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Influence of Amount and Method of Irrigation Water Application on Leaching of Atrazine

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ABSTRACT

A study was conducted to relate leaching of a herbicide, atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4,-diamine], and inorganic water tracers, Br^- and Cl^-, to the amount of deep-percolating water produced from irrigation. Soil at the site was classified as a Dehli Loamy Sand (Mixed, Thermic, Tepic Xeropsamment) which was an unstructured sandy soil that was low in organic C content, conditions conducive to solute leaching. The relationship between depth of solute movement and amount of deep-percolating water was measured in sprinkler, basin, and furrow irrigation methods. Soil distribution of inorganic tracers indicated that graded levels of added water treatments, which were based on reference evapotranspiration, produced corresponding increases in the depth of percolated water. Atrazine's soil distribution indicated greater downward movement in response to increases in amount of deep-percolating water. Magnitude of leaching differed between irrigation methods and increased in the order: sprinkler < basin < furrow. Simulations using the LEACHM model provided a physically based explanation for the differences in water movement between sprinkler and basin methods. The total amount of applied water was similar at each level of percolation but sprinkler irrigations were more frequent, resulting in more evaporation and, consequently, less water available for deep percolation. Both amount and method of water application are important factors that determine pesticide movement and that, in irrigated agriculture, must be considered as integral components of pesticide management.

The Pesticide Contamination Prevention Act authorized the California Department of Food and Agriculture to modify uses of pesticides in areas where they have leached through soil to groundwater (Connelly, 1985). Leaching of agricultural chemicals has been shown to occur during recharge of groundwater whereby water moves from the surface through the soil profile to a groundwater aquifer (Wehtje et al., 1984). Extensive use of irrigation in the San Joaquin Valley, CA, has been implicated in offsite movement of agricultural chemicals that has resulted in environmental contamination problems such as increased nitrate content of groundwater (Schmidt and Sherman, 1987). The amount of recharge water that results from irrigation is a function of the irrigation method used and the amount of water applied in each event (Yamauchi, 1984). Climatic and soil conditions further modify the amount of water that is available for downward movement through the soil profile (Ochs et al., 1983). In California, personnel from the University of California, under contracts from the Office of Conservation in the Department of Water Resources (DWR), have developed the Water Budget Method to determine irrigation requirements of crops (Snyder, et al., 1985). The method utilizes an estimate of evapotranspiration, denoted reference evapotranspiration (ET_o), that is based on a grass cover. The estimate is corrected for specific crops and then used in determining amount and frequency of irrigation events. One purpose of metered applications is to maximize water use by crops while minimizing the amount of water that is removed by deep percolation.

Budgeting irrigation water also could be useful in mitigating downward movement of solutes (Wagenet and Hutson, 1986). Leaching of nitrate has been related to the amount of deep-percolating water produced from ponded water (Biggar and Nielsen, 1978). The water treatments were based on graded levels of evapotranspiration (ET) values for a corn (*Zea mays*) crop. Irrigation by sprinkler, based on ET, has been suggested as a method to control nitrate leaching in sandy soils (Hergert, 1986). A similar approach also might be effective in management of soil-applied pesticide residues. The utility of this technique for reducing pesticide leaching is unknown because no field data are available that quantify the relationship between depth of pesticide leaching and amount of percolating water produced from different methods of irrigation.

This study was conducted to determine if the amount of deep percolating water produced by irrigations could be quantitatively related to leaching of a herbicide. In order to assess the effectiveness of water budgeting in mitigating pesticide movement, water treatments were expressed as a proportion of ET_o. A second objective was to compare patterns of solute soil distribution between methods of water application, i.e., sprinkler, basin, and furrow. The study was conducted on bare soil to produce a baseline data set that described soil and water relationships in the absence of a crop and that could be useful in validating solute movement models.

MATERIALS AND METHODS

Study Design

Soil at the site in Fresno, CA, was mapped as a Delhi Loamy Sand, 0-2% slope, (USDA-SCS, 1971). Soil distributions of surface-applied atrazine and inorganic water tracers were measured in response to incremental increases of percolating water produced from irrigation. Atrazine was used because it was

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Abbreviations: ET, evapotranspiration; ET_o, reference evapotranspiration; DWR, California Department of Water Resources; GC, gas chromatography; MDL, minimum detection limit; ANOVA, analysis of variance; ANOVCOV, analysis of covariance; SD, standard deviation.

known to leach to groundwater as a result of agricultural applications (Wehtje et al., 1984). Bromide was used in 1987 as a conservative tracer to describe water movement (Bowman, 1984). Chloride was used as a conservative tracer in 1988 because chemical analysis was faster. Three levels of percolating water, which for discussion purposes are designated as low, medium, and high, were produced within three methods of irrigation, namely macrosprinkler (sprinkler), basin flooding (basin) and level furrow (furrow) (Jensen, 1983). Originally, three levels of deep percolation were to be produced by adding water proportioned as 0.75, 1.25, and 1.75% of daily, accumulated ET_0 values acquired from a DWR weather station in Fresno. Missing daily values were encountered in 1987 so treatments in 1988 were based on daily averages calculated from the previous 5 yrs' data. Three graded levels of ET_0 treatment were produced within each year but exact percentage values differed between years (Table 1).

