gages. Rainfall was applied using rainfall simulators (Evans et al., 1998) until runoff had occurred for 0.5 h from each plot. The simulated rainfall events were severe; for instance, a storm having an intensity of 64 mm h^{-1} and duration of 0.5 h has a return period of approximately 50 years (Hershfield, 1961), while the higher rainfall intensities would have return periods of greater than 100 years if maintained for 1 h. The water source for the simulators was municipal water. Covers were placed over the plot gutters to ensure that only runoff entered the gutters.

The elapsed time between the beginnings of simulated rainfall and runoff was noted and recorded for each plot. Runoff samples (approximately 1000 mL) were collected at 2, 4, 6, 8, 14, 22, and 30 min after initiation of runoff. The time associated with the collection of each sample was noted and used later to calculate flow rates, which was in turn used to form flow-weighted composite samples. The composite samples were placed (with no headspace) in unused amber glass bottles and stored in the dark at 4°C, and the unused portions of the seven individual samples were discarded (i.e., only the composite samples were analyzed). The composite samples were transported to the Kentucky Geological Survey (KGS) laboratory for analysis within 24 h of collection. The composite samples were subsequently analyzed using gas-liquid chromatography (U.S. Environmental Protection Agency, 1988) by KGS technicians. The detection limits for the tests were 1, 80, and 0.1 μg L^{-1} for 2,4-D, mecoprop, and dicamba, respectively. The concentration and mass transport (calculated from runoff and concentration data) data were analyzed according to one-way ANOVA. For ANOVA purposes, nondetectable concentrations were taken as one-half the detection limit. Means were separated using the Student-Newman-Keuls method when ANOVA indicated a significant treatment effect.

The experiment was conducted 14-18 July 1997. The weather conditions at the site during this period are given in table 3. No precipitation occurred during the five-day period.

Table 3. Weather conditions from 14/07/97 to 18/07/97

Date (mm/dd/yy)	Air Temperature			Relative Humidity		Soil Temperature (10 cm depth)			
						Grass		Bare	
	Max*	Min	Ave	Max	Min	Max	Min	Max	Min
	---------(°C)---------			-----(%)-----		-------------(°C)-------------			
14/07/97	32	19	26	100	67	23	21	29	23
15/07/97	31	19	25	100	55	24	21	30	24
16/07/97	32	17	24	100	45	24	21	31	24
17/07/97	33	19	26	100	48	24	21	31	24
18/07/97	33	21	27	99	51	24	22	32	25

* "Max" is maximum, "Min" is minimum, and "Ave" is average.

Table 4. Statistics of runoff variables

	Pre-Runoff Rainfall (mm)	Runoff (mm)	Rainfall:Runoff Ratio (%)	Curve Number
Maximum	118.2	28.5	27.3	65.5
Minimum	39.0	1.6	1.6	28.6
Mean	68.6	12.3	10.9	48.5
Standard deviation	20.7	6.4	6.5	9.9

RESULTS

RUNOFF

Runoff from the plots was generally low in comparison to amounts applied and highly variable. Statistics of pre-runoff rainfall (amount of simulated rainfall applied prior to the beginning of runoff), runoff, runoff-to-total rainfall ratio, and curve number (Soil Conservation Service, 1972; calculated for each plot) are given in table 4. The mean calculated curve number (48.5) is approximately 20% less than the tabulated curve number (58-61) for this soil, cover and antecedent moisture condition.

The data in table 4 are not differentiated according to treatment, because the runoff variables were not significantly related to any treatment. The pre-application rainfall amounts were insufficient to produce an effect on runoff. As indicated in table 3, daily air temperatures during the experiment were relatively high (daily maximum temperatures averaged 32°C), which would have produced a high evapotranspiration relative to the pre-application rainfall. High evapotranspiration and plot-to-plot variability thus dominated any tendency of the pre-application rainfall to increase runoff. Similarly, varying rainfall intensity by ±37% was insufficient to overcome plot variability and produce significant rainfall intensity effect on runoff.

