ATRAZINE LEACHING AND ITS RELATION TO PERCOLATION OF WATER AS INFLUENCED BY THREE RATES AND FOUR METHODS OF IRRIGATION WATER APPLICATION

July, 1990

Environmental Hazards Assessment Program

STATE OF CALIFORNIA
Department of Food and Agriculture
Division of Pest Management, Environmental Protection and Worker Safety
Environmental Monitoring and Pest Management Branch
1220 N Street, Sacramento, California 95814

EH 90-7

ATRAZINE LEACHING AND ITS RELATION TO PERCOLATION OF WATER AS INFLUENCED BY THREE RATES AND FOUR METHODS OF IRRIGATION WATER APPLICATION

By

John Troiano and Cindy Garretson[1]

and

Charles Krauter and Jim Brownell[2]

JULY, 1990

Field Monitoring: Jacob Aniku, Nancy Carr, Chris Collison, Joan Fleck, Cindy Garretson, Raley Naito, Jeff Pickett, John Sitts, Kirsten Winkler, Jesse Ybarra

---

[1] Environmental Hazards Assessment Program, California Department of Food and Agriculture, Sacramento, CA.

[2] California State University, Fresno, CA.

ABSTRACT

Leaching of atrazine and bromide or chloride was related to the amount of deep percolating water produced from irrigations. Atrazine is an herbicide and bromide and chloride are inorganic tracers that are used as surrogates for the measure of water movement in soil. Deep percolating water and subsequent solute movement were compared between four methods of water application: sprinkler, basin, furrow, and drip. In each method, three amounts of water were applied to bare soil which were calculated as 0.75, 1.25, and 1.75 fractions of reference evapotranspiration measurements (ETo). Water applications were based on ETo because the amount of infiltrated water from a treatment could be related to climatic conditions. ETo values were obtained from the California Irrigation Management Information System (CIMIS) weather station located at Fresno, California.

Very little atrazine, bromide or chloride was recovered in soil sampled directly beneath drip emitters, precluding any comparison to the other irrigation methods. In sprinkler, basin, and furrow treatments, increases in the amount of water applied caused an incremental increase in the downward movement of the inorganic tracers, as observed by their soil distribution down to a depth of 3 meters. A corresponding increase in the downward movement of atrazine was also measured in those irrigation methods; a first-order linear relationship was measured between the amount of water added and the location of the center of mass of atrazine residue in the 3-meter soil column. The center of mass was about 0.6 meters deeper with every 0.5 increment in the level of ETo. Although the slope for this relationship was similar between methods, the magnitude of leaching differed between irrigation methods. Location of the center of mass was approximately 0.4 meters deeper in basin than in sprinkler irrigation and about 0.6 meters deeper in furrow than in basin irrigation. Owing to the experimental design, the treatment differences may have been caused by location of the irrigation study sites. However, measurements of soil infiltration rate and soil texture were similar between locations. A more probable explanation for treatment effects was the difference in method of water application. Sprinkler treatments had the shallowest center of mass because irrigations were made frequently with smaller amounts of water added per event compared to basin and furrow irrigations. Thus, more water was subject to loss by evaporation in sprinkler irrigation resulting in less infiltrated water. The deepest center of mass was measured in the furrow irrigation method because water was applied to only 1/2 the soil surface area compared to basin treatments. Consequently, in this sandy soil, furrow irrigation would have caused greater downward flux of water than in basin irrigation. Overall, the measure of ETo as related to the amount of infiltrated and, subsequently, deep percolated water may be a useful criterion for adopting modified uses that limit pesticide movement. However, any recommendation must also take into account differences in irrigation frequency and amount of water applied per irrigation event, which in turn may be influenced by the choice of irrigation method. Since leaching was related to the amount of water available for deep percolation, irrigations should be limited based on the amount of water lost per event to deep percolation.

ACKNOWLEDGEMENT

The efforts of everyone who participated in the study and who gave their advice and encouragement were greatly appreciated. Of particular note were the efforts of Jim Dillard, CSU Fresno Farm Manager, who was instrumental in the selection and development of the study site, and of Greg Jorgenson, who gave much practical advice on the design of the irrigation systems. The reviews of Bruce Johnson, Tom Mischke, Mark Pepple, and Don Weaver were much appreciated as well as the statistical advice of Sally Powell and illustration services of Linda Heath.

Disclaimer

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Pesticide Contamination Prevention Act (PCPA) authorizes the California Department of Food and Agriculture to modify uses of pesticides in areas where they have leached through soil to ground water (Connelly, 1985). Successful development of modified use recommendations requires knowledge of the environmental fate of pesticides applied over the range of agricultural management practices currently used in California. However, the objective of most previous research has been to describe rates of pesticide application that provide the most efficacious control of targeted pests. Fate of the pesticide in the environment is not usually described (Tweedy, 1983).

One route of ground water contamination by agricultural chemicals occurs through recharge of ground water whereby water moves from the surface through the soil profile to a ground water aquifer (Whetje _et_ _al._, 1984; Freeze and Cherry, 1979). Recharge may result from natural rainfall or from anthropogenic additions, such as from irrigation events (Bouwer,1987). Since summertime climatic conditions are hot and dry in most of California's agricultural areas, irrigation is common and necessary in order to attain profitable yields.

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 terms of crop water use, when water moves below the root zone, it becomes unavailable to the crop. Such a condition could be described as overwatering because the addition of water is greater than the amount needed to sustain maximum crop growth.

In an effort to reduce the amount of overwatering that may occur, water budgeting methods have been devised to control the amount of water added per irrigation event. In California, personnel from the University of California, through contracts with 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 daily evapotranspiration to describe how much water a crop requires for growth which eventually determines the amount and frequency of irrigation events that meet these requirements.

Budgeting irrigation water would be also advantageous in mitigating pesticide movement in soil because solute movement occurs as a result of dissolution in deep percolating water (Wagenet and Hutson, 1986). Leaching of nitrate has been related to amount of deep percolating water produced from ponded water treatments that were based on graded levels of evapotranspiration values for a corn crop (Biggar and Nielsen, 1978). With respect to comparisons of leaching between irrigation methods, a theoretical application of the Water Budget Method to different types of irrigation has been developed based on a relative measure of irrigation efficiency between methods (Grant et al., 1986). The utility of this technique for reducing pesticide leaching is unknown because no field data are available that compare pesticide movement in soil under different irrigation methods with water applied at standardized application rates. Some studies have been conducted to compare the effect of irrigation method on crop growth, soil salinity and incidence of root pathogens in soil (Bernstein et al., 1973; Bucks et al., 1974; Feld and Menge, 1990; Muirhead et al., 1989; Zekri and Parsons, 1988).

The objective of this study was to establish a relationship between the leaching of a pesticide and the amount of deep percolating water produced from irrigations. Water application treatments were expressed as a proportion of ETo enabling an assessment of the effectiveness of water budgeting in mitigating solute movement. In addition, the usefulness of ETo to index watering amounts was compared in four irrigation methods: sprinkler, basin, furrow and drip. This study was conducted on bare soil to produce a baseline data set that describes soil and water relationships in the absence of a crop that would subsequently be used to validate solute movement models.

MATERIALS AND METHODS

Study Design

The movement of water and pesticide was measured in relation to incremental increases in addition of water to soil. Water budget methods have been derived to ration amounts of water applied in irrigations according to crop requirements and climatic conditions (Snyder, et al., 1985). In this study, levels of water addition were based on an estimated measure of evapotranspiration with water and chemical movement measured in four methods of irrigation. Comparisons of the patterns of leaching between methods provided an indication of the utility of this approach across irrigation methods.

In order to provide a range in percolating water from irrigation treatments, water was applied at rates based on 0.75, 1.25, and 1.75 reference evapotranspiration (ETo). Data for daily ETo values were acquired from a CIMIS weather station located in Fresno, California (Appendix I). Each level of water application was made in sprinkler, basin-flooding, level furrow, and drip irrigation methods (Jensen, 1983). Level furrow will be denoted as 'furrow' and basin-flooding will be denoted as 'basin' throughout this report. Treatment replication within a year was not possible because of constraints on resources. However, the whole study was replicated in time the next summer. In 1987 ETo levels were based on cumulative data for that year but some values had to be estimated because daily values were not always reported. In 1988, an average value was derived from daily 1983-1986 data and used as the daily estimate for ETo in 1988. Since very little solute was recovered beneath drip emitters in 1987, ETo levels in drip treatments were reduced in 1988 to 0.5, 1.0 and 1.5.

The study was conducted on a field site located in Fresno, California and owned by the California State University System. The soil mapping unit was a Delhi Loamy Sand (Soil Conservation Service, 1971). Atrazine and a conservative inorganic tracer were applied to soil prior to initiation of irrigation treatments. Atrazine was used because it was known to leach to ground water as a result of agricultural applications (Spalding *et al.*, 1980; Wehtje *et al.*, 1984). Bromide was used in 1987 as a conservative tracer to describe water movement (Bowman, 1984). Owing to the number of samples taken, chloride was used in 1988 because chemical analysis was faster. In 1987, soil was sampled twice after about 45 days of accumulated ETo values and in 1988, soil was sampled once after approximately 40 days of accumulated ETo values.

Four soil cores were taken to the 3-meter depth in each plot using a hand-driven bucket auger. Twenty 0.15-meter soil segments were taken in each core. Analyses for atrazine, bromide or chloride, and water content down to 3-meters were conducted on each sample. Soil texture and organic matter content were determined on one core per plot. Neither atrazine at a minimum detection limit (MDL) of 2 parts per billion (ppb) nor bromide at an MDL of 400 ppb were detected in background samples taken at the site. Chloride was detected in background soil samples at a maximum concentration of 4 ppm.

Application of Bromide, Chloride and Atrazine

Dates for atrazine, bromide and chloride applications to each plot, subsequent soil coring, and the amount of water used to water-in the chemicals are given in Table 1. For each plot, 44 grams of Aatrex® 80 with 37.6 g atrazine as active ingredient and either 1047 grams of potassium bromide (703 g bromide) in 1987 or 2200 grams calcium chloride (1408 g chloride) in 1988 were dissolved together in 2.7 liters of de-ionized water which was then broadcast over the soil surface with a backpack sprayer. The sprayer was equipped with a boom containing 4 Teejet® nozzles (model #8002LP) spaced 48.3 cm apart. The solution was applied at 138 x 10^3pascals (20 PSI) at a walking velocity of 0.95 meters/second (2 mph). This corresponded to a rate of application of 4.5 kg/hectare (4 lbs/acre) active ingredient for atrazine, 84 kg/hectare (75 lbs/acre) for bromide and 168 kg/hectare (150 lbs/acre) active ingredient for chloride. The chemicals in each treatment were watered-in on the same day of application with sprinkler irrigation. Watering-in with a small sprinkler irrigation or rain event is usually recommended on the label to set pre-emergence herbicides into soil (Table 1). Rates of application were measured in 1987 by collecting spray on plastic-coated aluminum foil. However, the recoveries were very low so the data were determined unreliable. In 1988, application rates were measured by burying 0.24 l glass Mason® jars containing 100 g of dry soil into soil so that the lip of the jar was flush with the soil surface. The average measured rates of application were 3.84 Kg/ha for atrazine and 110 Kg/ha for chloride. Both were lower than their intended rates which may have been partially due to application to the sides of the plots causing application to a larger area than intended.

Table 1. Bromide and atrazine treatment dates, amounts of water used to water-in solutes and irrigate plots, and subsequent soil sampling dates.