Three irrigated-sites, each 9.14 by 18.28 m in dimension were longitudinally orientated within each irrigation method and they were spaced 5 m apart in basin and furrow methods and 10 m apart in the sprinkler method. Along the north–south transect, basin and furrow irrigated sites were separated by 5 m and basin and sprinkler treatments separated by 30 m. One-half of each site, a 9.14- by 9.14-m square, was used each year so percolation treatments were applied to different plots between years. Low, medium, and high percolation treatments were sequentially placed along an east–west transect in 1987. In 1988, the location of the extreme treatments were reversed so although treatments were not completely randomized, the design controlled potential systematic differences in soil variation which may have occurred across ET_0 treatments within an irrigation method.

Irrigation Treatments

Sprinkler irrigations were applied 1 d wk^{-1} with the amount based on the previous week's accumulated ET_0 deficit. Duration of event was adjusted to attain low, medium, and high levels of percolating water–events lasted about 4, 6 or 8 h to provide the three rates of water percolation. Water was applied through four impact macrosprinklers (Model no. 10–20, Weather Tec, Clovis, CA), each situated on a corner of the plot and rotating 360°. Sprinkler irrigation distribution uniformity, measured with catch cans, averaged 80% and the rate of water application to plots averaged 1.09 cm hr^{-1}.

In practice, volume of water applied in basin or furrow methods is similar between irrigations. Irrigation to ET is accomplished by varying the frequency of events. For this study, irrigation occurred when accumulated ET_0 deficit equalled 18 cm which resulted in application of one, two, or three irrigations corresponding to low, medium, and high percolation treatments, respectively (Table 1). Water in the basin method was applied to the entire surface area of the treated site. Water in the furrow method was applied in level furrows, each site containing nine furrows located on 1.02-m centers.

Application of Solutes

Forty-four grams of commercially available Aatrex 80 W (33.4 g atrazine as a.i. in a wettable powder formulation, Ciba-Geigy Corp., Greensboro, NC) was dissolved in 2.7 L of deionized water together with 1.047 kg KBr in 1987 or 2.2 kg $CaCl_2$ in 1988. The solution was sprayed onto soil through a boom containing 4 Teejet nozzles (model no. 8002LP) spaced 48.3 cm apart, at 0.138 MPa pressure and at a walking velocity of 0.95 m s^{-1}. A fresh solution was broadcast onto each treated site (9 sites per year). Based on a surface area of 83.5 m^2 for each site, theoretical application rates were 4 kg ha^{-1} a.i. for atrazine, 84 kg ha^{-1} for Br^- and 169 kg ha^{-1} for Cl^-. The solutes were watered into the soil on the same day of application with 1.5 cm of sprinkler irrigation. Average rate of atrazine application ± standard deviation (SD) measured in 1988 was 3.8 ± 2.5 kg ha^{-1}.

Soil Sampling and Analyses

Soil was sampled in 1987 after 42 d and in 1988 after 39 d of accumulated daily ET_0. Four soil cores were sampled from each plot with samples taken in 0.15-m increments down to the 3-m depth. Cores in each plot were spaced 3.2 m apart and they were located on a southeast–northwest diagonal. Soil in furrow sites was sampled from the middle of the furrows. A cylindrical polyvinyl chloride plastic sleeve, 31 cm in length with an inner diameter of 10 cm, was driven into the soil prior to sampling to prevent surface soil from falling into the borehole. The first 0.15-m sample was taken through the sleeve with an 8-cm i.d. bucket auger and the entire sample collected in a plastic bag. The auger was cleaned in soapy water, rinsed with well water, then with deionized water, and lastly washed with isopropanol before re-insertion through the sleeve into the borehole. Upon collection of subsequent samples, loose soil was removed from the auger by striking it with a rubber mallet

Table 1. Description for each irrigation treatment of the number of events, total amount of water applied, cumulative reference evapotranspiration ET_0 value for the study period, and relationship of the amount of water added to the cumulative ET_0 value.

Irrigation method and water percolation treatments	No. of events	Study interval					
		15 June–26 July 1987			15 May–22 June 1988		
		Water added	ET_0	% of ET_0†	Water added	ET_0	% of ET_0†
		mm	mm		mm	mm	
Sprinkler							
Low percolation	5	200	320	0.63	220	230	0.96
Medium percolation	5	340	320	1.06	360	230	1.57
High percolation	5	470	320	1.47	510	230	2.22
Basin							
Low percolation	1	190	320	0.59	220	230	0.96
Medium percolation	2	380	320	1.19	370	230	1.61
High percolation	3	560	320	1.75	510	230	2.22
Furrow							
Low percolation	1	190	320	0.59	220	230	0.96
Medium percolation	2	380	320	1.19	370	230	1.61
High percolation	3	560	320	1.75	510	230	2.22

† Values used in regression analysis as a quantitative index for percolated water treatments.

after which the soil retained in the bucket was placed into a plastic bag.

Three subsamples after thorough mixing were taken from the plastic bag: one sample for atrazine analysis was placed into a glass jar, immediately frozen on dry ice and kept at -4 °C until submission to the contracted laboratory for atrazine analysis; one for soil texture, organic matter and Br^- or Cl^- analyses was placed into a plastic bag and air dried; and one for gravimetric analysis of water content was placed into a tared glass jar. Analyses for sand, silt and clay content were conducted using the hydrometer method (Bouyoucos, 1962). Organic matter was determined using dichromate reduction with silver sulfate added (California Fertilizer Assoc., 1980). Soil texture and organic matter were measured on one of the four 3-m cores taken in each treated site. Water content was determined gravimetrically by drying the soil samples at 105 to 110 °C for 24 h. Bulk density of the soil had been approximated in a previous study where intact soil samples were taken with a motorized drilling rig. (Troiano and Garretson, 1988).

