Relating Simazine Performance to Irrigation Management[1]

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Abstract: Although water is crucial to the performance of preemergence herbicides, pesticide performance has rarely been related to irrigation management. This 2-yr study investigated the effect that amount of irrigation water applied had on activity of simazine. Three rates of simazine at 0, 1.12, and 2.24 kg/ha were applied to a 3-yr-old nectarine orchard that was irrigated with microsprinklers. The performance of simazine was compared between irrigation treatments initially targeted to provide water at 110 (efficient) and 175% (overwatered) of crop water requirements. Simazine effectiveness was based on the survival of oat and cucumber plants that were seeded at 0, 14, 28, 56, and 84 d after herbicide application. A longer time interval to 50% survival indicated prolonged herbicidal activity. Results were consistent between years in that simazine's performance was consistently greater in efficient irrigation treatments. The greatest increases were measured at the higher simazine application rate (2.24 kg/ha); overall averages for the length of time to reach 50% survival for cucumber were 50 and 23 d and for oats were 55 and 15 d for efficient and overwatered irrigation treatments, respectively. Use of an efficient irrigation management technique could have enhanced simazine's performance through a decreased leaching of residues from the weed root zone or less chemical or biological degradation (or both). Adoption of efficient irrigation management has been identified as a best management practice to mitigate leaching of pesticide residues to groundwater in coarse soils in California. This study indicates that efficient irrigation improves simazine performance and that both factors, pesticide application and irrigation management, should be considered when developing a weed management system.

Nomenclature: Simazine; cucumber, *Cucumis sativus* L.; nectarine, *Prunus persica* L.; oat, *Avena sativa* L.

Additional index words: Bioassay, groundwater contamination, herbicide performance, irrigation efficiency.

Abbreviations: ELISA, enzyme-linked immunosorbant assay; ETo, evapotranspiration.

INTRODUCTION

Although preemergence herbicide use is an integral part of many successful agricultural operations, residues have been shown to move off-site into surface and groundwater (Hallberg 1989; Leonard 1990). In California, residues of several preemergence herbicides, specifically atrazine, bromacil, diuron, norflurazon, prometon, and simazine, have been detected in domestic well water samples and their presence has been attributed to nonpoint source agricultural applications (Troiano et al. 2001). One pathway for movement to groundwater is by leaching where herbicides move with water as it percolates to groundwater. For example, in California, simazine residues have been detected in areas with coarse soils and where leaching has been determined as the predominant pathway (Troiano et al. 1994).

Much of the agricultural area in California is typified by a Mediterranean climate where summers are hot and dry with a low annual rainfall of 25 cm or lower. Most of the rain occurs during the winter season. Under these climatic conditions, percolation of water due to rainfall is low. Recharge of groundwater occurs primarily through water lost to percolation during crop irrigations (Schmidt and Sherman 1987). Water-budgeting methods have been derived that supply ample water for crop growth but minimize the amount of water lost to deep percolation (CDWR 2001; Snyder et al. 1985). Reductions in the leaching of agricultural chemicals through the soil profile, such as nitrate (Ritter and Manger 1983) and atrazine

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(Troiano et al. 1993) residues, are potential benefits from the adoption of efficient irrigation management practices. In areas sensitive to leaching, adoption of efficient irrigation management has been identified as a "Best Management Practice" to mitigate leaching of preemergence herbicide residues (Troiano et al. 1998).

Water is crucial also for assuring herbicide performance because it is necessary for activation of herbicides, for incorporation of herbicides into soil, and for transport of herbicides into target plants (Ashton et al. 1989; Burtch and Gantenbein 1989; Carey and Bendixen 1989). In fact, most preemergence herbicide labels contain statements indicating that water is necessary to incorporate residues into soil and to facilitate uptake of residues by weed seedlings. But exposure to too much water after application, either by rainfall or irrigation, can reduce efficacy by moving herbicides out of the active zone (Leistra and Green 1990; Ogg 1986). It also has been shown that overwatering can result in crop injury due to downward movement of herbicides with water that percolates into the crop root zone (Kempen 1993). As a result of these observations, many labels also contain statements that indicate potential for crop injury when too much water is applied to coarse soils.