Treatment	Date of Tracer and Atrazine Application		Amount of Water Applied in		Week of Soil Coring	
	M/day	Julian	Watering-in Events	Irrigation Events	M/day	Julian
			------------cm-------------			
Study Conducted in 1987						
Sprinkler						
0.75 ETo	6/16	167	1.5	20	7/27	208
1.25	6/16	167	1.3	34	7/27	208
1.75	6/15	166	1.5	47	7/27	208
Basin						
0.75	6/11	162	1.3	19	7/27	208
1.25	6/11	162	1.8	38	7/27	208
1.75	6/12	163	1.5	56	7/27	208
Furrow						
0.75	6/11	162	1.7	19	7/27	208
1.25	6/11	162	1.9	38	7/27	208
1.75	6/12	163	1.8	56	7/27	208
Drip						
0.75	6/15	166	1.7	20	7/27	208
1.25	6/12	163	2.1	34	7/27	208
1.75	6/12	163	2.4	47	7/27	208
Study Conducted in 1988						
Sprinkler						
0.75 ETo	5/16	137	0.9	22	6/20	171
1.25	5/16	137	0.9	36	6/20	171
1.75	5/16	137	0.9	51	6/20	171
Basin						
0.75	6/5	157	0.9	22	6/20	171
1.25	5/29	150	0.9	37	6/20	171
1.75	5/22	143	0.9	51	6/20	171
Furrow						
0.75	6/5	157	0.9	22	6/20	171
1.25	5/29	150	0.9	37	6/20	171
1.75	5/22	143	0.9	51	6/20	171
Drip						
0.50	5/16	137	0.9	15	6/20	171
1.00	5/16	137	0.9	29	6/20	171
1.50	5/16	137	0.9	44	6/20	171

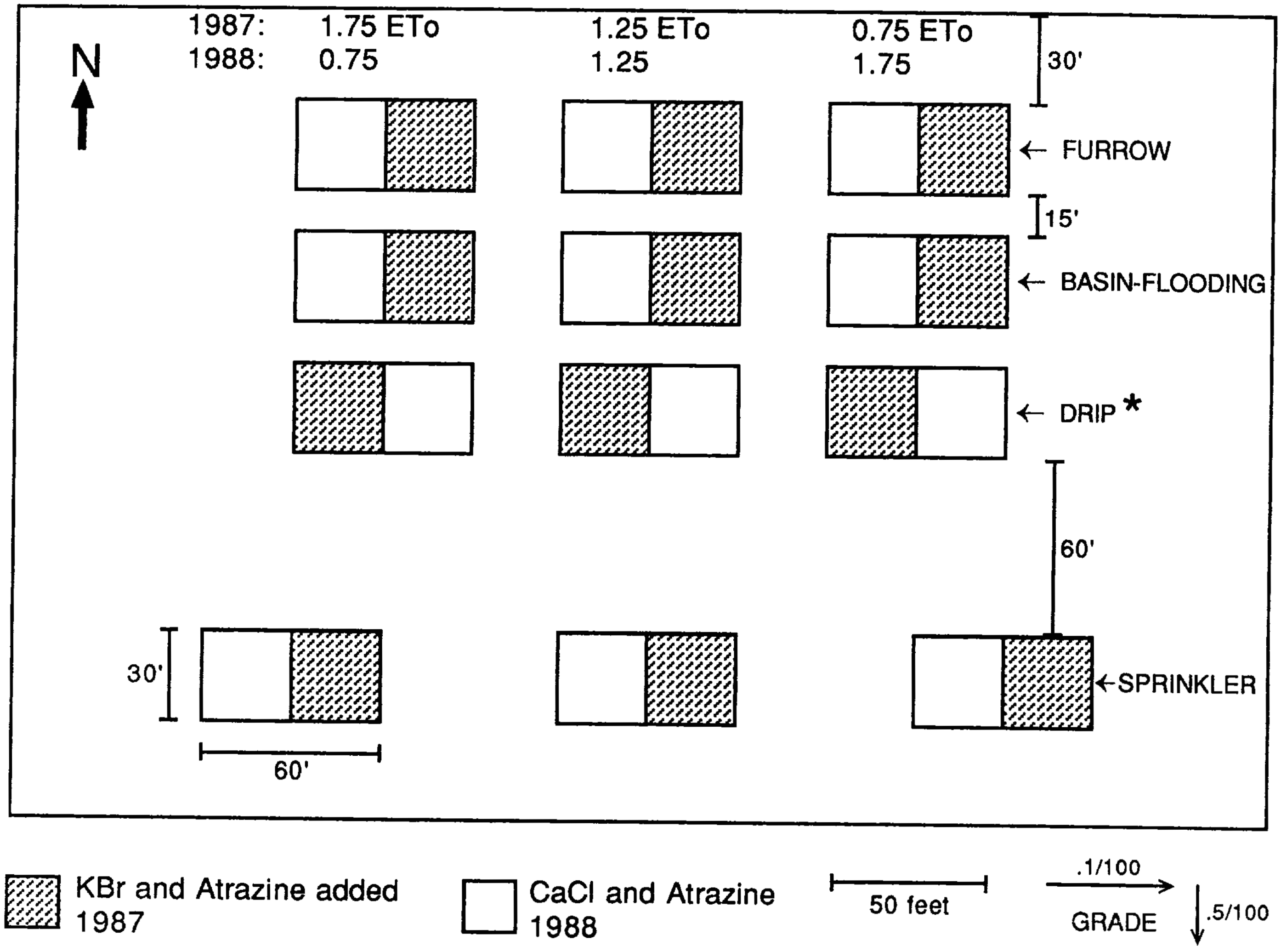
Application of Irrigation Treatments

Basin and Furrow Treatments

Basin and furrow irrigations are usually infrequent with large amounts of water applied per event compared to sprinkler and drip irrigation. Plot size, soil, and pumping conditions at the site were factored into the initial estimate of the amount of water delivered to each plot in each irrigation event. Each irrigated site was 9.14 x 18.28 meters (30 by 60 feet) of which one-half, a 9.14 x 9.14 meter square plot, was used for the 1987 study (Figure 1). The other square plot was used in the 1988 replication of the study. The infiltration rate of the soil was measured prior to the study in December, 1985, with a single-ring cylinder infiltrometer (Haise _et_ _al._, 1956). The measurements were replicated in December, 1989, and the combined data set was used to test for potential differences in soil between locations of the irrigation methods. The estimates taken in 1985 were used in design of the irrigation treatments.

Since the soil had a fast infiltration rate, large amounts of water could be applied without flooding over berms or furrow ridges. The pumping rate from the well was approximately 428 l/hr (113 gal/hr). Through experimentation, it was determined that at full pumping capacity 15 minutes was required to disperse the water over a 9.14 x 9.14 meter plot. In order to adequately test the dynamics between furrow and basin irrigations, each irrigation was scheduled to last at least twice as long as the amount of time needed to flood the plot. Daily ETo values were accumulated until the water requirement for the plot was approximately 15,000 liters. A few irrigations were made at

Figure 1. Location of irrigation sites for 1987 and 1988.



* ETo levels were .5, 1.0, and 1.5 in 1988

smaller amounts in order to fulfill the ETo treatment requirements. In accordance with these parameters, the frequency of large water applications was: one at the 0.75 ETo rate of water application, two at the 1.25 ETo rate and three at the 1.75 ETo rate. The amount of water applied in each soil coring interval is given in Table 1 and the schedule for individual events is given in Appendix I.

The water application system in basin irrigation plots was insufficient to evenly flood the entire surface area, so each plot was then divided into 9 subplots with water applied to 3 subplots at a time. Irrigation of all 9 subplots occurred in less than 1 hour. Water application in the furrow method was made to level furrows on 1.02 m (40-inch) centers with 9 furrows per plot each with a run length of 9.14 meters.

Sprinkler and Drip Treatments

Compared to basin and furrow irrigation, application of water in sprinkler and drip treatments were made more frequently with less water applied per irrigation. Sprinkler and drip applications were made weekly with duration of irrigations adjusted to attain the specified level of ETo.

For the sprinkler method, irrigations were made one day a week with daily durations varying around 4, 6 and 8 hours for the 0.75, 1.25, and 1.75 ETo treatments, respectively (Appendix I). Water was applied through 4 Rainbird sprinklers, rotating 360° with an application rate of 15 liters/minute. The radius of the wetted circle from one sprinkler was 9.14 meters so when sprinklers were situated on the 4 corners of the plot, the rate of water application was effectively equal to a full circle from one of the sprinklers. Sprinkler irrigation distribution uniformity, measured with catch cans, averaged approximately 80% and the rate of water application to plots averaged 1.09 cm/hr which was close to the calculated value of 1.08 cm/hr. Problems were encountered in 1987 with the sand filter on the well pumping system during the first week of irrigation, so initial treatments in sprinkler had to be made over a three day period (Appendix I).

In 1987, drip irrigations were made 5 days per week with daily durations varying around 2, 3 and 4 hours for the 0.75, 1.25 and 1.75 ETo treatments, respectively. In 1988, drip irrigations were made twice weekly but with continuous runs of approximately 3 hours, 6 hours and 9 hours for the 0.5, 1.0 and 1.5 ETo treatments, respectively. ETo values were lowered in 1988 because no chemicals were recovered from beneath the emitters in 1987. Water application in the drip method was made through emitters located in a 1-meter square grid spaced throughout the entire plot for a total of 90 emitters. At the spacing used, the entire area of the plot was wetted due to lateral flow of water; wet soil was encountered in the area between the emitters at about 0.15 meters below the surface of the soil. Therefore, the amount of water added to fulfill accumulated ETo values was based on the surface area of the plot. Based on the theoretical flow rate of 3.8 liters/hour from each emitter, the entire plot received 341 liters/hour. Distribution uniformity, measured from collections made from individual emitters, averaged 90% and the actual flow rate measured from emitters was 3.7 liters/hour. The amount of water applied in each soil coring interval is given in Table 1 and the schedule for individual events is given in Appendix I.

Soil Sampling and Analyses

Four 3-meter soil cores were sampled from each plot. Cores in each plot were spaced 3.2 meters apart and they were located on a southeast-northwest diagonal. In furrow plots, cores were taken from the middle of the furrow and in drip plots cores were taken directly beneath the emitter.

Soil samples were taken with a 7.94-cm (3-1/8 inches) inner-diameter bucket auger. In a previous study, some contamination of samples was found to occur with this method due to surface soil that had fallen down the borehole (Troiano, 1987). To reduce this source of contamination, a cylindrical PVC plastic sleeve, 30.5 cm in length with an inner diameter of 10.2 cm, was driven into the soil prior to sampling. The first 0.15 meter sample was taken through the sleeve and the entire sample collected in a plastic bag. Excess soil from inside the sleeve was then manually removed down to the 0.15 meter depth using a clean plastic glove. The auger was then cleaned in soapy water, rinsed with well water, then de-ionized 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 before placement into plastic bags.

Immediately after collection from the borehole, each soil sample was thoroughly mixed by tumbling in a large plastic bag. Three aliquots were taken from the bag: one was placed into a 0.45-liter (1 pint) glass jar for atrazine analysis; one was placed into a plastic bag for soil texture, organic matter and bromide or chloride analyses; and one was placed into a tared 0.23-liter glass jar for gravimetric analysis of water content. The sample taken for atrazine analysis was immediately frozen on dry ice and kept at -4° C until submission to the contracted laboratory. Soil in the plastic bag was air-dried prior to soil texture, bromide and chloride analyses. 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 (Rauschkolb, 1980). Soil texture and organic matter were conducted on one core per plot and data are given in Appendix II. Water content was determined gravimetrically by drying the soil samples at 105-110° C for 24 hours (Millar _et al._, 1965). The contracted laboratory also determined water content of samples. An initial comparison indicated that water values determined by the contracted laboratory were close to those determined from the 0.23 liter jar samples so water content values from the laboratory were accepted and used in data analysis. Raw data for gravimetric determination of water content in each sample are given in Appendix III. No detectable levels of atrazine or bromide were measured in the well water at minimum detectable limits (MDL's) of 0.06 and 100 ppb, respectively. Chloride was detected in well water at 10 ppm.