Infiltration rate of the soil was measured twice, once prior to the study in December 1985, and again after the study in December 1989. Infiltration measurements were made with a double-ring cylinder infiltrometer (Haise et al., 1956). Water loss from the inner ring was measured with a hook gauge with water in the inner ring maintained at a depth of 15 cm and the outside ring kept full. Readings were made every 5 min for the first 30 min and then at 10-min intervals for up to an additional 60 min. Measurements were replicated three times in each treated site. Rate of infiltration was rapid for the first 5 min so infiltration was determined as the slope of the linear portion of the curve attained after the first 5 min.

Chemical Analysis

Bromide concentration in soil was analyzed with a specific ion electrode using the method suggested by the manufacturer (Orio Research, 1982). Chloride in soil was analyzed with a chloridometer and using a procedure suggested by the manufacturer (Haake Buchler Instruments, Saddlebrook, NJ). Analyses for atrazine were conducted by APPL laboratory, Fresno, CA. A 100-g subsample of soil was extracted in 150 mL ethyl acetate in the presence of 50 g sodium–sulfate. The sample was sonicated for 7 min and then filtered through no. 40 ashless filter pater. The extraction procedure was repeated two more times, the combined extract rotoevaporated to dryness at 65 °C, and then redissolved in 5 mL ethyl acetate. Atrazine residue was detected using a gas chromotograph (GC; model no. 5890, Hewlett-Packard, Avondale, PA) equipped with SPB-5 and SPB-35 columns (Supelco Inc., Bellefonte, PA). Oven temperature was ramped from 67 ° to 290 °C at a rate of 20 °C/min^{-1}. Method recovery was 92.3% ± 19.3% at 15 μg kg^{-1}, 79.7% ± 9.8% at 150 μg kg^{-1} and 82.3% ± 15.2% at 1500 μg kg^{-1} standards. The average relative difference between matrix duplicate spiked samples was 9.5%; many of the larger deviations were measured at the lowest spike level of 10 μg kg^{-1} and 35 of the 52 paired samples had a relative difference at or below 10%. Atrazine was not detected in reagent or matrix blank samples. The average coefficient of variation for 19 triplicate GC injections was 3.8%. Results from an accompanying storage dissipation study indicated that atrazine did not degrade under storage conditions used in the study.

Neither atrazine at a minimum detection limit (MDL) of 2 μg kg^{-1} nor Br^{-1} at an MDL of 400 μg kg^{-1} were detected in background soil samples. Chloride was detected in background soil samples at an average concentration of 3.1 mg kg which was subtracted from subsequent measurements. No detectable levels of atrazine or bromide were measured in the well water used for irrigation at MDL's of 0.06 and 100μg L^{-1}, respectively. Chloride was detected in well water at 10 mg L^{-1}.

Data Analysis

Linear regressions were conducted for each irrigation method to relate percolation treatment to herbicide leaching. The proportional values of ET_o in Table 1 were used as a surrogate index for percolation treatment that was the independent factor in regressions. Dependent variables were the average water content of the entire 3-m soil core, the amount of tracer or atrazine recovered per 3-m soil core, and the depth at which the center (50%) of recovered atrazine mass was located in each 3-m core. Location of the center of mass for surface-applied solutes had previously been used to relate amount of water infiltrated from rainfall to solute leaching (Smith et al., 1984). Depth for center of recovered mass was determined as a linear extrapolation between segment means of cumulative mass with depth within each 3-m soil core. Data for both years were combined and the effect for year, when significant, indicated systematic differences between year, otherwise its sums of squares was included in the error term. Effects of treatments on dependent variables were also presented graphically and aided in the interpretation of regressions.

Analysis of covariance (ANOVCOV) was used to measure differences between regressions produced for each irrigation method. Since the location of irrigation methods were not randomized between years, ANOVCOV was used only to indicate potential differences between regression equations and only used when regressions were of the same order. Additional data on soil texture and infiltration rate were used to determine similarity of soil properties between locations of irrigation methods. The ANOVCOV was conducted as a split-plot with irrigation method as the whole plot and levels of ET_o as the split within each irrigation method. Two a priori main effect contrasts were made, one to compare the effect in sprinkler with the average effect in basin and furrow methods, and a second to compare the effects between basin and furrow methods. Analyses were conducted using SAS software and significance reported when $P < 0.05$ (SAS Inst., 1988).

RESULTS AND DISCUSSION

Soil Measurements

The soil was predominantly sandy with values near 90% throughout the 3-m profile. Clay content was 3.4% at the surface but tended to increase with depth until a value of 8.9% was measured at the 3-m depth. The coefficients of variation for sand content calculated at each depth ranged from 1.2 to 5.0%, indicating low variation in soil texture throughout the site. Organic carbon content averaged 0.71% in the surface 0.15-m segment and the value dropped rapidly with depth to very low levels. Organic carbon content of the first 0.15-m soil segment was similar between irrigation methods; average organic C ± SD was 0.80 ± 0.07, 0.67 ± 0.09, and 0.77 ± 0.31% for sprinkler, basin, and furrow methods, respectively. The combination of low organic C content and sandy, unstructured soil should have been conducive to pesticide movement because the soil had a low potential for pesticide adsorption and high hydraulic conductivity (Wagenet and Hutson, 1986). Variation in bulk density also was small with values ranging from 1.5 to 1.68 g cm^{-3}. No significant effects on infiltration rate was measured with respect to location of irrigation methods; rates averaged across all ET_o treated sites and across 2 yr were 0.48, 0.49 and 0.43 cm min^{-1} for location of sprinkler, basin, and furrow methods, respectively.

