Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Adamson DM, Sbatella GM, Kniss AR, Dayan FE (2024). Reduced irrigation impact on soil-applied herbicide dissipation and rotational crop response. Weed Technol. **38**(e11), 1–8. doi: 10.1017/wet.2023.85

Received: 5 September 2023
Revised: 9 November 2023
Accepted: 15 November 2023

Associate Editor:
Drew Lyon, Washington State University

Nomenclature:
Atrazine; dimethenamid-P; ethalfluralin; imazethapyr; isoxaflutole; pendimethalin; pyroxasulfone; saflufenacil; trifluralin; corn, *Zea mays* L.; dry bean, *Phaseolus vulgaris* L.; sugar beet, *Beta vulgaris* L.

Keywords:
Pesticide fate; crop rotation; herbicide persistence; soil half-life; drought; soil moisture

Corresponding author:
Andrew R. Kniss; Email: akniss@uwyo.edu

Reduced irrigation impact on soil-applied herbicide dissipation and rotational crop response

Daniel M. Adamson[1], Gustavo M. Sbatella[2], Andrew R. Kniss[3] and Franck E. Dayan[4]

[1]Graduate Research Assistant, Department of Plant Sciences, University of Wyoming, Laramie, WY, USA; [2]Assistant Professor (deceased), Department of Plant Sciences, University of Wyoming, Powell, WY, USA; [3]Professor, Department of Plant Sciences, University of Wyoming, Laramie, WY, USA and [4]Professor, Department of Agricultural Biology, Colorado State University, Fort Collins, CO, USA

Abstract

Soil-applied herbicides are important for controlling weeds in many crops but risk damage to susceptible rotational crops if they persist. Field studies were conducted in Powell, WY, from 2015 through 2017 to evaluate the effect of reduced water availability on soil-applied herbicide dissipation. Eight soil-applied herbicides, applied to dry bean or corn, were exposed to three season-long irrigation treatments (100%, 85%, and 70% of estimated crop evapotranspiration [ETc]) by overhead sprinkler. Soil samples were collected to a depth of 10 cm from 0 to 140 d after application, and soil herbicide concentrations were quantified using gas or liquid chromatography and mass spectrometry. Herbicide concentrations were regressed over time to produce a soil half-life estimate for each herbicide and irrigation treatment. Reduced irrigation decreased dry bean yield by up to 77% and corn yield by up to 50%. After adjusting for precipitation, the lowest irrigation treatment received 78% and 76% as much water as the full irrigation treatment in 2015 and 2016, respectively. This significantly increased the soil half-life of imazethapyr but did not increase the soil half-life of atrazine, pyroxasulfone, saflufenacil, ethalfluralin, trifluralin, or pendimethalin. Reduced irrigation did not increase carryover injury to rotational crops from these herbicides 1 yr after application. Instead, carryover response was determined by the inherent persistence of individual herbicides. Imazethapyr (0.1 kg ai ha^{-1}) injured rotational sugar beet, and isoxaflutole (0.1 kg ai ha^{-1}) injured rotational dry bean. Pyroxasulfone (0.2 kg ai ha^{-1}), atrazine (2.0 kg ai ha^{-1}), saflufenacil (0.1 kg ai ha^{-1}) + dimethenamid-P (0.6 kg ai ha^{-1}), ethalfluralin (0.8 kg ai ha^{-1}), trifluralin (0.6 kg ai ha^{-1}), and pendimethalin (1.1 kg ai ha^{-1}) did not injure rotational crops regardless of irrigation treatment. Drought stress sufficient to cause up to 77% crop yield loss did not increase soil-applied herbicide carryover.

Introduction

Water management has always been a key challenge to agricultural food production. Historical hurdles to water management in semiarid and arid climates were primarily concerned simply with providing water to crops through irrigation, fallowing, or planting adapted crop varieties. Modern challenges to agricultural water use present growing complexity in the face of increasing nonagricultural water demand, salinization, and climate-induced changes to regional hydrologic cycles (Barnett et al. 2004; Pendergrass et al. 2017; Pereira 2017; Sabo et al. 2010). Currently a vast majority of agricultural land, both irrigated and rain fed, is impacted by water stress, with 76% and 56% of global croplands experiencing water scarcity for at least 1 mo yr^{-1} and at least 5 mo yr^{-1}, respectively (Rosa et al. 2020).

Considering the increasing pressure on water resources, agricultural land managers must prepare for limited water availability in the future by maximizing irrigated water use efficiency (Jensen et al. 2014) and preparing to manage recurring drought (Adee et al. 2016; Wilhelmi and Wilhite 2002). However, because agroecosystems are complex, many management hurdles must be considered to reduce agricultural water consumption, and research should be concerned not only with water's direct effect on crop yield but with how the whole agroecosystem is affected, including weed management.