With respect to irrigation, some studies have compared differences in performance of herbicides between irrigation methods but none has explicitly related performance to the amount of water applied. For example, in comparisons where only one level of water was applied, enhanced herbicide performance was observed in microsprinkler vs. drip irrigation (Fisher et al. 1988), and better performance has been noted for sprinkler irrigation than for furrow irrigation (Jordan et al. 1963).

This study was conducted to measure effectiveness of simazine application at two different levels of water applied through irrigation. The study was conducted in a young planting of nectarines, and the effectiveness of simazine was chosen because it is registered for use on deciduous tree crops and because it has a propensity to leach through soil. Levels of water application were based on measures of crop evaporation with one representing an efficient management of irrigation water and the other an overwatered condition. In addition, because the site was clean cropped, cucumber and oats were planted and their survival rate monitored to indicate the potential longevity of simazine's herbicidal activity after application.

MATERIALS AND METHODS

Site Description and Experimental Design. The study was conducted in a 3-yr-old nectarine block located on the California State University, Fresno farm. Trees were planted on a 5.48 × 5.48-m spacing. Irrigation water was supplied through full circle microsprinklers identified in the manufacturer's catalog as violet color nozzles,[3] which delivered 0.757 L/min at a pressure of 126 kPa. Emission uniformity of the sprinklers was tested on 13 emitters, and it was measured at 98%. The sprinklers were spaced one per tree in the center of the tree line. The soil was identified as a Hanford sandy loam, a typic Terricorthent. Soil properties measured at 15-cm depth were soil texture, 75% sand, 16% silt, and 9% clay; pH, 7.1; and organic matter, 1%. Simazine had not been used in this block before the study, and residues at an MDL of 2 ppb were not detected in background soil samples taken before the study. Soil samples were analyzed for simazine residues by the California Department of Food and Agriculture Chemistry Lab Services using an enzyme-linked immunosorbent assay (ELISA) developed by Lucas et al. (1991). The method was previously tested for application to soil analysis in a controlled study by comparing ELISA results with those obtained by standard gas chromatographic methodology (Goh et al. 1992).

The study was a two by three factorial randomized complete block design: irrigation treatments were applied at two levels of potential percolating water and simazine applied at three levels. Treatments were randomized across three blocks, and the site was blocked because of a gradient in soil infiltration rate measured in a north–south transect. Each treated plot consisted of nine nectarine trees. The study was replicated for 2 yr in 1993 and 1994, and the treatments were randomly distributed throughout the blocks in both years.

Simazine was applied at 0, 1.12, and 2.24 kg/ha with the highest rate chosen because of restrictions given on the label on the amount applied to young nectarines. Treatments were applied to each plot using a backpack sprayer pressured with carbon dioxide. The swath width was 1.52 m applied to each side of the tree line. Simazine was applied on April 28, 1993, and on March 31, 1994. Residues were not detected in soil before application in 1994, indicating no carryover of residues from the applications made in 1993.

Irrigation treatments were initiated at the start of each growing season with treatments targeted at 110 and 175% of crop needs and theoretically producing percolation treatments of 10 and 75% of the applied water, respectively. The 110% treatment was selected because

[3] Microspinklers, Rain Bird Corporation, 145 North Grand Avenue, Glendora, CA 91741-2469.

it reflected a good irrigation management practice where water for plant growth was not limiting but with some of the applied water lost to deep percolation past the root zone. This water treatment will be referenced as the efficient water treatment, whereas the 175% treatment will be referenced as the overwatered treatment. Irrigations were applied once per week, with the depth of each watering based on reference evapotranspiration (ETo) measurements that were obtained from a local weather station. ETo values reflect water requirements of a well-watered grass, and therefore weekly cumulative values were adjusted by the crop coefficient for nectarines and by the canopy area. In 1993, adjustments in depth of water were not made according to growth periods. In 1994, the volumes were adjusted in three phases: (1) rapid growth, which was from leafout until full maximum size, (2) midseason growth, from the end of rapid growth until decreased transpiration, and (3) late season growth, which ended at leaf drop. According to the pattern followed in 1994, irrigation treatments in 1993 were short by approximately 16% and overall equaled 92% for the efficient irrigation treatment and 159% for the overwatered treatment. Because the trees were young, applying less than the theoretical amount of water to the trees in 1993 had no visible effect on growth or yield of trees, but the treatments still would have produced the desired effect of producing differences in percolating water in the shallow surface zone of soil. Because of the Mediterranean climate, rainfall during the 84-d seeding period was low. In 1993, total rainfall for the study period was 1.5 cm, which compares with an ETo of 56.6 cm, and in 1994, rainfall was 7.9 cm, which compares with an ETo of 45.7 cm. Hence, water supplied by irrigation was the major source for deep percolation.