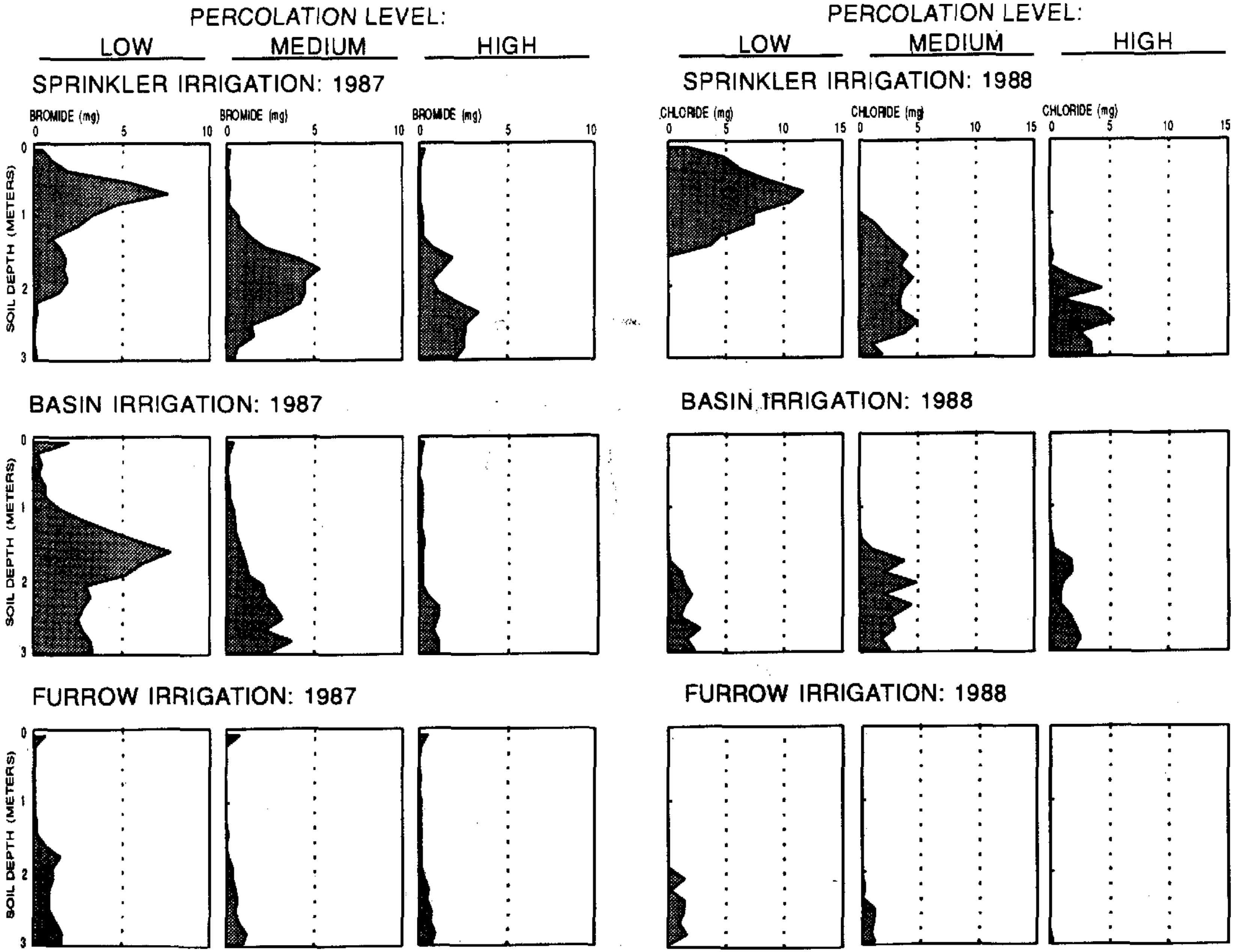

Fig. 1. Soil distribution of inorganic tracers from each percolation and irrigation method treatment and from each year. Values are the average of four cores per treated site and represent milligrams of BR⁻ or Cl⁻ recovered at each sampled depth.

Table 2. mass of inorganic tracer and atrazine recovered for the entire or segmented portions of a 3-m soil core in each irrigation treatment and in each replicate year. Significance level is reported for the linear coefficient for regression of the amount recovered at each treatment replicate on ET_o level.