Water management and weed management are directly related. Water placement and timing influence weed distribution, weed density, weed diversity, and herbicide performance. Soil-applied herbicides (SAHs) are particularly sensitive to soil water. Water is arguably the most important factor affecting the performance, movement, and dissipation of SAHs, as it directly influences adsorption (Stickler et al. 1969), leaching (Fait et al. 2010; Helling et al. 1988), volatilization (Grover et al. 1997), and abiotic (Wolfe et al. 1990) and biotic degradation of SAHs in soil (Colquhoun 2006; Van Eerd et al. 2003). Numerous studies have documented that SAHs are more persistent in dry soil (Flint and Witt 1997; Moyer et al. 2010; Mueller and Steckel 2011; Reinhardt and Nel 1993), meaning that irrigation and precipitation are critical factors when considering SAH management (Yaron et al. 1985).

The reoccurring risk of drought and the inevitable reduction of water allotted to agriculture in the future mean that farmers must use complementary herbicide and water management practices, but reductions in soil water raise concerns of increased persistence or carryover of SAHs (Colquhoun 2006). Commonly, herbicide dissipation field studies are performed in rain-fed systems, and carryover injury to rotational crops is noted during the occurrence of drought. In exemplary studies, increased SAH carryover was observed in dry years that had only 54%, 43%, 42%, or even 28% precipitation compared to a wet study year (Hayden and Smith 1980; Moyer et al. 2010; Mueller et al. 2014; Mueller and Steckel 2011). However, this level of severe drought is not a complete representation of predicted agronomic water management in the future, and dissipation should also be examined in the scope of moderate drought, reduced irrigation, and altered climatic and irrigation precipitation timings.

Relatively few studies have directly examined the effects of altered irrigation on herbicide persistence and carryover in the soil. DaSilva et al. (2003) reported better performance and reduced dissipation of simazine in an efficiently irrigated orchard compared to an overwatered one. Shaner and Wiles (2009) also worked with atrazine in a variety of deficit irrigation cropping systems but observed that prior use and preconditioning were more important in determining dissipation than water. Half-life of atrazine was not significantly different in continuous corn for full (530 to 560 mm) and deficit (410 to 440 mm) irrigation.

As agronomic water management evolves, we cannot afford to lose the use of SAHs, which remain important tools for weed control and herbicide resistance management (Vencill et al. 2012; Young 2006). The generalization that herbicide persistence increases in dry soil should be refined in an era when availability of irrigation water is decreasing and precipitation variability may be increasing. The objective of this work was to investigate how an agronomically viable water deficit (sufficient to produce a profitable yield) impacts SAH dissipation and potential for rotational crop injury.

Materials and Methods

Study Design and Crop Management

Field experiments were initiated in 2015 and 2016 at the Powell Research and Extension Center in Powell, WY (44.78°N, 108.75°W). The soil corresponds to the Garland series (fine-loamy over sandy or sandy skeletal, mixed, superactive, mesic Typic Haplargids). The upper profiles of the soil are characterized by a loam to clay loam texture with pH 7.8 and organic matter of 1.2%. Precipitation and temperature for Powell for 2015 and 2016 are presented in Table 1.

Table 1. Temperature and precipitation for Powell, WY, in 2015 and 2016.

	Average temperature		Precipitation	
Month	2015	2016	2015	2016
	C		mm	
Jan	−6	−5	3	1
Feb	0	2	2	1
Mar	5	5	3	4
Apr	8	9	12	17
May	11	12	51	30
Jun	20	20	14	6
Jul	21	21	7	14
Aug	20	20	11	6
Sep	17	14	0	40
Oct	11	9	20	32
Nov	−1	4	2	6
Dec	−5	−9	3	2

Table 2. Herbicide application rates and labeled crop application sites.

Herbicide	Rate	Crop
	kg ai ha^{-1}	
Atrazine	2.00	corn
Isoxaflutole	0.09	corn
Saflufenacil + dimethenamid-P	0.07 + 0.61	corn
Pyroxasulfone	0.18	corn
Imazethapyr	0.11	dry bean
Pendimethalin	1.06	dry bean
Ethalfluralin	0.84	dry bean
Trifluralin	0.56	dry bean

The study was designed as a split-plot randomized complete block design with three replicates for each treatment, with irrigation rate (whole plot) and herbicide (split plot) as factors. Each experiment lasted 2 yr. In the first year, corn and dry bean were planted in 55-cm rows into plots that measured 33.5 m wide and 40 m long, allowing for different overhead sprinkler irrigation rates to provide 100%, 85%, or 70% of estimated crop evapotranspiration (ETc) to the whole plots. Whole plots were subdivided into split plots 6.7 m wide and 40 m long for herbicide treatment. Herbicide treatments applied to the split plots for each crop are described in Table 2.

In the second year of the experiment, rotational crops were planted over the original plots to determine the effects of herbicide carryover. The original 40-m length of the main plots was split into thirds and planted with a rotational crop as a strip across all main plots in the block (effectively making the study a strip-split-plot design for the second-year crop response). Plots originally cropped to corn the first year were rotated to dry bean and sugar beet in the second year. Plots originally cropped to dry bean in the first year were rotated to corn and sugar beet in the second year. This approach exposed rotational crops to the combinations of herbicide and irrigation rate applied the preceding year. The study was conducted twice: the first study was initiated in 2015 and completed in 2016, whereas the second study was initiated in 2016 and completed in 2017.