Bromide concentrations in soil were analyzed with a specific ion electrode using the method suggested by the manufacturer (Orion, 1982). A twenty-five gram sample of air-dried soil was weighed into a 125 ml Erlenmeyer flask to which 50 ml of 0.1 M ISA solution was added. The flask was covered with parafilm and shaken for 30 minutes at 2500 rpm. Solution was filtered through

#40 Whatman filter paper into 50 ml flasks where electrode readings were made. The meter was calibrated on a daily basis and temperature was recorded.

Chloride in soil was analyzed with a chloridometer and using a procedure suggested by the manufacturer (Haake Buchler Instruments, Inc, 244 Saddlebrook Rd., Saddlebrook, N.J.). A twenty-five gram sample was mixed with twenty-five ml of water and shaken for 30 minutes at 2500 RPM. The solution was filtered through #40 Whatman filter paper and then measured on the chloridometer. Methods and raw data for inorganic tracer concentration in each sample are given in Appendix IV.

Pesticide Analyses and Quality Control

Analyses for atrazine were conducted by APPL laboratory, Fresno, California. The extraction and detection method is given in Appendix V as well as results for quality control and dissipation studies. A standard amount of terbuthylazine (TBZ) was added to each sample before extraction as a surrogate compound to provide a correction for matrix effects and instrument variation. Raw data for atrazine and TBZ content in each sample are given in Appendix III.

Quality control samples were included to measure analytical error resulting from:

1. Analytical methodology. Method percent recovery was determined by measuring the recovery of atrazine in background soil samples spiked at 15, 150 and 1500 ppb in at least 10 replicate samples at each level. This procedure

was repeated three times. Recovery was determined on blind submitted samples spiked at 10, 50 and 100 ppb and duplicate extractions were conducted on 10 samples to determine variation in the extraction procedure.

2. Matrix effects. One matrix blank sample was analyzed per sample extraction set. One set of duplicate matrix spike samples was analyzed per sample extraction set.

3. Reagent effects. One reagent blank was analyzed per sample extraction set to measure any possible interference.

4. GC precision. Three injections were made from the same extract on 19 different samples.

5. Storage dissipation. Clean soil samples were spiked at 100 ppb then frozen along with the soil samples obtained from the field sampling. Three samples were analyzed immediately. Subsequently, three samples were submitted with each of the first 5 sets of 80 samples that were submitted to the laboratory.

Quality control procedures for bromide and chloride analyses included a daily check of a matrix spike sample, a duplicate sample included in every set of samples and a standard sample read after every 10th sample (Appendix III).

Data Analysis

The objectives of the study were: 1) to determine if the amount of deep percolating water produced by irrigations could be related to leaching of a pesticide and 2) to determine the similarity of patterns in soil distribution of solutes between irrigation methods. For objective 1, increases in the amount of deep percolation was produced by adding water at 3 rates that were proportional to measured values of ETo in increments of 0.5 units. Regression analyses were then conducted for each irrigation method to determine significant relationships between dependent variables and the ETo level. For objective 2, analysis of covariance (ANOVCOV) was used to measure differences between regressions produced by each method. The ANOVCOV was conducted as a split-plot with irrigation method as the whole plot, levels of ETo as the split within irrigation method, and treatments replicated over years (Figure 1). Significant interaction in the ANOVCOV indicated differences in slopes between methods, and significant main effects in the absence of interaction indicated parallel regression lines with only differences in elevation. *A priori* contrasts were made: 1) to compare the effects between sprinkler and basin irrigations where water was applied to the entire surface area of the plot but the pattern of water application with respect to frequencies and amount differed (SvB), 2) to compare the effects between basin and furrow irrigation where the frequency and amount applied per application were similar but water was applied to only 1/2 the plot area in furrows (BvF), and 3) to compare the effects between furrow and drip irrigation where water in both methods was applied to only a portion the plot but the pattern of water application with respect to frequency and amounts differed (FvD). Analyses were conducted using SAS software (SAS Institute Inc., 1988).

Dependent variables were the average water content of each soil core, the amount of bromide or atrazine recovered per 3-meter soil core, and the location of the center of mass recovered in the 3-meter core. These depths were determined as a linear extrapolation between segment means of cumulative mass with depth. Effects of treatments on dependent variables were also presented graphically.

In order to determine the amount of bromide, chloride and atrazine recovered per core, concentration values in each 0.15 meter segment were converted to mass recovered per segment according to the following equations:

Bromide and Chloride

Eq. 1: $\text{mg Bromide} = \text{ppm Bromide or Chloride} \times 742\ \text{cc} \times 1.55\ \text{g/cc} \times 10^{-3}\ \text{mg}/\mu\text{g}$

where 742 cc was the volume of the 0.15 m sample and 1.55 g/cc was the average bulk density of the soil which had previously been determined (Troiano, 1987). Bromide was not detected in background samples but chloride was detected in 2 background cores at an average concentration of 3.1 ppm so values were corrected by subtracting 3.1 ppm from each segment mean (Appendix IV).

Atrazine

Eq. 2:

$$\text{mg Atrazine} = ((\text{ppb Atrazine} / \%\text{TBZ} * 0.01) \times (1 + \text{Water Content})) \times 742\ \text{cc} \times 1.55\ \text{g/cc} \times 10^{-6}\ \text{mg/ng} \times 1.176$$

Atrazine values were first corrected by the TBZ standard surrogate compound added to each sample. Since atrazine analyses were conducted on fresh mass, values were corrected for water content. A correction factor of 1.176 was used to adjust for an average of 85% method recovery measured in QC samples.

One datum from a surface 0-0.15 meter segment in the 0.75 ETo sprinkler treatment was missing. Since atrazine values in this segment were high and estimates could bias the results, this core was omitted from mass balance calculations. One other datum was missing from the 2.29-2.44 segment in the 0.75 ETo furrow treatment. Values at this depth in that core were much less than at the surface so an estimated value would have less effect on mass balance calculations. An estimated value was calculated as the mean of the preceding and subsequent values in that core. Lastly, the solute distribution of core 2 in the 1.25 ETo sprinkler treatment in 1987 was dissimilar compared to the other 3 replicate cores in the plot so this data was not used in mass balance calculations.

RESULTS AND DISCUSSION

All raw data for this study is available in a separate appendix available upon request to the Environmental Monitoring Branch of CDFA.

Summary of Quality Control and Dissipation Data

Results of the quality control data indicated that methodology for atrazine soil analysis was acceptable. The method recovery was 92.3%±19.3% at 15 ppb, 79.7%±9.8% at 150 ppb and 82.3%±15.2% at 1500 ppb 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 ppb 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 for the storage dissipation study indicated that atrazine did not degrade under storage conditions used in the study.

Soil samples were analyzed for bromide and chloride after acceptable method development of bromide and chloride assays. Since quality control samples were run simultaneously with each analytical set, data were accepted or samples reanalyzed based on the quality control results.

Site Description

The soil was predominantly sandy with values near 90% throughout the profile (Table 2). Clay content was low at the surface, at 3.4%, but tended to increase with depth until a value of 8.9% was measured at the 3 meter depth.

Table 2. Average sand, silt, clay and organic carbon content of soil measured at each sampled depth.

Depth (Meters)	Soil Texture Sand (%)	Silt (%)	Clay (%)	Organic Carbon (%)
0.08	88.6±4.3[a]	8.1±3.8	3.4±1.3	0.71±0.19
0.23	90.7±2.6	5.6±2.0	3.7±1.3	0.25±0.16
0.38	90.0±1.4	5.5±1.4	4.5±0.9	0.10±0
0.53	90.3±1.4	4.3±1.2	5.4±1.1	0.10±0
0.69	90.1±2.0	4.3±1.5	5.5±1.6	0.07±0.05
0.84	90.3±1.9	4.5±1.2	5.2±1.7	0.01±0.03
0.99	90.0±1.8	4.1±1.4	5.9±1.2	0.06±0.05
1.14	89.7±1.1	4.7±0.8	5.7±1.0	0.05±0.05
1.30	90.3±1.7	4.4±0.7	5.3±1.6	0.03±0.05
1.45	89.7±1.4	4.8±1.2	5.6±1.4	0.02±0.04
1.60	89.7±1.2	4.8±1.4	5.5±1.8	0.03±0.05
1.75	89.2±2.0	4.6±0.9	6.2±2.1	0.03±0.05
1.91	88.1±3.0	5.0±1.3	6.9±3.1	0.02±0.04
2.06	89.4±1.9	4.8±1.1	5.9±1.6	0.01±0.03
2.21	87.1±4.3	5.6±1.8	7.4±3.3	0±0
2.36	88.2±4.0	4.8±1.4	6.9±3.4	0±0
2.51	88.1±4.0	6.1±2.1	5.9±3.0	0±0
2.67	87.2±2.4	6.0±2.0	6.9±2.6	0±0
2.82	86.5±4.0	6.5±1.9	7.0±2.9	0.01±0.029
2.97	84.3±4.2	6.8±1.9	8.9±3.1	0±0

[a] Value is the mean ± standard deviation of 12 cores.

These changes were apparent during soil coring where a change in texture was noted in the deepest segments in all cores. The coefficients of variation for sand content calculated at each depth ranged from 1.2 to 5.0%, indicating low amount of variation in soil texture throughout the site. Organic carbon content averaged 0.71% in the surface 0.15 meter segment and the value dropped rapidly with depth to very low levels (Table 2). Organic carbon content was similar between locations of the four irrigation methods; average percent organic carbon±standard deviation was 0.8±0.07, 0.67±0.09, 0.77±0.31 and 0.6±0.1 for sprinkler, basin, furrow and drip methods, respectively. The combination of low organic carbon content and sandy soil should have been conducive to pesticide movement because the soil had a low potential for pesticide adsorption and high hydraulic conductivity (Leistra, 1986; Nielson _et al._, 1986; Wagenet and Hutson, 1986;)

Infiltration data were analyzed by ANOVA to measure potential differences in soil infiltration rate between the locations where irrigation methods were situated (Tables 3 and 4). Year was considered a blocking factor. Only the effect of year was significant with mean values of 0.33 and 0.65 cm/min for 1985 and 1989, respectively. Differences in years may have been related to differences in soil moisture because soil appeared drier when sampled in 1989. The sums of squares for the location of irrigation methods (rows) and ETo treatments (columns) was small, indicating similar soil hydraulic properties throughout the experimental site.

Table 3. Average infiltration rate of soil measured in each treatment site.

Location of Irrigation Methods (Rows)	Location of ETo Treatments (Columns)						Row Average
	Western Side		Middle		Eastern Side		
	1985	1989	1985	1989	1985	1989	
	cm/min						
Sprinkler	-[a]	0.43[b]	0.31	0.88	0.22	0.58	0.48
Basin	0.31	0.78	0.27	0.67	0.23	0.62	0.49
Furrow	0.68	0.71	0.38	0.62	0.38	0.71	0.54
Drip	0.28	0.43	0.24	0.76	0.32	0.88	0.47
Column Average	0.49		0.52		0.48		

---

[a] No sample.

[b] Value is the mean of 3 replicate measurements made per plot.

Table 4. Analysis of variance for the effect of potential differences in the infiltration rate of soil between locations of main effect treatment sites.

Source of Variation	Degrees of Freedom	Sums of Squares[a]	Mean Square	Significance Level
Year	1	1.8232	1.8232	0.001
Irrigation Methods (Rows)	3	0.0618	0.0206	0.77
ETo Treatments (Columns)	2	0.0497	0.0249	0.69
Rows x Columns	6	0.4178	0.0696	0.53
Error 1 (Rows x Columns (Year))	10	0.8017	0.0802	
Year x Row	3	0.3414	0.1138	0.001
Year x Column	2	0.2514	0.1257	0.001
Year x Row x Column	5	0.2088	0.0418	0.001
Error 2 (subsamples)	47	0.2636	0.0056	

---

[a] Type III Sums of Squares used because of one cell with missing data.