Response variable	1987 study Percolated water treatment†			1988 Study Percolated water treatment†			Exact α-level for linear term
	Low	Medium	High	Low	Medium	High	
	mg						
Tracer—mass recovered/core†							
Sprinkler	37	36	23	69	47	28	0.02*
Basin	59	25	8	17	31	19	0.16
Furrow	13	6	6	11	7	3	0.01
Atrazine—mass recovered‡							
Sprinkler							
Total	0.31	0.54	0.48	0.40	0.83	1.11	0.03
Above 0.15 m	0.12	0.23	0.05	0.26	0.27	0.09	0.21
Below 0.15 m	0.19	0.31	0.43	0.14	0.56	1.03	0.01
Basin							
Total	0.50	0.34	0.49	1.26	1.03	0.70	0.17*
Above 0.15 m	0.16	0.09	0.03	0.34	0.23	0.05	0.02*
Below 0.15 m	0.34	0.25	0.46	0.92	0.80	0.65	0.56*
Furrow							
Total	0.53	0.31	0.16	1.72	1.51	0.93	0.03*
Above 0.15 m	0.10	0.07	0.01	0.32	0.19	0.06	0.03*
Below 0.15 m	0.43	0.24	0.15	1.40	1.32	0.87	0.04*

* Indicates that the coefficient for year also was significant in regression at 0.05 probability level.

† Refer to Table 2 for exact percentage of ET_o values used for regression analyses.

‡ Values are the average of four cores. Theoretical amount of each solute applied per core was 42 mg for Br^- in 1987, 84 mg for Cl^- in 1988, and 2.25 mg for atrazine in both years.

Tracer Soil Distribution and Soil Water Content

In sprinkler irrigation, soil distribution of inorganic tracer showed that the incremental increases in water application, as indexed by ET_o, were effective in producing different amounts of deep percolating water; tracer soil distribution was visually deeper as water treatments progressed from low to high percolation (Fig. 1). Significant regressions for amount of tracer recovered per core were also measured when ET_o was used as a quantitative index for percolation treatments. Mass of tracer recovered per core linearly decreased with increase in ET_o level which was due to movement below the 3-m depth caused by increased percolation of water (Table 2).

Movement of tracer was visually deeper in the basin method than in the sprinkler method of water application (Fig. 1). The regression for amount recovered per core was not significant which was affected by an aberrant, small estimate for amount recovered at the low percolation treatment in 1988. This may have been an artifact caused by the method used to correct for the presence of background levels of Cl^- or it may have been caused by variation in application of solute to that plot.

The least amount of tracer was recovered in the furrow method which was potentially caused by even greater downward movement than in basin irrigations and/or by lateral movement of water and tracer to drier soil located between furrows. Although recovery was low, residues were detected in the deepest segments even at the lowest percolation treatment and a linear decrease in mass was measured as percolation increased (Table 2). As will be shown, data for atrazine provided evidence to support greater downward flux in the furrow method.

Average water content of the entire 3-m soil core increased as percolation treatments progressed from low to high in all methods of water application (Fig. 2). Since significant linear regressions were measured in all methods, ANOVCOV was conducted to measure similarity of regressions between methods. Only the main effect for percolation treatment was significant indicating that slopes and elevations (mean of all percolation treatments within an irrigation method) were similar between methods: average water content of the entire soil core was increased by about 0.8% with each 0.5% increment in ET_o level.

Atrazine Content and Distribution in Soil

Soil distribution of atrazine differed from that of the inorganic tracers because reactions with soil retarded herbicide movement relative to water (Fig. 1 vs. 3) (Rao and Davidson, 1980). Also, the recovery by depth of a pesticide is confounded by the presence of different rates of dissipation within a soil column. Ou et al. (1988) measured lower rates of aldicarb {α-methyl-α(methylthio)propanol 0-[(methylamino)carbonyl]oxime} degradation deeper in soil where organic C content was low. Decreases in degradation rate with depth have also been reported for atrazine (Lavy et al., 1973). Atrazine mass recovered per core in this study was partitioned into the amount recovered above and below the 0.15-m depth for two reasons: (i) based on the organic C content of soil at this site, lower rates of degradation would have been expected below the 0.15-m depth; and (ii) residues moved below 0.15 m would represent a loss of efficacy because they would be unavailable for herbicidal activity.

In sprinkler irrigation, atrazine residues were moved deeper in the soil profile as amount of percolating water increased (Fig. 3). Significant regression indicated that total amount of atrazine recovered per core increased