Bioassay for Simazine Performance. Simazine performance was determined by measuring the survival rate of indicator plant species seeded in each plot. Oat, a monocotyledon species, and cucumber, a dicotyledonous species, were seeded at 14, 28, 56, and 84 d after simazine application in both years. Another seeding at the time of simazine application (0 d) was added in 1994 to verify the effectiveness of simazine at both application rates. A total of 50 oat and 20 cucumber seeds were planted within a polyvinyl chloride plastic ring that was 30.4 cm in diameter and 7.6 cm in height. At each seeding, three rings were placed within each treated plot, resulting in a total of 150 oat and 60 cucumber seeds planted per replicate. Each ring was situated between 1.06 and 1.52 m from a microsprinkler emitter. The number of seedlings that emerged was measured approximately 7 d after seeding, and the number of plants that survived was measured 24 d after seeding. Survival rate was calculated as the ratio of the number of plants that survived divided by the number of plants that emerged. Data for the three rings in each replicate plot were summed before calculation of the survival rate.

Statistical Analysis. Main effects of simazine and irrigation and their interaction on survival rate were initially measured using a two-way ANOVA conducted for each seeding date. Before statistical analysis, the proportional survival rate was transformed as the arcsine of the square root (Ahrens et al. 1990). Sums of squares for simazine treatment were partitioned into linear and quadratic orthogonal polynomial treatment contrasts.

To provide a measure of efficacy for the entire treatment period, a second ANOVA was conducted to measure effects on the estimated day at which 50% survival was observed. Simazine killed all plants when seeded at day 0, the day of simazine application, so longer time intervals until observation of 50% survival indicated greater effectiveness of treatments. This estimate was derived by subjecting data for all time intervals from each block to nonlinear regression analysis. First, an exploratory analysis was conducted with the TableCurve 2D[4] program to determine a common equation. The simplest yet most robust fit to the data was a power function with the form:

$$y = ax^b. \qquad [1]$$

Y was the response expressed as the transformed proportional survival rate, and x was the day at which the plants were seeded. A nonlinear regression analysis was conducted with the NLIN program in SAS using the Marquardt method to provide estimates for a and b coefficients for a fit to the data from each block (SAS 1990). The value for 0 d was set at 0.001 to facilitate computation. An estimate of the day at which 50% survival was attained for each treatment was determined by transforming the power equation into a linear equation. The value of x was determined when survival was set at ln of 0.7854, which is the transformed value when proportional survival is 0.5. A combined ANOVA over years was used to test for effects of species, simazine application rate, water irrigation treatments, and their interactions on estimated survival time (McIntosh 1983). Survival rates in control plots where simazine was not applied were lower in 1993 than in 1994, and in the initial combined ANOVA, the effect for year was sig-

[4] TableCurve 2D program, Aisn Software Inc.®, licensed through Jandel Scientific, San Rafael, CA 94901.

Table 1. Back transformed[a] mean survival rates and standard deviation (SD) of cucumber and oats at 0, 1.12, and 2.24 kg/ha simazine herbicide treatments applied to efficient or overwatered microsprinkler irrigation treatments.