Table 5. Summarized statistics of runoff concentration data (30 samples)

	Runoff Concentration		
	2,4-D	Dicamba	Mecoprop
Mean (μg L^{-1})	16.4	0.42	94.2
Standard deviation (μg L^{-1})	12.4	0.41	59.8
Maximum (μg L^{-1})	45.5	1.59	212
Minimum (μg L^{-1})	0.5	0.05	40
Below detection limit*	3	7	14
Skewness	0.700	1.22	0.635

* Number of samples.

CONCENTRATIONS IN RUNOFF

Statistics of TRIMEC constituent concentrations in runoff are summarized in table 5. Runoff concentrations of 2,4-D ranged from non-detectable to 45.5 μg L^{-1}. Dicamba concentrations ranged from non-detectable to 1.59 μg L^{-1}, and mecoprop concentrations from non-detectable to 166 μg L^{-1}. Maximum 2,4-D and dicamba concentrations in this study were considerably less than values reported by Harrison et al. (1993), amounting to only 15% and 1% of the maximum values observed by those researchers. Runoff concentrations of 2,4-D never exceeded the MCL of 70 μg L^{-1}. Stream flow concentrations of 2,4-D reported by Felton and Powell (1994), however, were more than an order of magnitude less than those of this study, probably reflecting dilution by untreated areas that contributed to flow in the Felton and Powell (1994) study. Runoff concentrations of mecoprop, when detected, were generally disproportionately large in comparison to its fraction in TRIMEC, due likely to its relatively high wash-off fraction (table 1) and persistence.

RAINFALL DELAY EFFECTS

Runoff concentrations of 2,4-D ($p = 0.006$) and dicamba ($p < 0.001$) were significantly affected by rainfall delay. As indicated in table 6, two days between herbicide application and simulated rainfall decreased mean 2,4-D concentration by 60% and mean dicamba concentration by more than 90%, while further decreases in mean runoff concentrations were not significant. The concentration decreases were consistent with degradation of TRIMEC constituents but were greater than what might have been expected based on the foliar half-lives given in table 1, possibly due to the relatively hot conditions (table 3) observed during the experiment. Mean mecoprop concentrations were unaffected by rainfall delay (table 6). Considering the reported similarities between foliar half-lives of mecoprop, 2,4-D and dicamba (table 1), a significant effect of time between herbicide application and simulated rainfall could reasonably have been expected. The difference suggests that mecoprop might be more persistent than the reported foliar half-life shown in table 1 and that more time between herbicide application and simulated rainfall might be necessary to observe an appreciable decrease in runoff mecoprop concentrations.

Table 6. Means and standard deviations of concentrations of TRIMEC constituents in relation to rainfall delay (three replications, application rate = 0.48 mL m^{-2}, rainfall intensity = 102 mm h^{-1}, no pre-application rainfall)

		Rainfall Delay (d)		
		0	2	4
	Constituent	-----------------(μg L^{-1})----------------		
2,4-D	Mean	36.9a	14.5b*	7.87b
	Standard deviation	8.76	6.73	5.84
Dicamba	Mean	1.30a	0.103b	0.093b
	Standard deviation	0.269	0.092	0.075
Mecoprop	Mean	62.8a	66.3a	111.3a
	Standard deviation	39.5	45.6	71.0

* Within-row means followed by the same letter are not significantly different ($p > 0.05$) as per the Student-Newman-Keuls Method.

Table 7. Means and standard deviations of runoff concentrations of TRIMEC constituents in relation to application rate (three replications, rainfall delay = 2 d, simulated rainfall intensity = 102 mm h^{-1}, no pre-application rainfall)

Constituent		Application Rate (mL^{-1}) 0	0.24	0.48	0.96
		------------------------(μg L^{-1})------------------------			
2,4-D	Mean	0.500 b*	15.5ab	14.5 b	30.6 a
	S.D.	0.000	7.0	6.7	9.6
Dicamba	Mean	0.050 b	0.398 ab	0.103 ab	0.623 a
	S.D.	0.000	0.410	0.092	0.317
Mecoprop	Mean	40.0 b	53.7 ab	66.3 ab	166.0 a
	S.D.	0.000	23.7	45.6	46.0

* Within-row means followed by the same letter are not significantly different ($p > 0.05$) significance level as per the Student-Newman-Keuls Method.