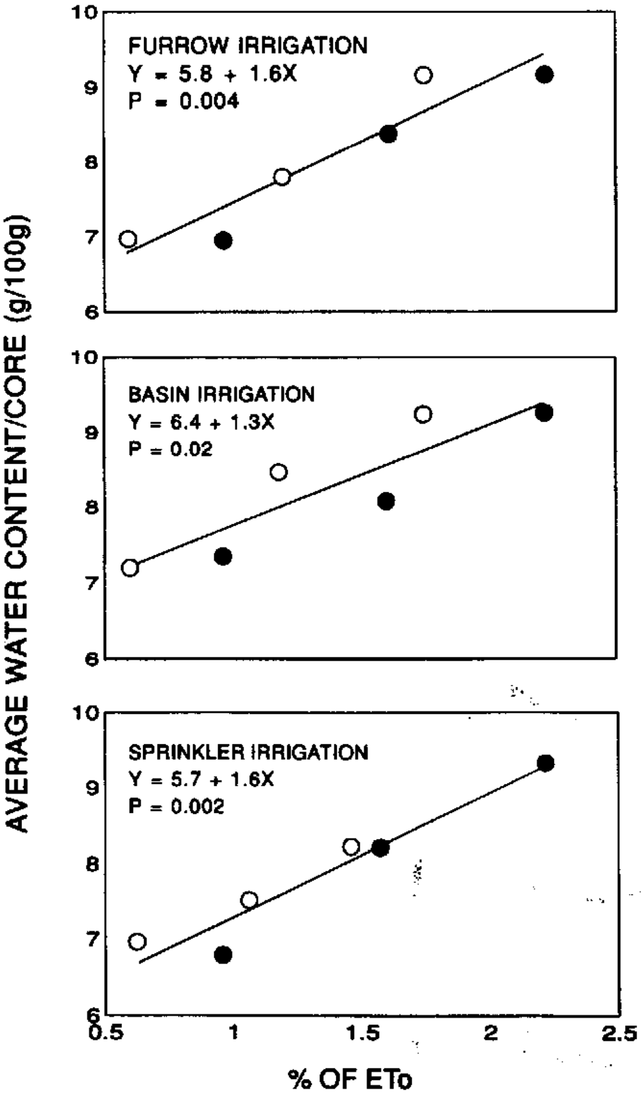

Fig. 2. Relationship between average water content of soil cores and amount of added water as indexed by ET_o values: 1987 data = open circles, 1988 data = filled circles.

with increase in ET_o level that was caused by increases in amount recovered below the 01.5-m depth (Table 2). Thus, conditions that promoted greater leaching also caused an increase in the amount of pesticide recovered per core because residues were moved below 0.15 m into areas of soil where the dissipation rate was slower.

Method of irrigation application affected the soil distribution and recovery of atrazine. Residues at the low percolation treatment were deeper in the soil profile in the basin method than in the sprinkler method, resulting in greater recovery of mass in soil below 0.15 m (Fig. 3 and Table 2). In contrast to sprinkler irrigation, accumulation of atrazine mass below 0.15 m was not measured in response to increased percolation, which could have been due to the large amount of residue moved below 0.15 m at the low percolation treatment and/or to movement of residue below 3.0 m at the high level of percolation (Fig. 3).

Deepest movement of residues occurred in the furrow method as evidenced by the presence of a prominent second peak lower in the soil profile and by the greatest recovery of mass in soil sampled below 0.15 m at the low percolation treatment (Table 2). The amount of atrazine recovered linearly decreased in all portions of the core with increase in percolation, presumably due in part to movement of residues past 3 m.

The effect for year was significant in most regressions with greater mass recovered in 1988. This was most likely related to the shorter time interval between pesticide and irrigation applications in 1988. However, soil distribution of atrazine was similar between years as indicated in analyses of depth to center of recovered mass–greater percolation of water increased the depth to the center of mass in all irrigation methods (Fig. 4). Since the response was linear and in the same direction for all methods, ANOVCOV was conducted to measure the similarity of regression equations. None of the interactions were significant, indicating similar slopes between methods, but contrasts between irrigation methods were significant. Based on the average difference between methods, depth to center of mass increased by about 0.4 m in the basin method when compared to the sprinkler method. Furrow treatments caused an additional 0.65 m increase in depth when compared to the basin method. Estimates for center of mass were probably lower than actual at high percolation treatments due to some residue movement below 3.0 m. However, based on recovery and soil distribution at the low and medium percolation treatments, there would have been little or no effect on the relative differences between methods causing only some underestimation in the slopes between all methods.

Contrasts between methods were constrained by the experimental design because the effects could have been related to differences in location of irrigation methods. Treatment effects, however, had a high probability of being caused by differences in method of water application rather than by site location because: (i) variation in soil properties was low throughout the study area as indicated by low coefficients of variation for soil texture and by similarity of organic C content between sites; and (ii) soil hydraulic properties were very similar between treatment locations as indicated by low variability in infiltration rate between sites.

Simulations using the LEACHM solute movement model provided a physical explanation for differences in water movement between methods of water application (Wagenet and Hutson, 1989). The LEACHM models the movement of water flow and solutes in soil with respect to specific site conditions of soil texture and climatic factors. Results for sprinkler and basin treatments are presented because the model best represented conditions where water was applied to the entire surface area of the plots, minimizing effects of lateral flow. Simulations were run using actual dates and irrigation treatment amounts and using pan evaporation data obtained from the local weather station. The amount of water that infiltrated and that was subsequently available for deep percolation was determined by subtracting the amount of water evaporated from the total applied. That quantity, for the purposes of this discussion, is labelled as "percolated" water in Table 3. Evaporation of water during the treatment period was greater in sprinkler treatments because surface soil was wetter due to more frequent irrigation applications than in the basin method. Greater evaporation resulted in less water available for deep percolation. A