		Efficient watering			Overwatered			
		Simazine treated at			Simazine treated at			
Year and species	Time seeded[b]	0 kg/ha Mean ± SD[c]	1.12 kg/ha Mean ± SD	2.24 kg/ha Mean ± SD	0 kg/ha Mean ± SD	1.12 kg/ha Mean ± SD	2.24 kg/ha Mean ± SD	ANOVA[c] significant effects
	Days	%						
1993—Cucumber	14	78 ± 2.1	18 ± 2.3	1 ± 1.8	71 ± 4.2	49 ± 11.8	10 ± 1.3	SL,SQ
	28	85 ± 0.2	40 ± 2.2	14 ± 4.1	92 ± 0.2	88 ± 0.1	67 ± 1.4	SL*I,SQ*I
	56	84 ± 0.8	61 ± 2.6	56 ± 2.1	85 ± 2.1	89 ± 1.3	78 ± 0.8	SQ*I
	84	83 ± 1.0	81 ± 1.6	53 ± 0.7	87 ± 1.0	66 ± 1.8	72 ± 0.4	SL*I
1993—Oats	14	71 ± 0.1	53 ± 0.3	3 ± 0.5	68 ± 1.2	64 ± 2.4	41 ± 1.3	SL*I
	28	53 ± 0.7	27 ± 3.9	9 ± 1.9	84 ± 2.0	56 ± 4.7	48 ± 0.2	I,SL,SQ
	56	78 ± 0.9	69 ± 0.1	49 ± 10.9	78 ± 1.4	71 ± 3.0	81 ± 0.2	NS
	84	73 ± 0.2	62 ± 1.7	42 ± 0.1	78 ± 1.8	76 ± 0.1	75 ± 1.0	SL*I
1994—Cucumber	0	94 ± 4.9	1 ± 1.8	0 ± 0.0	99 ± 0.6	0 ± 0.0	0 ± 0.0	SL,SQ
	14	94 ± 0.9	54 ± 21.9	25 ± 1.9	97 ± 0.1	69 ± 1.0	28 ± 3.2	SL,SQ
	28	87 ± 0.8	76 ± 1.6	43 ± 4.3	98 ± 1.4	92 ± 6.9	92 ± 0.7	I,SL
	56	96 ± 6.7	95 ± 0.9	84 ± 2.6	99 ± 0.6	98 ± 0.1	99 ± 1.8	SL*I
	84	95 ± 3.5	93 ± 1.0	93 ± 2.0	95 ± 0.2	95 ± 0.6	98 ± 1.5	NS
1994—Oats	0	99 ± 0.4	3 ± 8.9	0 ± 0.0	99 ± 0.5	0 ± 0.0	0 ± 0.0	SL,SQ
	14	96 ± 0.4	80 ± 4.0	43 ± 6.2	97 ± 0.2	90 ± 0.1	84 ± 0.3	SL*I
	28	88 ± 0.2	78 ± 3.0	40 ± 10.4	90 ± 2.0	89 ± 0.1	82 ± 0.6	SL*I
	56	89 ± 1.7	93 ± 0.2	73 ± 0.3	91 ± 0.7	94 ± 0.2	93 ± 0.2	SL*I
	84	93 ± 0.1	93 ± 0.2	92 ± 1.3	94 ± 0.1	93 ± 0.2	95 ± 0.7	NS

[a] Data for each subplot were transformed to the arcsine of the square root of the proportion survived. Back transformed proportion data were then re-expressed as percentage values.

[b] Measured from the time of simazine application to the plots.

[c] Significant effects at P = 0.05 where I = irrigation, SL or SQ = simazine linear or quadratic effects, SL*I or SQ*I = Interactive effects, and NS = no significance measured. Main effects not listed when interaction was significant.

nificant. In an attempt to remove the effect for years, data from each block were standardized to the survival rate measured in the control plots by dividing the survival rate measured in each simazine treatment with that measured in the corresponding control plot. These analyses will be referred to as the adjusted data, and they also were subjected to the combined ANOVA. Significant interactions of treatments by year were measured on the adjusted data so the ANOVA was decomposed into an analysis for each year. Interactive effects were graphically presented with the error bars for each mean calculated from the overall experimental variance, which was determined as the square root of the respective ANOVA error mean square.

RESULTS AND DISCUSSION

The means and standard deviations for the back transformation of transformed data are in Table 1. Although the transformation had little effect on the estimate for treatment means, the standard deviations for the transformed data were greatly reduced with an average reduction of 80% from the original value. A few treatments exhibited large variance, which in simazine treatments was usually caused by one of the three blocks exhibiting a higher than expected survival rate. A higher than expected survival rate could have been caused by variation in simazine and water applications in relation to the exact placement of the seeds. Addition of the day 0 treatment in 1994 confirmed the effectiveness of all simazine treatments in that essentially no plants survived at either application rate. Indication of day 0 marks the initiation of simazine application. Plants seeded at this time took approximately 7 d to emerge with an additional 17 d until the measurement of survival rate.