Treatment Effects on Soil Water Content and Tracer Soil Distribution

Regression analysis for each method of water application indicated that the average water content of the entire 3-meter soil core increased as a first-order linear-polynomial function (linear) of the amount of added water (ETo) (Tables 5 and 6). Water contents of treatments were similar between years for sprinkler, basin, and furrow methods, as indicated by the non-significant effect of years. Differences between years in the drip method may have resulted from the change in treatment levels between years.

Owing to the similar linear response measured between irrigation methods, ANOVCOV was conducted to determine similarity of slopes between methods. Only the interaction of the linear response to added water with the furrow versus drip contrast was significant at $P<0.10$, indicating a tendency for different slopes between these methods (Table 7). Based on percent moisture values, this effect was due to higher values at the 0.75 ETo drip treatment causing a shallower slope (Table 6). Values for drip treatments were consistently higher than the rest of the treatments causing a significant contrast between furrow and drip methods (Table 5). None of the other interactions or main effects were significant, indicating that the slopes were similar between sprinkler, basin and furrow methods. The average soil moisture of the entire 3-meter core increased by approximately 1% with each increase of 0.5 units in ETo level (Table 6).

Table 5. Average water content of the 3 meter soil core measured in each treatment.

	Soil Moisture Content at ETo Treatments of						Overall Average
	0.75		1.25		1.75		
Irrigation Method	1987	1988	1987	1988	1987	1988	
	g/100g						
Sprinkler	6.9	6.8[a]	7.5	8.2	8.2	9.3	7.8
Basin	7.2	7.3	8.5	8.1	9.2	9.3	8.3
Furrow	7.0	7.0	7.8	8.4	9.2	9.2	8.1
Drip[b]	8.7	8.3	9.4	8.7	10.3	9.8	9.2

[a] Value is the mean of 4 replicate soil cores taken per plot.

[b] Levels of ETo for drip irrigation were 0.5, 1.0, and 1.5 in 1988.

Table 6. Regression analysis of variance by irrigation method for the effect of ETo level on the average water content of the entire 3.0-meter soil core. Sums of squares for years and quadratic lack-of-fit were pooled into error when nonsignificant. Estimates of the parameters ± standard error for each regression are given by method. Year coded as 0 or 1 in the regression analysis.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Sprinkler Method			
Amount of Water-Linear	1	3.5910	0.016
Error	4	0.2197	
Regression: % Moisture = (5.44±0.62) + (1.90±0.47)*ETo Level			
Basin Method			
Amount of Water-Linear	1	3.8416	0.001
Error	4	0.0212	
Regression: % Moisture = (5.82±0.19) + (1.96±0.15)*ETo Level			
Furrow Method			
Amount of Water-Linear	1	4.9284	0.001
Error	4	0.0410	
Regression: % Moisture = (5.31±0.27) + (2.22±0.20)*ETo Level			
Drip Method			
Year	1	0.3889	0.029
Amount of Water-Linear	1	2.3770	0.002
Error	3	0.0252	
Regression: % Moisture = (7.00±0.21) + (1.54±0.16)*ETo Level + (0.51±13)*Year			

Table 7. Split-plot analysis of covariance testing equality of slopes (interaction terms) and elevation of lines (main effects) for regression of percent moisture content of soil on ETo level within each irrigation method. Tests of the contrast for years and quadratic lack-of-fit were nonsignificant so the sums of squares were pooled into respective error terms.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Whole Plot Analysis			
Irrigation Method	3		
Sprinkler vs Basin (SvB)	1	0.6348	0.17
Basin vs Furrow (BvF)	1	0.1042	0.53
Furrow vs Drip (FvD)	1	3.6223	0.016
Whole Plot Error	4	0.2241	
Split-Plot Analysis			
Amount of Added Water-Linear (EToL)	1	14.4837	0.001
Irrigation Method x EToL	6		
SvB x EToL	1	0.0023	0.85
BvF x EToL	1	0.0328	0.47
FvD x EToL	1	0.2278	0.07
Split-Plot Error	12	0.0581	

In sprinkler irrigation, the soil distribution of bromide and chloride showed an increase in downward movement of tracer with respect to increases in the amount of added water in both years (Figures 2 and 3). The amount of tracer recovered per core linearly decreased with increases in the amount of added water indicating movement below the 3-meter depth at the 1.25 ETo treatment (Tables 8 and 9). Deeper movement of inorganic tracers was indicated in basin irrigation than in sprinkler irrigation for each level of added water. This effect was clearly illustrated in the data for bromide in 1987. The recovery of chloride at the 0.75 ETo basin treatment in 1988 appeared low which may have been due to variation in application of solutes to that plot (Cameron *et al.*, 1979). A significant linear relationship between the amount of tracer recovered and the amount of water added was measured when this datum was excluded from the analysis.

The total amount of tracer recovered in furrow irrigation treatments was lower than in sprinkler and basin methods which was partially caused by even greater downward movement than in basin irrigations (Figures 2 and 3). It was possible that water and tracer may have moved laterally to drier soil located between the berms. Although the amount of tracer recovered was low, a linear decrease in mass was again measured as the amount of added water increased, an effect similar to that observed in sprinkler and basin irrigations where downward movement of water increased with each increment in ETo.

FIGURE 2. Soil distribution of bromide applied in 1987 and recovered in 3-meter soil cores sampled in sprinkler, basin and furrow irrigations. Data are the average of four cores.

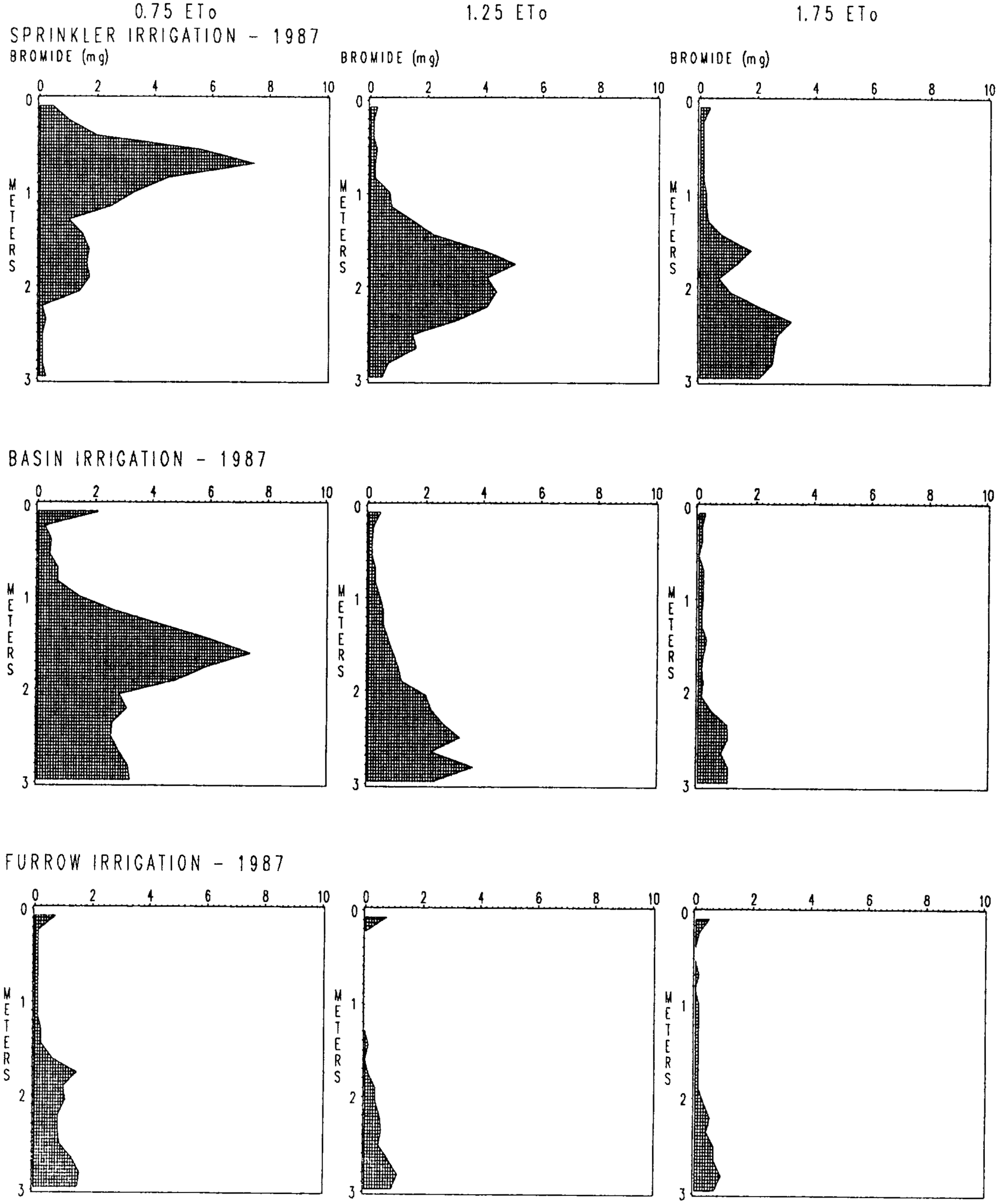


FIGURE 3. Soil distribution of chloride applied in 1988 and recovered in 3–meter soil cores sampled in sprinkler, basin and furrow irrigations. Data are the average of four cores.

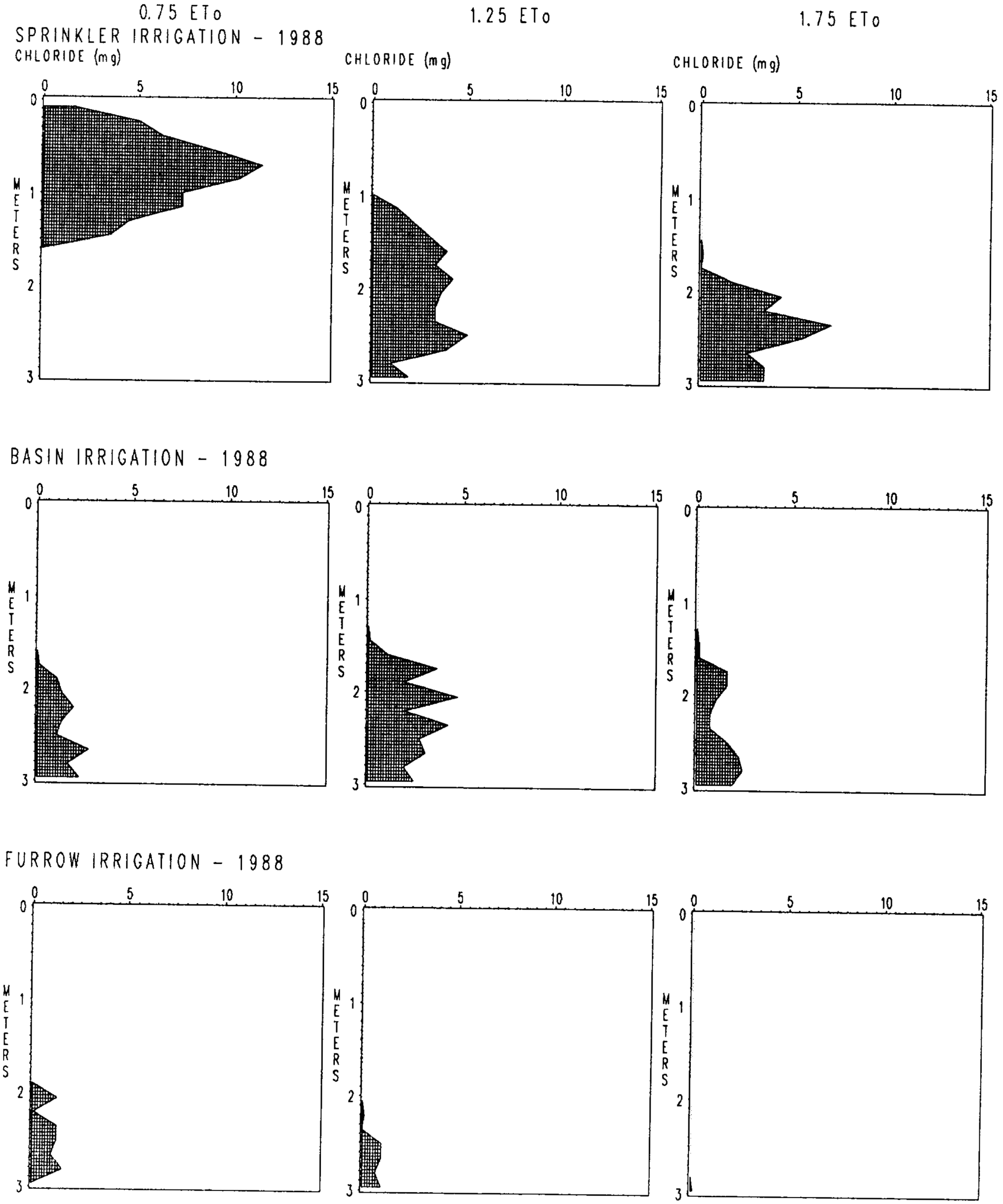


Table 8. Amount of bromide or chloride recovered per 3-meter soil core in each treatment.