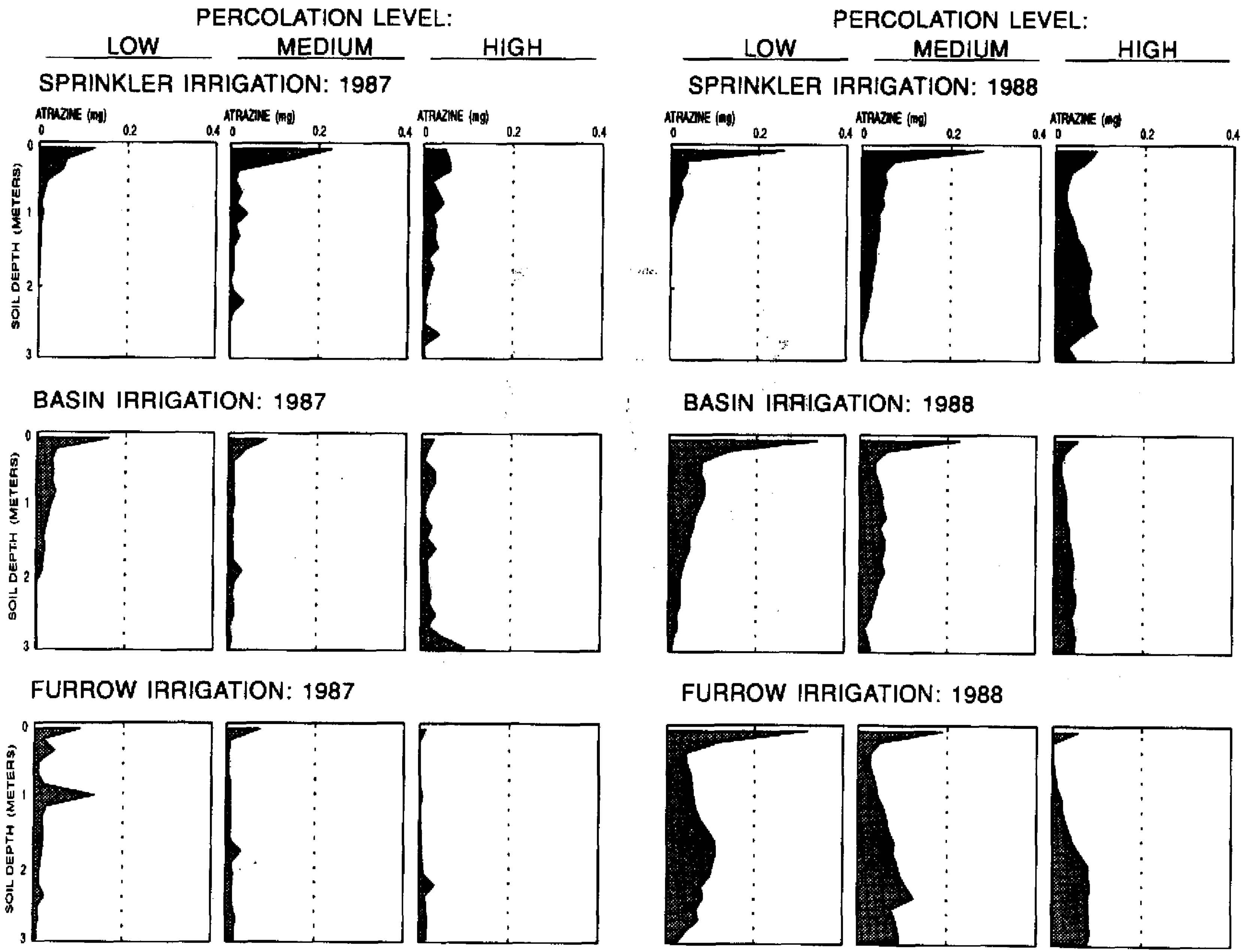

Fig. 3. Soil distribution of atrazine residue from each percolation and irrigation method treatment and from each year. Values are the average of four cores per treated site and represent milligrams of atrazine recovered at each sampled depth.

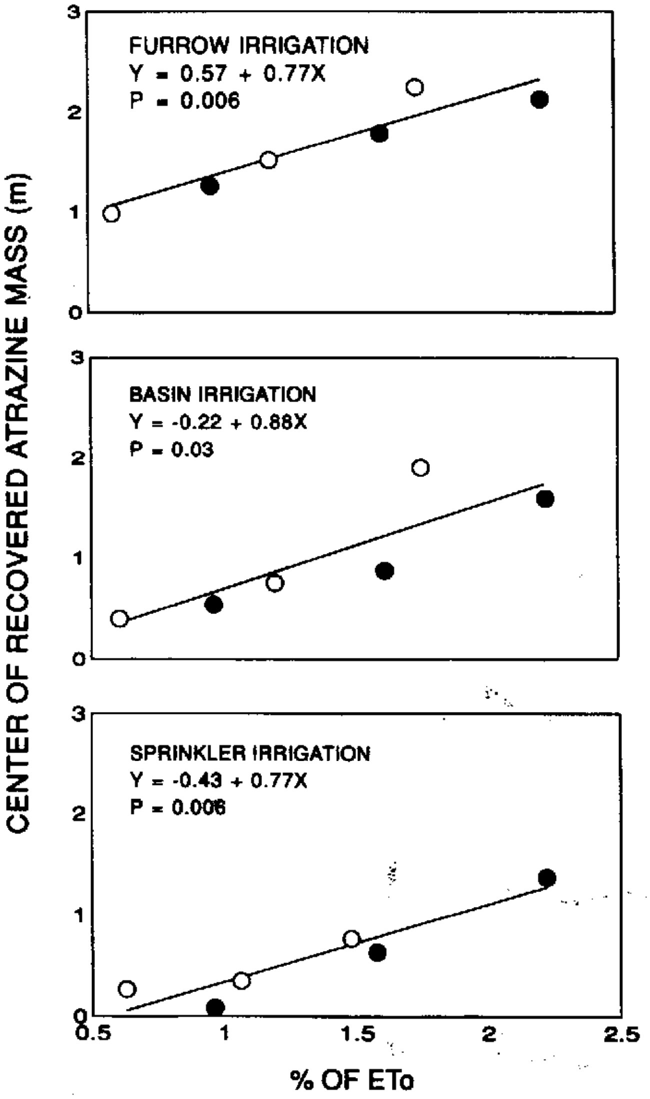

Fig. 4. Relationship between location of the center of recovered mass for atrazine residue and amount of added water as indexed by ET_o values: 1987 data = open circles, 1988 data = filled circles.