Significant interactions between simazine application rate and the amount of water applied were indicated by ANOVAs conducted for each seeding date. In 1993, significant interactions between simazine and irrigation treatments were measured for cucumber when seeded at 28, 56, and 84 d and for oats when seeded at 14 and 84 d after application (Table 1). In 1994, significant interactions were measured for cucumber when seeded at 56 d and for oats when seeded at 14, 28, and 56 d after simazine application. In most cases, the interaction appeared to be due to a prolonged effect of the 2.24-kg/ha simazine treatment on survival rate at the efficient water treatment.

The longer bioactivity of simazine applications in the efficient irrigation treatment was evident in a comparison

Table 2. Estimated parameters for a fit of the power function to survival of cucumber and oats in simazine-treated plots that received efficient or overwatered microsprinkler irrigation treatments. Data adjusted to survival measured in control plots.

	Treatment combination		Block 1			Block 2			Block 3		
Species, year	Simazine	Irrigation[a]	a[b]	b	P level[c]	a	b	P level	a	b	P level
	kg/ha										
Cucumber, 1993	1.12	Overwatered	0.561	0.170	0.019	0.486	0.246	0.017	0.786	0.158	0.007
	1.12	Efficient	0.119	0.562	0.003	0.124	0.569	0.008	0.111	0.551	0.008
	2.24	Overwatered	0.119	0.526	0.006	0.271	0.363	0.023	0.234	0.410	0.002
	2.24	Efficient	0.043	0.728	0.020	0.009	1.029	0.014	0.032	0.812	0.006
Cucumber, 1994	1.12	Overwatered	0.527	0.235	0.001	0.535	0.262	0.002	0.593	0.211	0.001
	1.12	Efficient	0.876	0.123	0.002	0.111	0.620	0.004	0.434	0.301	0.001
	2.24	Overwatered	0.355	0.351	0.001	0.225	0.461	0.010	0.251	0.414	0.002
	2.24	Efficient	0.336	0.328	0.001	0.081	0.664	0.001	0.054	0.769	0.001
Oats, 1993	1.12	Overwatered	0.678	0.164	0.029	0.611	0.232	0.001	0.656	0.170	0.024
	1.12	Efficient	0.286	0.341	0.011	0.499	0.224	0.012	0.570	0.170	0.003
	2.24	Overwatered	0.480	0.251	0.005	0.220	0.430	0.001	0.384	0.310	0.003
	2.24	Efficient	0.121	0.454	0.007	0.007	1.103	0.001	0.063	0.668	0.071
Oats, 1994	1.12	Overwatered	0.694	0.188	0.002	0.738	0.191	0.001	0.722	0.185	0.002
	1.12	Efficient	0.997	0.091	0.001	0.431	0.281	0.002	0.665	0.213	0.001
	2.24	Overwatered	0.618	0.220	0.001	0.634	0.221	0.001	0.657	0.193	0.001
	2.24	Efficient	0.477	0.251	0.002	0.186	0.429	0.001	0.044	0.809	0.003

[a] Designation of irrigation treatments as efficient and overwatered refers to irrigation water managed at 110 and 175%, respectively, of nectarine orchard crop requirements.

[b] Power function fit ($y = ax^b$) where y = transformed survival data, x = days initiation of herbicide treatment, and a and b = estimated parameters for fit of equation.

[c] Level of significance for fit of equation to data using nonlinear ANOVA (SAS) program with 2 degrees of freedom in model and 3 in error term.

of the time at which 50% survival was attained. This analysis was conducted on the four treatments where simazine was applied, and it was based on the data for all time intervals within a treatment. In 1994, the average survival rate for both species at the 0-kg/ha simazine treatment was 95%, whereas the rate was lower in 1993 at 78% (Table 1). In an attempt to account for potential differences between years, data were adjusted by standardizing the observed rates in each treatment to that measured in the control (0 kg/ha) treatment for each block. Estimated parameters for a fit of the power function to the adjusted data in each block are presented in Table 2. Overall, the fit of the power function provided an accurate representation for the effect of treatments over time. Some potentially problematic fits are illustrated in Figure 1. In Figure 1A, plants seeded in some blocks at the latest date in 1993 exhibited greater than the expected death rates. In this case, the power curve provided a reasonable interpretation of the data, i.e., survival rates increased over time. In Figure 1B, the set of blocks that contained the least significant probability value (Figure 1B, block 3) was plotted, but again the power curve produced a reasonable fit for the observed data. Table 3 contains the estimated time for seedlings to reach 50% survival in simazine treatments as derived from a fit of the power function to unadjusted and adjusted data. The following discussion focuses on the adjusted values, where year effects were minimized.