Irrigation Method	Amount of Inorganic Tracer Recovered at ETo Levels: 0.75	1.25	1.75
	----------	mg	----------
Bromide Recovered in 1987			
Sprinkler	36.7	34.9	22.4
Basin	57.2	24.7	7.5
Furrow	13.2	6.1	5.6
Drip	3.7	4.0	4.4
Chloride Recovered in 1988			
Sprinkler	66.1	40.2	22.8
Basin	13.3	27.8	14.3
Furrow	5.2	3.9	0.2
Drip[b]	0	0	4.9

---

[a] Value is the mean of 4 soil cores taken per plot.

[b] ETo values in 1988 were 0.5, 1.0, and 1.5.

Table 9. Regression analysis of variance conducted for each irrigation method for the effect of ETo level on the amount of inorganic tracer recovered per 3.0-meter soil core. When non-significant sums of squares for year and quadratic lack-of-fit were pooled into error. Estimates of the parameters ± standard error for each regression are given by method. Year coded as 0 or 1 in regression analysis.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Sprinkler Method			
Amount of Water-Linear	1	829.44	0.050
Error	4	111.68	
Regression: mg Tracer = (37.2±4.3) + (-14.4±5.3)*ETo Level			
Basin Method[a]			
Amount of Water-Linear	1	1359.60	0.008
Error	3	32.49	
Regression: mg Tracer = (30.7±2.6) + (-22.0±3.4)*ETo Level			
Furrow Method			
Year	1	40.56	0.039
Amount of Water-Linear	1	39.69	0.041
Error	3	3.30	
Regression: mg Tracer = (3.1±1.0) + (-3.2±0.9)*ETo Level + (5.2±1.5)*Year			

---

[a] Chloride value at the 0.75 ETo treatment in 1988 excluded from analysis.

In order to provide a relative measure of solute movement between treatments, the location of the center (50%) of recovered mass in each core was calculated for each treatment. Depth to center of mass for surface-applied solutes had previously been used to relate amount of infiltrated water from rainfall to solute leaching (Burns, 1975; Smith et al., 1984). In sprinkler treatments where the loss of mass below the 3 meter depth was the least, the center of mass was clearly moved deeper as the amount of added water increased. There was a significant linear increase in depth to center of mass as the amount of added water increased (Tables 10 and 11). Even though a large portion of mass was moved below the 3-meter depth in basin and furrow treatments, the location of the center of recovered mass indicated deeper movement of tracers, especially at the 0.75 ETo level. Owing to the magnitude of downward leaching caused by basin and furrow treatments, differences between levels of ETo were smaller as indicated by the shallower slopes and lower significance levels for those regressions (Table 11). Thus, location of the center of mass recovered in a core provided good separation between the levels of added water when most of the mass was maintained within the sampled soil column. Comparisons to drip irrigation treatments were excluded because very little mass was recovered from those treatments in either year (Table 8). Additional sampling was needed to determine the extent of horizontal movement of water and solutes in relation to vertical displacement (Gerstyl et al., 1981).

In summary, data for soil moisture content indicated that water additions based on ETo values provided increases in the moisture content of the 3-meter core in each irrigation method. Data for inorganic tracers confirmed that the

Table 10. Calculated soil depth at which the center of mass was located in the 3-meter soil core in each treatment.

Irrigation Method	Depth of 50% Mass Recovery at ETo Treatments of						Overall Mean
	0.75		1.25		1.75		
	1987	1988	1987	1988	1987	1988	
	meters						
Inorganic Cation							
Sprinkler	0.74[a]	0.70	1.83	2.02	2.30	2.33	1.65
Basin	1.66	2.39	2.30	2.23	2.39	2.44	2.24
Furrow	2.13	2.23	2.46	2.56	2.38	2.74	2.41
Atrazine							
Sprinkler	0.27	0.10	0.34	0.63	0.75	1.36	0.58
Basin	0.38	0.52	0.71	0.85	1.89	1.60	0.99
Furrow	0.98	1.24	1.47	1.76	2.25	2.10	1.63

---

[a] Value is the mean of 4 replicate soil cores taken per plot and based on bromide applications in 1987 and chloride applications in 1988.

Table 11. Regression analysis of variance conducted for each irrigation method for the effect of ETo level on the location of the center of mass in soil cores. Sums of squares for years and quadratic lack-of-fit were pooled into error. Estimates of the parameters ± standard error for each regression are given by method.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Sprinkler Method			
Amount of Water-Linear	1	2.5440	0.003
Error	4	0.0602	
Regression: Center of Mass (m) = (-0.34±0.32) + (1.60±0.25)*ETo Level			
Basin Method[a]			
Amount of Water-Linear	1	0.3333	0.03
Error	3	0.0210	
Regression: Center of Mass (m) = (1.27±0.24) + (0.69±0.17)*ETo Level			
Furrow Method			
Amount of Water-Linear	1	0.1444	0.075
Error	4	0.0252	
Regression: Center of Mass (m) = (1.94±0.21) + (0.38±0.16)*ETo Level			

---

[a] Chloride value at the 0.75 ETo treatment excluded from analysis.

incremental increases in water addition provided increases in percolation of water in sprinkler, basin, and furrow irrigation methods. Further, the magnitude of deep percolation was less in sprinkler than in basin irrigation and it may have been greatest in furrow irrigation. Recovery of tracer from beneath drip emitters was either non-detectable or barely measurable at any level of applied water, precluding observations on the amount of deep percolating water produced from those treatments.

Effect of Treatments on Atrazine Content and Distribution in Soil

The soil distribution of atrazine differed from that of the inorganic tracers because it reacts with soil constituents causing retardation in movement relative to water (Figures 4 and 5) (Jury *et al.*, 1983; Rao and Davidson, 1980). Also, the recovery by depth of a pesticide is confounded by the presence of different zones of microbial activity within a soil column, causing rates of breakdown to vary depending on depth. A positive correlation between organic carbon content of soil and biological degradation has been measured (Morrill *et al.*, 1982). Based on the organic carbon content of the soil at this site, higher rates of degradation would have been expected in the first 0-0.3 meters because organic carbon was present at an average of 0.5%. Organic carbon content was very low, averaging 0.03%, below the 0.3 meter depth. Thus, conditions that promoted greater leaching could cause an apparent increase in the amount of pesticide recovered in a core because residues would have been moved downward from an area of high to low biological degradation. This effect was observed in sprinkler irrigation (Tables 12 and 13). Analyses conducted on the total amount of pesticide recovered per core indicated a trend ($p<0.10$) towards an increase in mass with increase in

FIGURE 4. Soil distribution of atrazine applied in 1987 and recovered in 3–meter soil cores sampled in sprinkler, basin and furrow irrigations. Data are the average of four cores.

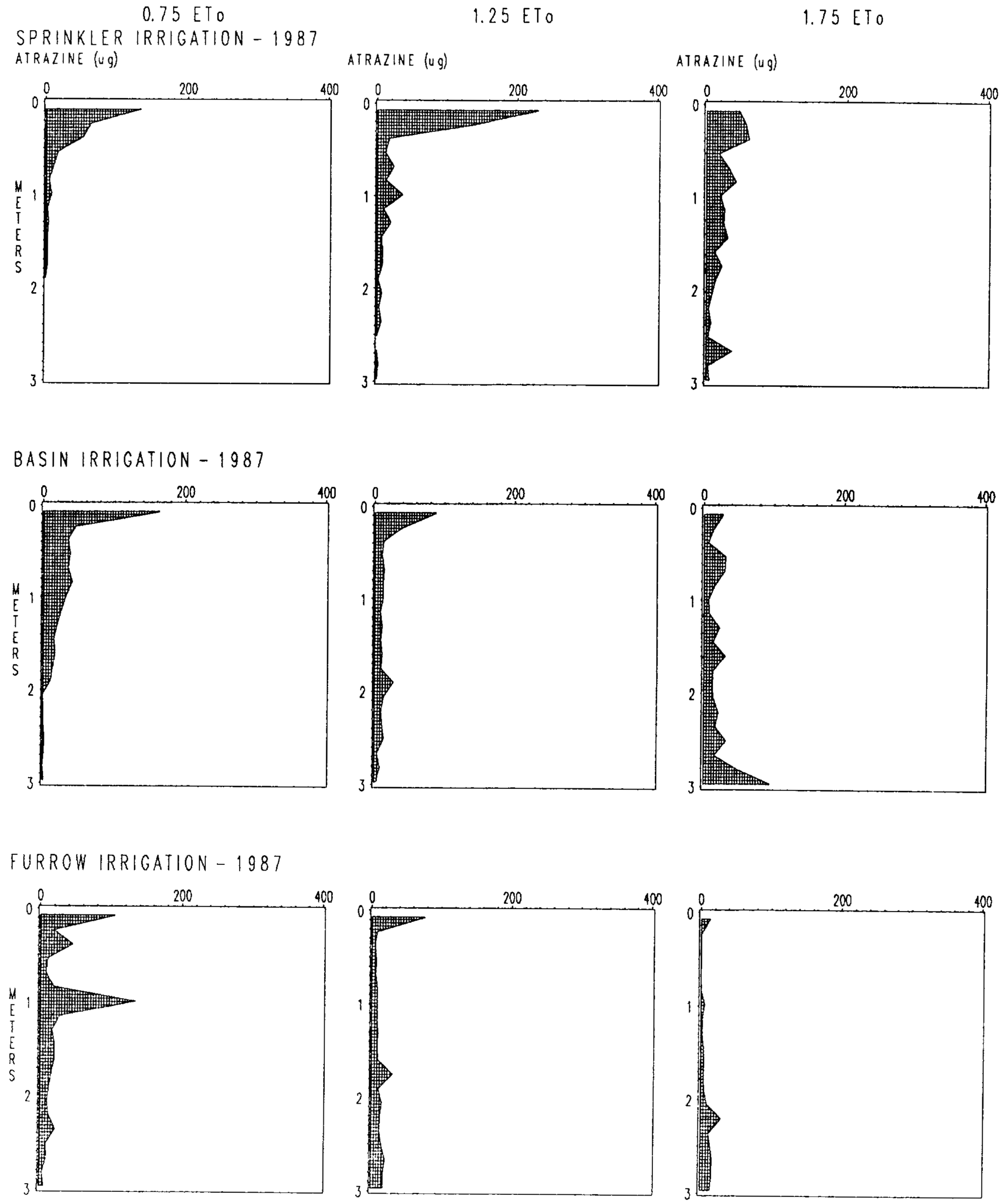
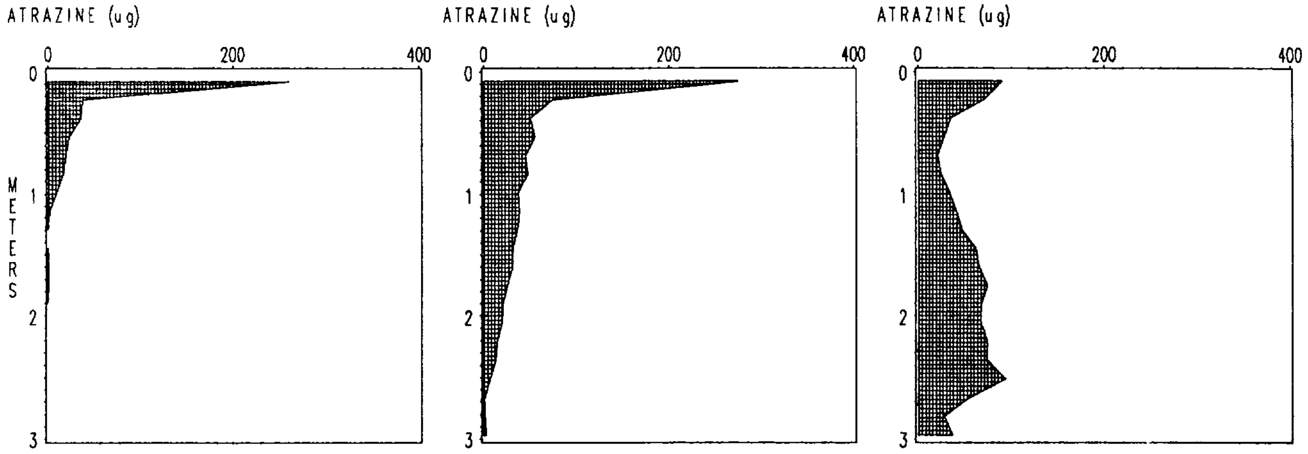