Application Rate Effects

Herbicide application rate had significant effects on runoff concentrations of 2,4-D ($p = 0.005$), mecoprop ($p = 0.008$) and dicamba ($p = 0.02$) (table 7). Concentrations of dicamba and mecoprop were appreciably greater than the detection limit only for the highest herbicide application rate with all other variables set to standard levels, and there were no differences among means at the three lower herbicide application rates (table 7). Similarly, the only significant differences among 2,4-D mean concentrations were between the highest and control herbicide application rates (table 7). The relationship between herbicide application rate and runoff concentration was therefore not linear when assessed two days following herbicide application, and there was no effect except at the highest (twice the recommended rate) herbicide application rate.

Rainfall Intensity Effects

Rainfall intensity significantly affected the runoff concentration of only mecoprop ($p = 0.039$), with the greatest concentrations associated with the highest simulated rainfall intensity (table 8). The lack of an effect on runoff 2,4-D and dicamba concentrations is most likely due to a combination of the properties of those TRIMEC constituents. As discussed earlier, the runoff results suggest that 2,4-D and dicamba might degrade more quickly than mecoprop, so there would have been less of these constituents available for detachment at the plant and thatch surfaces. Furthermore, the wash-off fractions given in table 1 indicate that the proportions of 2,4-D and dicamba removed in the water are generally less than that of mecoprop. Both factors would have acted to mask the presence of any rainfall intensity effect. The response of mecoprop concentration to intensity suggests that proportionately less soil filtering of detached mecoprop might be occurring at the higher rainfall intensities and, hence, greater delivery of detached mecoprop to the plot edge.

Table 8. Means and standard deviations of concentrations of TRIMEC constituents in relation to rainfall intensity (three replications, rainfall delay = 2 d, application rate of 0.48 mL m^{-2}, no pre-application rainfall)

Analyte		Rainfall Intensity (mm h^{-1}) 63.5	102	139.7
		-----------------(μg L^{-1})----------------		
2,4-D	Mean	19.5a*	14.5a	17.6a
	S.D.	10.9	6.73	13.0
Dicamba	Mean	0.623a	0.103a	0.437a
	S.D.	0.367	0.092	0.110
Mecoprop	Mean	100.0ab	66.3b	185.3a
	S.D.	52.0	45.6	31.9

* Within-row means followed by the same letter are not significantly different ($p > 0.05$) as per the Student-Newman-Keuls Method.

Pre-application Rainfall Effects

Pre-application rainfall depth had no significant effect on runoff concentration of any of the three constituents of TRIMEC. At a rainfall delay of 2 d, herbicide application rate of 0.48 mL m^{-2} and simulated rainfall intensity of 102 mm h^{-1}, mean (averaged over all levels) concentrations of TRIMEC constituents were 11.7, 0.23, and 69.0 μg L^{-1}, respectively. The hypothesis with regard to this variable was that the water applied to the plots prior to TRIMEC application would increase runoff and, thus, transport of TRIMEC relative to plots receiving no prior water. Runoff was unaffected by pre-application moisture, which was evidently dominated by the initial dryness of the soil and subsequent evapotranspiration.

Mass Transport

None of treatments significantly affected losses of TRIMEC components. Mass transport of 2,4-D ranged from 0.1 to 6.4%, averaging 1.51% (standard deviation = 1.47%) of amounts applied. Mass transport of dicamba as a fraction of amount applied was lower, ranging from 0.01 to 2.28%, averaging 0.38% (standard deviation = 0.51%) of applied. Mecoprop mass transport was a much higher proportion of amounts applied than the other two TRIMEC constituents, ranging from 0.8 to 42.9% of applied, with an average of 14.8% (standard deviation = 12.0%).