The combined ANOVA for treatment effects on length of time to reach 50% survival indicated significant interaction of treatments with years; thus, the analysis was decomposed to ANOVAs conducted within each year (Table 4). For 1993, there was a significant interaction between species, simazine, and irrigation water applications. As illustrated in interaction graphs for the effect of simazine and irrigation water application for each species, the responses were similar between species (Figures 2A and 2B). The length of time to 50% survival in both species was increased by the same magnitude in efficient water irrigation treatments at the 2.24-kg/ha simazine treatment. The interaction was caused by an enhanced effect of efficient irrigation at the 1.12-kg/ha treatment in cucumber that was not observed in oats. For 1994, the interaction between simazine and irrigation water applications was significant, indicating that treatment effects were similar in both species. According to interaction graphs of the overall mean for both species, the length of time to 50% survival was increased in efficient irrigation water treatments but only at the 2.24-kg/ha application rate (Figure 2C).

There was no effect of irrigation water level on survival rate in the control plots (0 kg/ha simazine), so the amount of water applied, per se, did not limit emergence and, subsequently, survival rates of seedlings (Table 1). The effect of efficient irrigation water treatment was to enhance the performance of simazine. Accordingly, loss

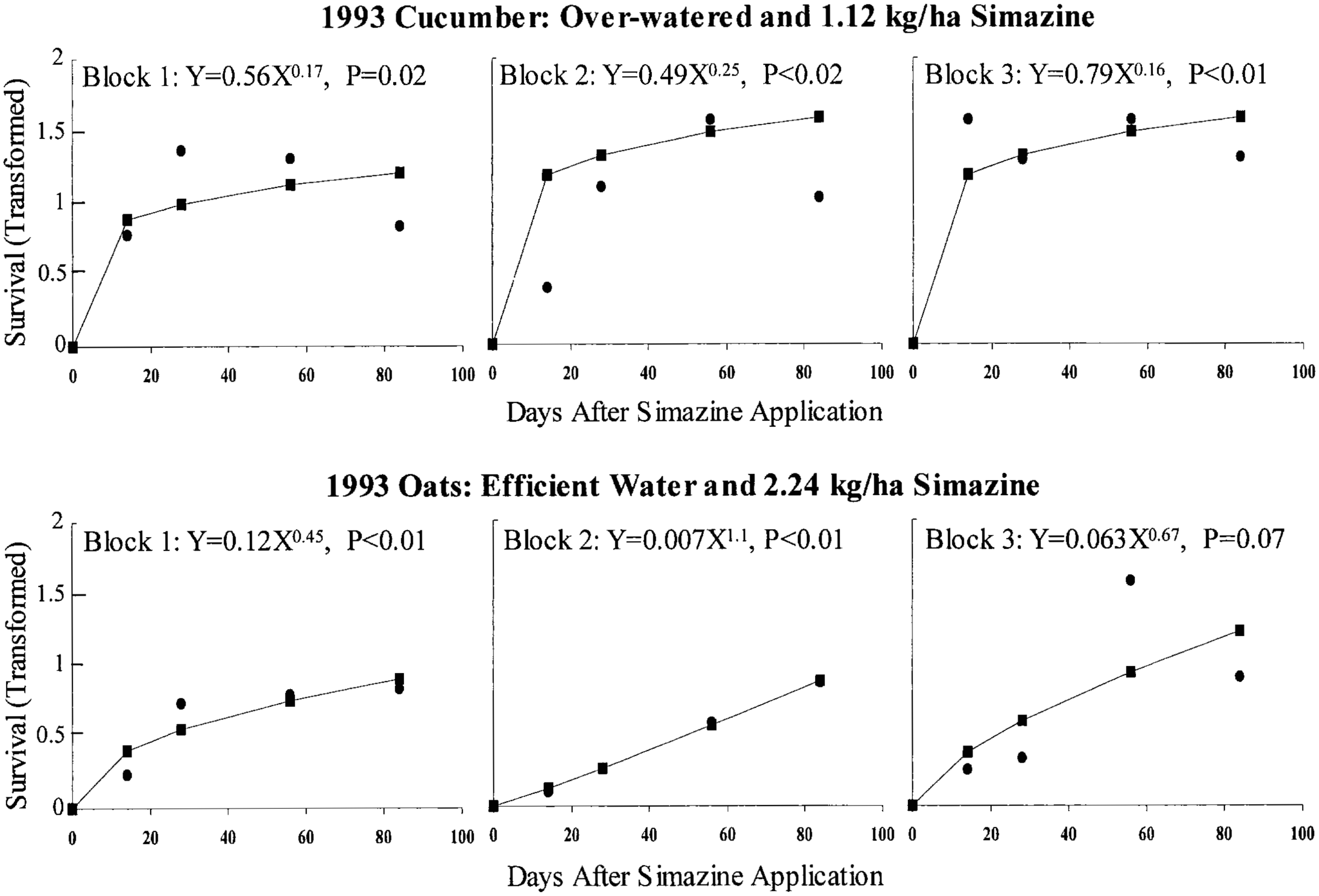

Figure 1. Comparison of observed to predicted values for transformed survival rate. Predicted values were derived from a fit of the power equation to transformed survival rates measured in each block. Solid circles, observed values; solid squares, predicted value and line.

of simazine's effectiveness in the overwatered irrigation treatments could have been caused by percolation of water through the effective root zone or by enhanced degradation of residues within the effective root zone, or both. With respect to deeper soil movement of water, simazine was chosen because it is prone to leach through soil, especially on coarser soils with low organic carbon content. Residues would have been dissolved in percolating water and moved to deeper layers of soil where they would not have been accessible for uptake by young cucumber or oat seedlings. Leaching of atrazine, a similar triazine preemergence herbicide, had previously been related to the amount of