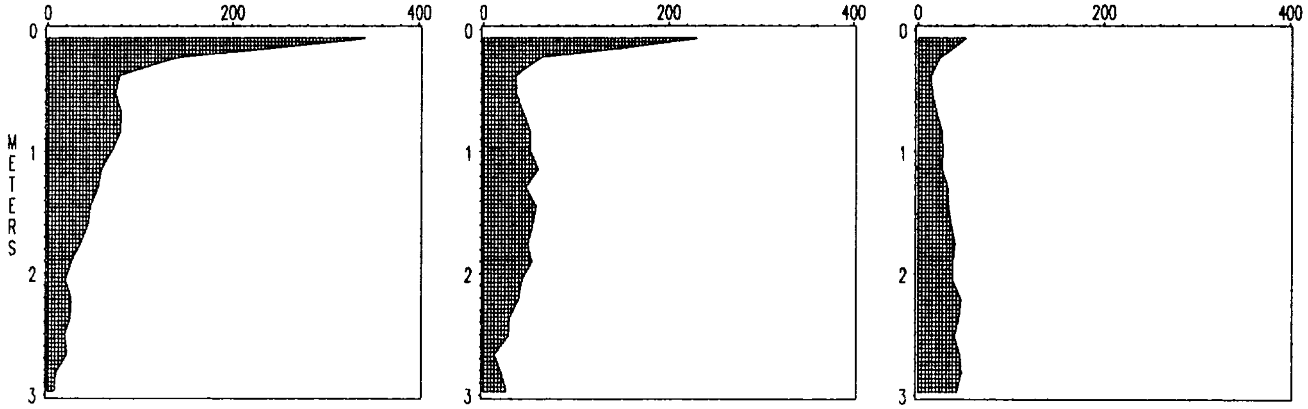
FIGURE 5. Soil distribution of atrazine applied in 1988 and recovered in 3-meter soil cores sampled in sprinkler, basin and furrow irrigations. Data are the average of four cores.

0.75 ETo 1.25 ETo 1.75 ETo

SPRINKLER IRRIGATION - 1988



BASIN IRRIGATION - 1988



FURROW IRRIGATION - 1988

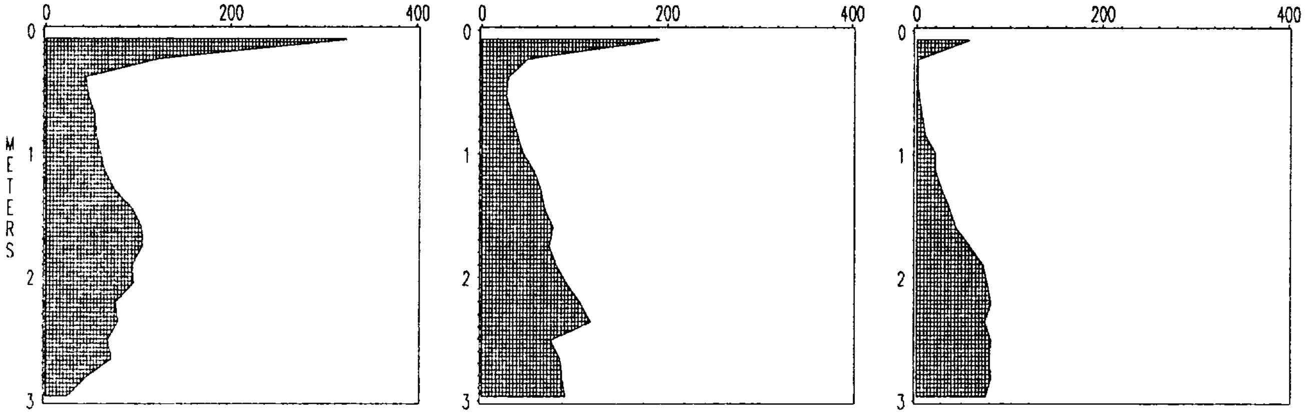


Table 12. Mass of atrazine recovered in each treatment in the entire 3-meter soil core and in two depth intervals; 0-0.3 meters and 0.3-3.0 meters.

Depth Interval and Irrigation Method	Atrazine Mass Recovered at ETo Treatments of 0.75		1.25		1.75	
	1987	1988	1987	1988	1987	1988
	mg					
Entire 3-meter Core						
Sprinkler	0.31	0.41[a]	0.54	0.83	0.47	1.09
Basin	0.50	1.26	0.33	1.01	0.47	0.68
Furrow	0.52	1.70	0.31	1.48	0.16	0.91
Drip[b]	0.03	0.02	0.18	0.021	0.17	0.012
0-0.3 Meters						
Sprinkler	0.20	0.30	0.37	0.35	0.10	0.16
Basin	0.21	0.49	0.13	0.29	0.04	0.07
Furrow	0.12	0.45	0.08	0.24	0.01	0.06
Drip	0.01	0.01	0.01	0.001	0.02	0.01
0.3-3.0 Meters						
Sprinkler	0.11	0.11	0.17	0.48	0.37	0.93
Basin	0.29	0.77	0.20	0.72	0.43	0.61
Furrow	0.40	1.25	0.23	1.24	0.15	0.85
Drip	0.02	0.01	0.17	0.02	0.15	0.002

---

[a] Value is the mean of 4 replicate soil cores taken per plot.

[b] ETo levels in 1988 were 0.5, 1.0, and 1.5.

Table 13. Regression analysis of variance by irrigation method for the effect of ETo level on the amount of atrazine mass recovered. Tests of the quadratic lack-of-fit were nonsignificant in all analyses so the sums of squares were pooled into error.

		Entire Core		0-0.3 Meters		0.3-3 Meters	
Source of Variation	D.F.	MSQ[a]	Pr>F	MSQ	Pr>F	MSQ	Pr>F
Sprinkler Method							
Year	1	0.1701	0.09	0.0033	0.66	0.1262	0.12
Amount of Water-Linear	1	0.1868	0.08	0.0129	0.41	0.2977	0.05
Error	3	0.0287		0.0139		0.0280	
Basin Method							
Year	1	0.4550	0.03	0.0382	0.07	0.2296	0.03
Amount of Water-Linear	1	0.0875	0.19	0.0827	0.03	0.0001	0.95
Error	3	0.0305		0.0049		0.0114	
Furrow Method							
Year	1	1.5895	0.01	0.0465	0.08	1.0924	0.01
Amount of Water-Linear	1	0.3409	0.03	0.0619	0.05	0.1123	0.05
Error	3	0.0229		0.0066		0.0108	

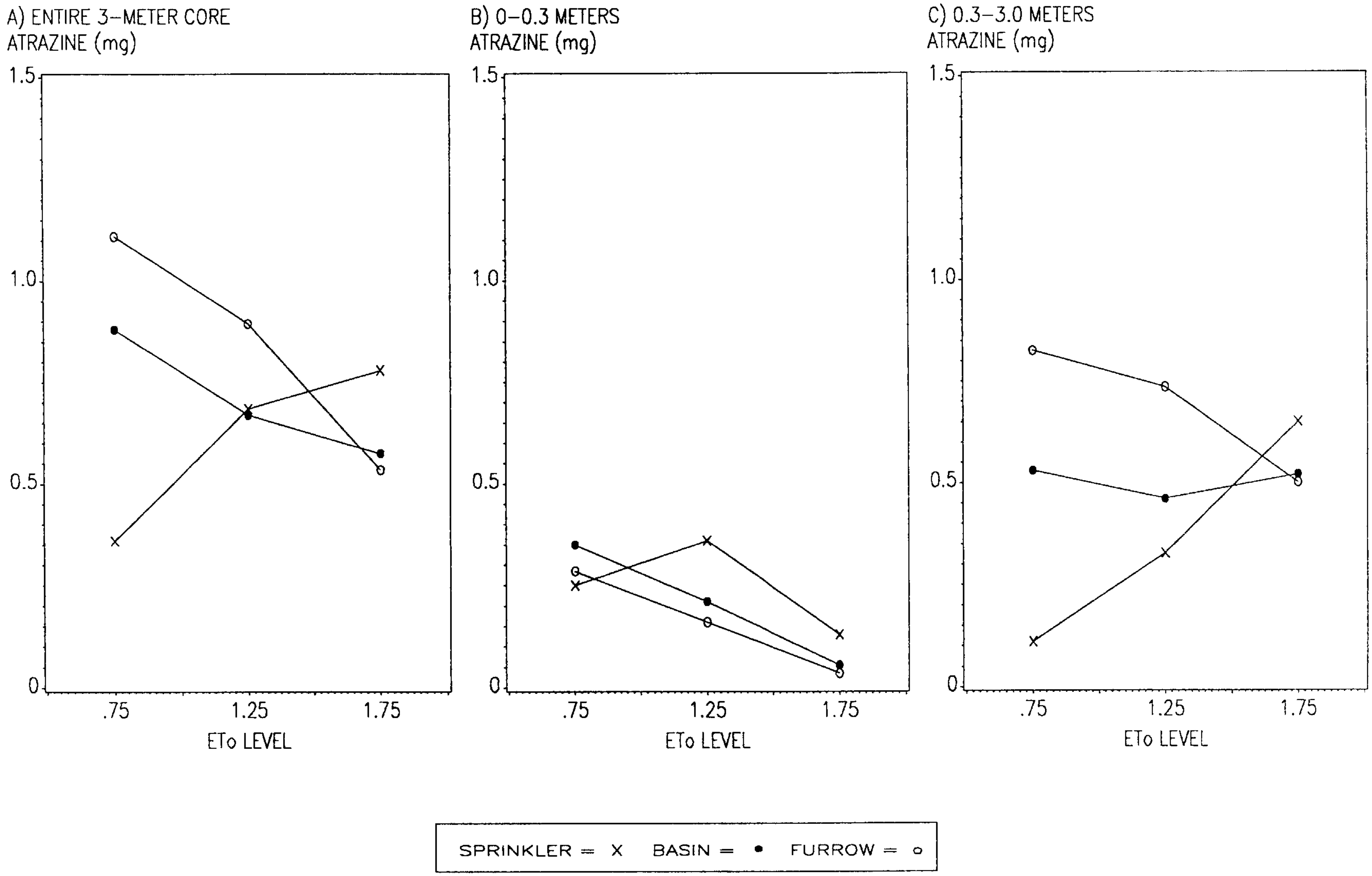
---

[a] MSQ denotes mean square.