Differences in mass transport expressed as a fraction of amounts applied were expected based on differences in wash-off coefficients (table 1). The high losses of 2,4-D relative to dicamba, however, were unexpected given dicamba's higher reported wash-off coefficient (0.65 as compared to 0.45 for 2,4-D) and lower organic carbon partitioning coefficient (K_{OC}; 2 as compared to 20 for 2,4-D) and suggest that a a different relationship between wash-off fractions is more appropriate for the conditions of this study. Relatively high mecoprop loss was expected due to mecoprop's high wash-off fraction (table 1). On average, however, mecoprop losses were approximately an order of magnitude greater than 2,4-D losses when expressed as proportions of amounts applied. In terms of mass transport, then, mecoprop appears to behave as if it has a higher foliage half-life, a higher wash-off fraction relative to 2,4-D and dicamba, or both.

Summary and Conclusions

The objectives of this study were to determine the effects of rainfall delay (0, 2, and 4 d following herbicide application), herbicide application rate (control, half the recommended rate, recommended rate and twice the recommended rate), simulated rainfall intensity (64, 102, and 140 mm h^{-1}), and pre-application rainfall (0, 13, and

25 mm) on runoff concentrations of TRIMEC constituents. Runoff samples were generated and collected from 30 plots and subsequently analyzed by gas chromatography. Concentration data were analyzed according to one-way ANOVA for each objective (no interactions were assessed). Herbicide application rate, rainfall delay and rainfall intensity significantly ($p < 0.05$) affected flow-weighted mean concentration of at least one TRIMEC constituent. Significant runoff concentration differences between the highest and other levels of herbicide application rate were detected for all TRIMEC constituents. Runoff concentrations of 2,4-D and dicamba were significantly different for the 0 d rainfall delay than the 2 and 4 d rainfall delays. Only mecoprop runoff concentration responded to differences in rainfall intensity, with the highest simulated rainfall intensity leading to highest concentration. Runoff and mass transport were unaffected by any treatment. Mass transport was higher for mecoprop, averaging 14.8%, than for 2,4-D and dicamba (1.51 and 0.38% on average, respectively).

The most important variables investigated were herbicide application rate and rainfall delay. The passage of only two relatively hot days following herbicide application reduced runoff concentrations of 2,4-D and dicamba by 60 and 90%. This finding supports results from similar studies and underlines the importance of paying heed to weather forecasts to avoid applying in advance of predicted rain in the near future. Herbicide application rate generally had the expected effect on runoff concentrations of TRIMEC constituents, even though the effects might have been damped to some degree by the passage of two days with relatively high air temperatures between herbicide application and simulated rainfall. The mass transport data suggest that caution should be exercised when assessing the potential for herbicide loss based on reported wash-off fractions. The relative amounts of TRIMEC constituents lost in runoff were at variance with expectations based solely on wash-off fractions. While the effects of wash-off potential were undoubtedly confounded with those of rainfall delay, an adjustment to the relative values of reported wash-off fractions might be warranted. Mecoprop may be more persistent than its reported foliar half-life would suggest since, in contrast to 2,4-D and dicamba, mecoprop concentrations exhibited no dependence on rainfall delays of zero to four days.

The experimental conditions were quite severe in some cases, involving rainfall intensities of 102 mm h^{-1} occurring the same day as TRIMEC application. Despite the severity of these conditions, application of TRIMEC at the recommended rate led to 2,4-D concentrations that were substantially below (approximately 50% of) the MCL. We conclude that when TRIMEC is applied at the recommended rate under comparable soil, vegetation and weather conditions, the potential for 2,4-D to exceed the MCL in runoff is low. Furthermore, the potential for causing any adverse impacts in receiving waters will be mitigated to the extent that the runoff is diluted by runoff originating from untreated areas or areas treated two or more days previously.

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