percolating water produced from irrigation (Troiano et al. 1993). With respect to enhancement of degradation pathways, increases in soil water content could have increased the dissipation of residues caused either by chemically induced hydrolysis or by biological degradation. In general, degradation rates are greater as soil water content increases (Baer and Calvet 1999; Cupples et al. 2000).

Adjusting the data to the survival rate in control plots did not remove all year effects. Although the adjustment resulted in some lowered values for the 1993 data, the statistical analysis was unaffected. The cause for the effect between years is unclear but it may have been due to a combination of differences in climatic and experimental conditions. The study in 1993 was initiated at the end of April, whereas in 1994 the study was initiated at the end of March. The later start in 1993 provided higher average air temperature (22.7 vs. 19.1 C) and solar radiation (328 vs. 289 W/m^2) and slightly lower rainfall. Also, as stated previously, irrigation management differed between years with actual applications lower than targeted applications in 1993. One of the consequences of less water application in the hotter year (1993) may have been to retain residues in the upper soil layers for an extended period of time, prolonging the bioactivity of simazine treatments and emphasizing the effect of irrigation water applications (Figure 2). The consistency in treatment effects between years is biologically more

Table 3. Effect of simazine treatments applied to efficient or overwatered microsprinkler irrigation treatments on the estimated time for seedlings to reach 50% survival rate. A longer time period indicates prolonged herbicidal activity.

Treatment combination		Estimated time for 50% seedling survival			
		Cucumber		Oats	
Simazine	Irrigation[a]	1993 Mean ± SD	1994 Mean ± SD	1993 Mean ± SD	1994 Mean ± SD
kg/ha		days			
Unadjusted data[b]					
1.12	Overwatered	11 ± 7	5 ± 1	16 ± 8	3 ± 1
1.12	Efficient	41 ± 7	12 ± 13	32 ± 1	5 ± 6
2.24	Overwatered	33 ± 9	13 ± 3	25 ± 7	4 ± 1
2.24	Efficient	69 ± 12	30 ± 11	81 ± 14	28 ± 17
Data adjusted to survival in control plots[b]					
1.12	Overwatered	5 ± 3	5 ± 1	3 ± 1	2 ± 1
1.12	Efficient	30 ± 5	10 ± 12	11 ± 7	4 ± 4
2.24	Overwatered	25 ± 10	13 ± 3	12 ± 6	3 ± 1
2.24	Efficient	60 ± 12	25 ± 11	60 ± 16	15 ± 25

[a] Designation of irrigation treatments as efficient and overwatered refers to irrigation water managed at 110 and 175%, respectively, of nectarine orchard crop requirements.