additions of water. Analyses of the soil core partitioned into 0-0.3 and 0.3-3 meter depth segments indicated that the increases in residue were located in the subsurface soil in the 0.3-3.0 meter segment (Figure 6). For basin irrigation, a significant decrease in mass with increase in added water was measured in the surficial 0-0.3 meter segment (Tables 12 and 13). Residues were moved from the surface and accumulated in the subsurface soil at the 0.75 ETo level as indicated by the increase in mass in the 0.3-3 meter segment when compared to sprinkler irrigation (Figure 6c). Further accumulation of mass in the subsurface soil was not measured in response to incremental additions of water because residues were moved below 3 meters at greater levels of ETo. The soil distribution of atrazine in furrow irrigation indicated more leaching than in basin irrigation because of the presence of a prominent second peak lower in the soil profile, especially at the 0.75 ETo level. Recovered mass decreased as the amount of added water increased, presumably due to greater leaching past the lowest sampled depth.

Recovery of atrazine was very low in all drip treatments which precluded comparisons to the other irrigation methods (Table 12). Also, atrazine was applied two to three days prior to the initial irrigation event in 1988 in order to provide a more equal interval for degradation between pesticide application and the onset of irrigation. Owing to the measurement of significant effects with the pooled data over years, patterns of leaching were unaffected whereas the amount of residue recovered was greater in 1988 because of less time for degradation between pesticide and water application.

FIGURE 6. Relationship between mass of atrazine recovered and amount of added water (ETo level) in sprinkler, basin and furrow irrigations for: A) entire 3-meter core; B) 0-0.3 meters; and C) 0.3-3 meters.


A) ENTIRE 3-METER CORE

B) 0-0.3 METERS

C) 0.3-3.0 METERS

Table 14. Regression analysis of variance by irrigation method for the effect of ETo level on the depth to 50% recovery of cumulative atrazine mass. Tests for years and for quadratic lack-of-fit were nonsignificant in all analyses so their sums of squares were pooled into error. Estimates of the parameters ± standard error for each regression are given by method.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Sprinkler Method			
Amount of Water-Linear	1	1.2432	0.048
Error	4	0.1574	

Regression: Center of Mass (meters) = (-0.87±0.52) + (1.12±0.40)*ETo Level

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Basin Method			
Amount of Water-Linear	1	1.9321	0.003
Error	4	0.0468	

Regression: Center of Mass (meters) = (-0.69±0.28) + (1.39±0.22)*ETo Level

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Furrow Method			
Amount of Water-Linear	1	1.0712	0.003
Error	4	0.0234	

Regression: Center of Mass (meters) = (-0.34±0.20) + (1.04±0.15)*ETo Level

The location of the center of mass provided a measure of the magnitude of treatment effects on leaching because it was based on the depth at which pesticide residue was detected. A significant linear relationship was measured in all irrigation methods between the location of the center of mass and the amount of added water such that the location of the center of mass increased in depth as the amount of added water increased (Tables 10 and 14).

Since the response was linear for all methods, ANOVCOV was conducted to measure similarity of regression equations between methods. None of the interactions between method of water delivery and amount of added water were significant, indicating that the slopes were similar between regressions (Table 15). Overall, depth to center of mass in a core increased by about 0.6 meters for each 0.5 unit increment in ETo level. However, both main effect contrasts were significant indicating differences in the elevation of regressions between methods (see overall means in Table 10). At similar levels of added water, depth to center of mass was increased by 0.4 meters in basin treatments as compared to sprinkler treatments. Furrow treatments caused an additional 0.6 meter increase in depth as compared to basin irrigations. Since variation in soil properties was low and hydraulic properties were very similar between treatment locations, significant effects had a high probability of being caused by differences in method of water application, not by bias in site location.

Table 15. Split-plot Analysis of Covariance testing equality of slopes and elevation of lines produced for the regression of depth to 50% recovery of cumulative atrazine mass on ETo level with in each irrigation method. Sums of squares for years and quadratic lack-of-fit were pooled into whole-plot and split-plot error terms, respectively.

Source of Variation	Degrees of Freedom	Mean Square	Significance Level
Whole Plot Analysis			
Irrigation Method	2		
Sprinkler vs Basin (SvB)	1	0.8269	0.050
Basin vs Furrow (BvF)	1	1.0208	0.038
Whole Plot Error	3	0.0810	
Split-Plot Analysis			
Amount of Water-Linear (EToL)	1	4.1772	0.001
Irrigation Method x EToL	2		
SvB x EToL	1	0.0378	0.49
BvF x EToL	1	0.0630	0.38
Split-Plot Error	9	0.0742	

Incorporation of different methods of water delivery into the study design provided a basis to determine how patterns of water application affected leaching of solutes. Since sprinkler events were more frequent and of less volume per event compared to basin applications, more water would have been subject to evaporation in sprinkler applications. This effect was reflected in simulations using the LEACHM model (Hutson et al., 1989). LEACHM models the movement of solutes and water flow in soils with respect to specific site conditions of soil texture and climatic factors. Results from LEACHM had been shown to produce reasonable agreement to the field data generated at our site in terms of soil distribution of solutes. The amount of water evaporated from the soil was estimated from the LEACHM model for sprinkler and basin treatments (Table 16). Sprinkler and basin treatments are presented because model simulations best represented conditions where water was applied to the entire surface area of the plots which minimizes effects of lateral flow. Simulations were run using actual dates and amounts for each irrigation application and using pan evaporation data obtained from the local weather station. Evaporation of water from the soil surface, as estimated from the model simulations, was greatest in sprinkler treatments which also resulted in less water available for deep drainage. 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. A plot of the depth to center of atrazine mass against infiltrated water produced from sprinkler and basin treatments in 1987 and 1988 indicated a significant linear relationship between these variables at $p<0.001$ and $r^2=0.88$ (Eq. 3) (Figure 7).

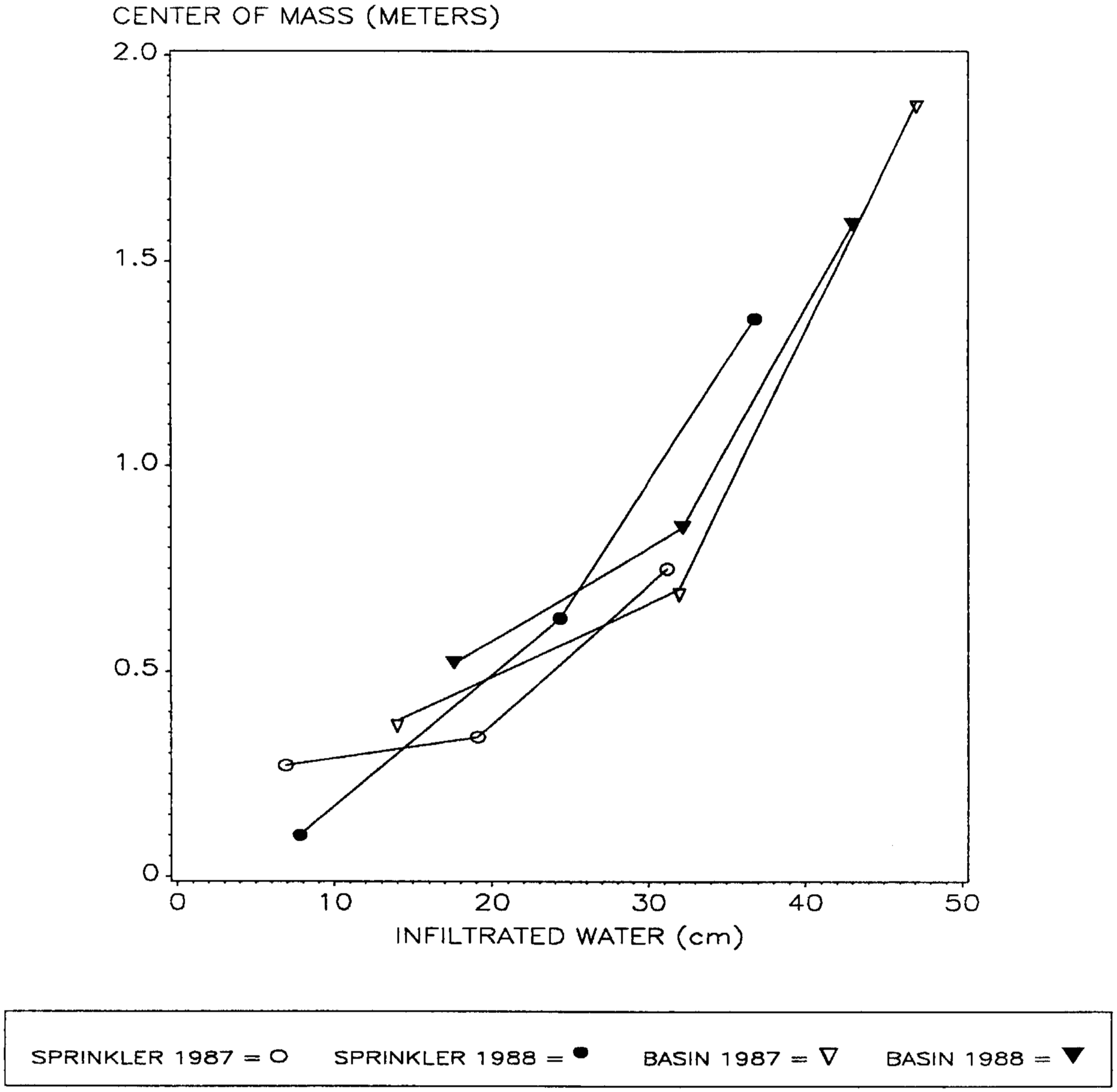
Table 16. Amount of water added in each treatment and estimated amount of water evaporated from the surface and drained past 3 meters using the LEACHM model.

Treatment	Amount of Water		
	Added	Evaporated	Infiltrated[a]
	cm		
Sprinkler - 1987			
0.75 ETo	21.6	14.7	6.9
1.25 ETo	35.1	16.0	19.1
1.75 ETo	48.6	17.4	31.2
Sprinkler - 1988			
0.75 ETo	22.7	14.8	7.8
1.25 ETo	39.2	14.9	24.3
1.75 ETo	51.8	15.0	36.8
Basin - 1987			
0.75 ETo	20.0	6.0	14.0
1.25 ETo	39.4	7.4	32.0
1.75 ETo	56.9	9.8	47.1
Basin - 1988			
0.75 ETo	22.7	5.2	17.6
1.25 ETo	37.9	5.7	32.2
1.75 ETo	52.2	9.2	43.0

---

[a] Calculated as the difference between added and evaporated columns.

FIGURE 7. Relationship between location of the center of mass in 3–meter sampled soil cores and the amount of infiltrated water produced from sprinkler and basin irrigations in 1987 and 1988.