significant linear relationship was observed when depth to center of recovered atrazine mass was plotted against percolated water calculated for all sprinkler and basin treatments (Fig. 5). According to the equation in Fig. 5, depth to center of mass increased by approximately 0.4 m for each 100-mm increment of percolated water produced during the treatment period. Differences, between methods of application could then be ascribed solely to differences in the amount of percolated water produced by each treatment.

Downward movement of pre-emergent herbicides has been reported to be less in treatments that provided small rather than large increments of water (Lange and Bendixen, 1981). Also, efficacy of herbicide applications has been shown to be greater when applied in sprinkler-irrigated fields than in furrow irrigated fields (Jordan et al., 1963). Differences in the amount of depth of deep-percolating water caused by each irrigation method and the observed effects on solute movement in this study provide a physical basis for explanation of those results.

Table 3. The LEACHM model results estimating amount of water evaporated from each sprinkler and basin irrigation treatment. Percolated water was calculated as the difference between amount of water added and evaporated.

Method of application and percolated water	Amount of water		
	Added	Evaporated	Percolated
	mm		
Sprinkler, 1987			
Low percolation	216	155	61
Medium percolation	351	168	183
High percolation	485	183	302
Sprinkler, 1988			
Low percolation	227	154	73
Medium percolation	372	155	217
High percolation	518	156	362
Basin, 1987			
Low percolation	201	62	139
Medium percolation	394	75	319
High percolation	569	101	468
Basin, 1988			
Low percolation	227	73	154
Medium percolation	375	73	302
High percolation	522	100	422

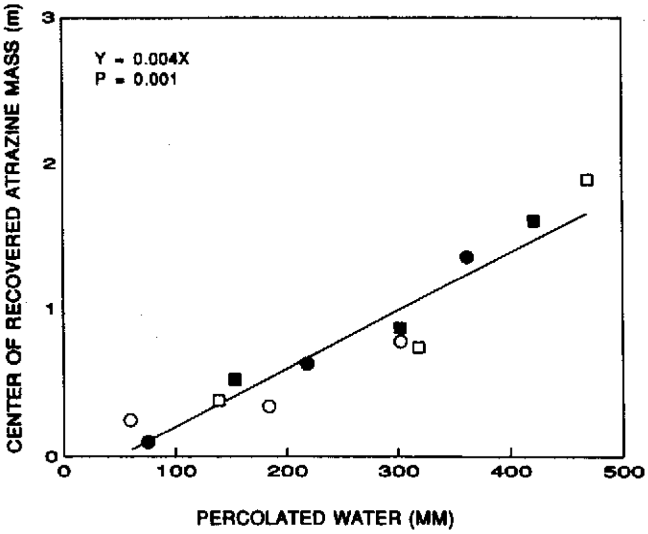

Fig. 5. Relationship between location of the center of recovered mass for atrazine residue and the simulated amount of percolated water produced from sprinkler and basin treatments: sprinkler 1987 = open circles, sprinkler 1988 = filled circles, basin 1987 = open squares, basin 1988 = filled squares.

The overall relationship between atrazine movement and amount of percolated water produced by treatments underscores the importance of retaining water, on a per event basis, in the root zone of crops. In areas vulnerable to leaching, water should be managed to minimize loss of water to deep percolation because not only is water unavailable for crop growth once is moves past roots but because dissipation rates decrease when residues move deeper in the soil profile. Since irrigation is the major source of percolating water in much of California, it should be possible to use water management practices to maintain pesticide residues near the soil surface thereby minimizing the potential for groundwater contamination.

CONCLUSIONS

1. Leaching of atrazine increased in direct relation to increases in the amount of percolating water produced by irrigation. The close association between leaching and amount of deep-percolating water produced by irrigation treatments was expected because leaching occurs through dis-solution of solute in soil solution and, subsequently moves with soil water. These results underscored the importance of using water budgeting techniques to reduce pesticide leaching by decreasing deep percolation. Water management methods that are based on measurements of ET_0 could be used to manage pesticide leaching. The data for sprinkler irrigation illustrated the benefit of this approach: residues at the lowest level of water percolation were confined to the upper layers of soil where residues more readily dissipated.

2. Even through the total amount of water added at each percolation level was similar between irrigation methods, the magnitude of leaching differed between methods with sprinkler < basin < furrow. Downward movement of water and atrazine was least in the sprinkler method where more frequent irrigations maintained a shallower wetting depth. Simulation of the study using the solute transport model LEACHM comparing sprinkler and basin methods indicated that water applied by the sprinkler method was subject to more evaporation than in the basin method. Greatest movement of atrazine was observed in the furrow method where a greater downward flux of water was produced by application of water to only one-half the soil surface area.

Both amount and method of water application are important factors that determine pesticide movement and that, in irrigated agriculture, must be considered as integral components of pesticide management.

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