[b] Estimates for both unadjusted and adjusted data produced from fits of a power function to survival data. However, only parameters for adjusted data are reported in Table 2.

Table 4. ANOVA table for effect of species, simazine, and irrigation water applications on estimated time until 50% survival of oat or cucumber seedlings. Data adjusted to survival measured in control plots.

Year	Effect	ANOVA statistics		
		DF	Mean square	P level[a]
1993	Block	2	134.14	0.200
	Species	1	404.94	0.030
	Simazine (sim)	1	4403.21	0.001
	Irrigation water amount (irrig)	1	5092.17	0.001
	Species × sim	1	29.56	0.535
	Species × irrig	1	4.05	0.817
	Sim × irrig	1	936.17	0.003
	Species × sim × irrig	1	328.90	0.052
	Residual error	14	72.93	
1994	Block	2	4.38	0.033
	Species	1	4.15	0.061
	Simazine (sim)	1	17.62	0.001
	Irrigation water amount (irrig)	1	14.33	0.002
	Species × sim	1	0.06	0.810
	Species × irrig	1	0.24	0.634
	Sim × irrig	1	5.52	0.034
	Species × sim × irrig	1	1.45	0.249
	Residual error	14	43.85	

[a] Exact probability level for effect.

significant than the overall differences between years. Efficient irrigation improves simazine performance and efficiency despite differences in environmental conditions.

This study illustrates the potential importance that irrigation decisions have with respect to herbicidal activity. A large portion of California is classified as Mediterranean in climate, so irrigation is required for crop production. Historically, irrigation management and pesticide application decisions have been made independently. The result of this study indicates that linking these two decision-making areas together should result either in cost savings with respect to herbicide expenditures or in increased effectiveness of herbicide applications. For example, if a grower were to move toward reduction of percolating water through improved irrigation management, one might experience better product effectiveness when using standard rates. Alternatively, rates of application could be potentially lowered without reduction in efficacy. Benefits of efficient irrigation may be realized in coarse-textured soils where the potential for percolating water is highest and where organic carbon content is low, providing little sorption and retardation of herbicide movement. The soil for this study was a sandy loam with low organic carbon content. Potential for increased simazine efficiency in relation to irrigation management on finer-textured soils requires further study. Lastly, the effect of irrigation management on herbicide effectiveness should be investigated for pesticides with lower potential to move off-site, such as

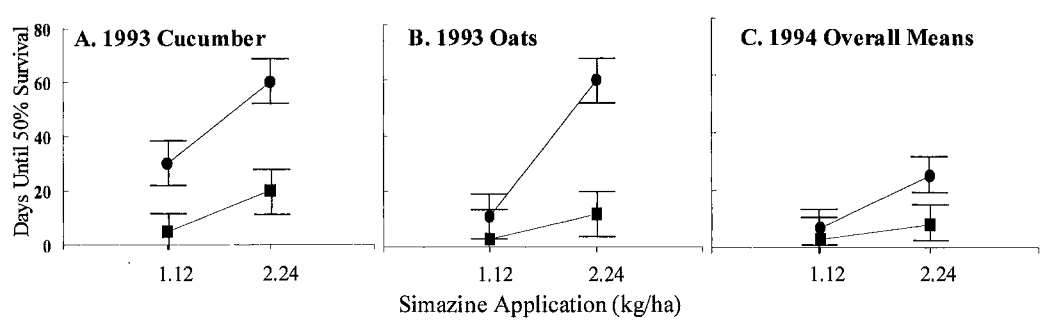

Figure 2. Interaction graphs for the effects of simazine and irrigation water applications on the length of time to reach 50% survival of seedlings, where A and B are data plotted for each species in 1993, and C is a plot of the overall means for both species in 1994. Error bars for each mean were based on overall experimental variance, which was calculated as the square root of the error mean square from the ANOVA for each year. Solid circles, efficient irrigation treatments; solid squares, overwatered irrigation treatments.

those with very high sorption, fast degradation, or extremely low water solubility.

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