This relationship is described by equation 3:

Eq. 3 $$Y = (-0.25 \pm 0.13) + (0.04 \pm 0.005) * X$$

where Y represents the center of the mass in meters, X represents the amount of infiltrated water in cm and the estimates of the intercept and slope ± their standard errors are given. According to equation 3, depth to center of mass increased by approximately 0.4 meters for each 10 cm increment of infiltrated water. Hence, the magnitude of atrazine leaching could be expressed as a function of the amount of infiltrated water produced by each irrigation which in this situation was the amount of percolated water produced by a given method of application. This result is similar to that observed for inorganic tracers (Burns *et al.*, 1975). Also, the relationship between atrazine movement and amount of infiltrated water underscores the importance of retaining water, *on a per event basis*, in the root zone of crops. One large basin or furrow irrigation leached residue deeper than multiple sprinkler irrigations. Management of water in areas vulnerable to leaching should be made to minimize loss of water to deep percolation because once water moves past the roots it is unavailable to support crop growth and because degradation rates apparently decrease once pesticide residues are carried below the active microbial zone. Since the choice of irrigation method has potential impact on the extent of leaching, studies are in progress to further define pesticide movement in cropped conditions as related to rates and method of water application in irrigation.

CONCLUSIONS

One objective of the study was to relate pesticide leaching to amounts of water added by irrigation. Water applications were made based on graded levels of daily ETo measurements which could then be related to magnitude of leaching through regression analysis. The soil distribution of inorganic tracers for water movement indicated that within each of three methods of water application - sprinkler, basin, and furrow - the depth of deep percolating water increased with each 0.5 unit increment in ETo level. Although the pattern of soil distribution for the pesticide, atrazine, reflected retardation in movement when compared to conservative water tracers, atrazine's leaching was also increased with the amount of added water. Within an irrigation method, the depth to the center of mass recovered in a core increased by approximately 0.6 meters with each 0.5 unit increment in ETo level. The close association between leaching and amount of deep percolating water produced by irrigation treatments was expected because leaching occurs through dissolution of solute in soil solution and subsequently, moves with soil water. Of significance was the relationship between amount of deep percolating water and magnitude of atrazine residue leaching because it indicated that water budgeting techniques also affect pesticide leaching directly through effects on the amount of deep percolating water produced. Hence, water management methods that are based on measurements of ETo could also be potentially used to manage pesticide leaching. The data for sprinkler irrigation illustrated the importance of this approach: residues at the lowest level of water addition were confined to the upper layers of soil where residues were available for degradation.

The second objective of the study was to obtain data on how different methods of water application might modify leaching of pesticides. Downward movement of water and atrazine residue was least in the sprinkler method where irrigations were made one day per week, providing enough water to replenish the previous weeks daily accumulated ETo values. In the basin method, events were less frequent and of greater volume per event which produced greater depths of deep percolating water and pesticide leaching. Simulation of the study using the solute transport model LEACHM indicated that water in sprinkler irrigation was subject to more evaporation than in basin irrigation and explains why more water infiltrated and subsequently, percolated in basin irrigations. It should be noted that although the study was conducted on bare soil, water lost to evaporation in sprinkler irrigation would have potentially been available for crop growth if plants were present. Also, the bulk of water that percolated in basin and furrow irrigations would have travelled beyond the active portion of the root zone of most crops and thus, would have been unavailable to support crop growth. Therefore, effective use of water budgeting techniques will also have to consider the pattern of water application inherent in the choice of irrigation method. Studies are in progress to provide additional data on differences in pesticide leaching between methods of water application in cropped conditions.

Very little solute whether inorganic tracer or atrazine was recovered in cores taken beneath drip emitters. More frequent and detailed sampling of soil located from both beneath and between drip emitters is needed in order to adequately describe solute movement in low volume systems where horizontal movement to non-irrigated areas could occur.

RECOMMENDATIONS

1. When the Environmental Monitoring and Pest Management Branch makes a recommendation concerning the use of soil-applied pesticides, whether they be new or modified uses, irrigation rates and method should be a major component of the use recommendation.

2. Water budgeting can be an effective approach to establishing limits on irrigation events so that leaching of pesticides is reduced while ensuring an adequate supply of water to crops.

3. The application of a water budgeting approach to various irrigation methods needs further investigation. Water applied more frequently in sprinkler irrigation caused less leaching than water applied in larger infrequent events in basin and furrow irrigation. Since this study was conducted on bare soil, we recommend that additional studies occur in cropped conditions to confirm this conclusion.

REFERENCES

1. Bernstein, L. and L.E. Francois. 1973. Comparisons of drip, furrow, and sprinkler irrigation. Soil Science, 115(1):73-XX.

2. Biggar, J.W. and D.R. Nielsen. 1978. Field monitoring of soil water constituents in the unsaturated zone. p 106-121. In L.G. Everett and K.D. Schmidt (ed.) Establishment of water quality monitoring programs. Proc. American Water Resources Association, San Francisco, Ca. 12-14 June 1978. American Water Resources Association, Minneapolis, Minn., Technical Publication Series no. TPS79-1.

3. Bouwer, H. 1987. Effect of irrigated agriculture on groundwater. Journal of Irrigation and Drainaige Engineering, 113(1):4-15.

4. Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analyses of soils. Agronomy J., 54:464-465.

5. Bowman, R.S. 1984. Evaluation of some new tracers for soil water studies. Soil Sci. Soc. Amer. J., 48(5):987-993.

6. Bucks, D.A., L.J. Erie and O.F. French. 1974. Quantity and frequency of trickle and furrow irrigation for efficient cabbage production. Agronomy J., 66:53-57.

7. Burns, I.G. 1975. An equation to predict leaching of surface-applied nitrate. J. Agric. Sci. 85:443-454.

8. Cameron, D.R., C.G. Kowalenko and C.A. Campbell. 1979. Factors affecting nitrate nitrogen and chloride leaching variablility in a field plot. Soil Sci. Soc. Amer. J., 43:455-460.

9. Connelly, L. 1985. AB2021-Pesticide Contamination Prevention Act. Article 15, Chapter 2, Revision 7, Food and Agricultural Code, California.

10. Feld, S.J. and J.A. Menge. 1990. Influence of drip and furrow irrigation on Phytophthora root rot of citrus uner field and greenhouse conditions. Plant Disease, 74(1):21-27.

11. Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, N.J. 604pp.

12. Gerstl, Z., S.S. Saltzman, L. Kliger, and B. Yaron. 1981. Distribution of herbicides in soil in a simulated drip irrigation system. Irrig. Sci., 2:155-166.

13. Grant, J, D.A. Goldhammer and M. Gagnon. 1986. The water budget method: irrigation scheduling for southern San Joaquin Valley deciduous orchards. Division of Agriculture and Natural Resources, University of California, Leaflet 21419.

14. Haise, H.R., W.W. Donnan, J.T. Phelan, L.F. Lawhan and D.G. Shockley. 1956. The use of cylinder infiltrometers to determine the intake characteristics of irrigated soils. Agricultural Research Service and Soil Conservation Service, USDA. ARS 41-7, May, 1956, 10pp.

15. Hutson, J.L., R.J. Wagenet, and J.W. Biggar. 1989. Simulation of pesticide fate in some California soils. Final report for contract 8680, Environmental Monitoring Branch, California Department of Food and Agriculture, Sacramento, Ca. 55pp.

16. Jensen, E. 1983. Design and Operation of Farm Irrigation Systems. American Soc. of Agri. Eng., St. Joseph, Michigan, 289pp.

17. Jury, W.A., W.F. Spencer and W.J. Farmer. 1983. Uses of models for assessing relative volatility, mobility, and persistence of pesticides and other trace organics in soil systems. Hazard Assessment of Chemicals, 2:1-43.

18. Leistra, M. 1986. Modelling the behavior of organic chemicals in soil and ground water. Pesticide Sci., 17:256-264.

19. Millar, C.E., L.M. Turk and H.D. Foth. 1965. Fundamentals of soil science. 4th edition. John Wiley and Sons, New York, New York.

20. Morrill, L.G., B.C. Mahilum, and S.H. Mohiuddin. 1982. Organic Compounds in Soil: Sorption, Degradation and Persitence. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, pp 170-172.

21. Muirhead, W.A., J. Blackwell, E. Humphreys, and R.J.G. White. 1989. The growth and nitrogen economy of rice under sprinkler and flood irrigation in South East Australia. Irrig Sci., 10:183-199.

22. Nielson, D.R., M.Th. van Genuchten and J.W. Biggar. 1986. Water flow and solute transport processes in the unsaturated zone. Water Resources Research, 22(9):89s-108s.

23. Ochs, W.J., L.S.W. Willardson, C.R. Camp Jr., W.W. Donnan, R.J. Winger Jr., and W.R. Johnston. 1983. Chapter 7; Drainage requirements and systems. In E. Jensen (ed.); Design and operation of farm irrigation systems, American Soc. Agri. Engineers, St. Joseph, Michigan, pp 235-277.

24. Orion Research. 1982. Bromide in soils and plant tissue. In Handbook of Electrode Technology. pp B-3.

25. Rao, P.S.C. and J.M. Davidson. 1980. Estimation of pesticide retention and transformation parameters required in nonpoint source pollution models. In M.R. Overcash and J.M. Davidson (ed.); Environmental impact of nonpoint

26. Rauschkolb, R.S. 1980. Soil analysis method S:18.0, Organic matter dichromate reduction. In California Fertilizer Association, California Soil Testing Procedures Manual.

27. SAS Institute Inc. 1988. SAS/STAT User's Guide, Release 6.03 Edition. Cary, N.C.:SAS Institute Inc., 1988, 1028 pp.

28. Smith, A.J., L.R. Ahuja, and J.D. Ross. 1984. Leaching of a soluble chemical under field crop conditions. Soil Sci. Soc. Am. J. 48:252-258.

29. Snyder, R., D.W. Henderson, W.O. Pruitt and A. Dong. 1985. California Irrigation management information system final report June 1985. Ca. Department of Water Resources, Contract NO. B53812. Univ. Calif. Davis.

30. Soil Conservation Service. 1971. Soil survey: Eastern Fresno Area, California. United States Department of Agriculture in Cooperation Calif. Agricutural Experiment Station, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.pp 323.

31. Spalding, R.F., G.A. Junk, and J.J. Richard. 1980. Pesticides in ground water beneath irrigated farmland in Nebraska, August 1978. Pesticides Monitoring J. 14(2):70-73.

32. Troiano, J. 1987. Measurement of possible cross-contamination of soil samples during soil coring with the split-barrel or bucket auger method. Environmental Hazards Assessment Program, California Dept. of Food and Agriculture, Sacramento, Ca, EH87-06, 17 pp.

33. Tweedy, B.G. 1983. The future of chemicals for controlling plant diseases. In T. Kommedahl and P.H. Williams (ed.); Challenging problems in plant health. Amer. Phtyopathological Soc., St. Paul, Minnesota, pp 45-415.

34. Wagenet, R.J. and J.L. Hutson. 1986. Predicting the fate of nonvolatile pesticides in the unsaturated zone. J. Environ. Qual., 15(4):315-322.

35. Wehtje, G., L.N. Mielke, J.R.C. Leavitt and J.S. Schepers. 1984. Leaching of atrazine in the root zone of an alluvial soil in Nebraska. J. Environ. Qual., 13(4):507-513.

36. Yamauchi, H. 1984. Impact on groundwater resources of conversion from furrow to drip irrigation. Water Resources Bull., 20(40):557-563.

37. Zekri, M., and L.R. Parsons. 1988. Water relations of grapefruit trees in response to drip, microsprinkler, and overhead sprinkler irrigation. J. Amer. Soc. Hort. Sci. 113(6):819-823.