In 2015 and 2016, corn and dry bean were planted into clean-tilled seedbeds during the last week of May or first week of June. Following planting, but prior to crop emergence, herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 150 L ha^{-1} at 276 kPa and with a walking speed of 5 km h^{-1}. Completion of spraying took 6 to 8 h in winds that remained below 16 km h^{-1}. Herbicide rates are summarized in Table 2. Glyphosate (1.3 kg ae ha^{-1}) was applied at the same time in all plots to control any emerged weeds.

All plots were irrigated 19 mm following herbicide application to incorporate the herbicides. Afterward, all irrigations were scheduled according to estimated ETc using the FAO-56 Penman–Monteith method with basal crop coefficient values and crop growth stages adjusted to local climatic conditions (Allen et al. 1998). Irrigation for all treatments was initiated when the fully irrigated (100% ETc)

https://doi.org/10.1017/wet.2023.85 Published online by Cambridge University Press

Table 3. Herbicide extractant, analytical method, and recovery.[a,b]

Herbicide	Extractant	Method	Recovery
			% (*SD*)
Atrazine	dichloromethane	GC/MS[b]	84 (24)
Ethalfluralin	toluene	GC/MS	97 (7)
Imazethapyr	0.5 N NaOH	LC/MS	91 (2)
Isoxaflutole	NA	NA	NA
Pendimethalin	toluene	GC/MS	94 (12)
Pyroxasulfone	toluene	GC/MS	94 (4)
Saflufenacil	acetonitrile	LC/MS	91 (2)
Trifluralin	toluene	GC/MS	92 (16)

[a]Attempts to develop a successful extraction method for isoxaflutole were unsuccessful because of difficult recovery of the diketonitrile metabolite.
[b]Abbreviations: GC/MS = gas chromatography/mass spectrometry; LC/MS = liquid chromatography/mass spectrometry; NA = not applicable.

treatment had reached the non-yield-limiting root zone water depletion level. Irrigation volume was then adjusted to approximately 85% and 70% of the full amount using a variable rate irrigation system. Volumetric soil water content (m^3 m^{-3}) was monitored in eight locations for each irrigation treatment using GS1 soil moisture sensors (Decagon Devices, Pullman, WA, USA) placed at 7.6-cm and 15.2-cm depths. Yields of corn and dry bean were determined at physiological maturity by harvesting 3-m lengths of row in six locations per plot.

Herbicide Dissipation

Methods to study dissipation were based off Mueller and Senseman (2015). A sampling schedule was developed prior to herbicide application to account for typical degradation kinetics of herbicides. Soil samples were taken within 1 h of herbicide application, at 24 h following application, then at 7, 14, 21, 28, 42, 56, 70, 84, 112, and 140 d after application (DAA). Soil samples were collected using a golf hole cutter of 10.8 cm diameter and 10 cm depth. Three samples were taken per plot, homogenized, and placed into plastic freezer bags for storage. Samples were immediately placed in a cooler, then transported to a freezer within 1 h, where they remained until analysis. The sampler and collection materials were cleaned between plots with a water–ammonia solution to avoid cross-contamination.

Samples were kept frozen and allowed to thaw only once they reached the lab for analysis. In the lab, soil was rehomogenized in the plastic bag, then a 5-g subsample containing particles <2 mm was transferred into 11-mL glass screw-cap vials for extraction. A second subsample was collected to determine gravimetric moisture content (w/w).

Herbicide was extracted from soil by applying an appropriate solvent (Table 3). Liquid chromatography mass spectrometry (LCMS)-grade toluene was used for pyroxasulfone, pendimethalin, ethalfluralin, and trifluralin extractions. LCMS-grade dichloromethane was used for atrazine extractions. Liquid chromatography mass spectrometry (LCMS)-grade acetonitrile was used for saflufenacil extraction, and a 0.5 N solution of NaOH was used to extract imazethapyr. Five milliliters of solvent were added to the 5 g of soil, then the sample was vigorously shaken by hand. All samples were then shaken for 1 h on a shaker table oscillating at 240 rpm prior to centrifugation for 15 min at 2,000 rpm. A 3-mL aliquot of supernatant was transferred to a clean tube prior to adding another 5 mL of solvent to the soil as described in the previous step. Another 3-mL aliquot was combined with the first for a total of 6 mL of supernatant, of which 1 mL was transferred to a glass autosampler vial for analysis, where 10.1 μL of butylate was added as an internal standard (gas chromatograph/mass spectrometer [GC/MS] only).

Pyroxasulfone, atrazine, pendimethalin, ethalfluralin, and trifluralin were all analyzed on a GC/MS Shimadzu GC-2010 with an AOC-20i autoinjector, an AOC-20S autosampler, and a QP-2010 mass spectrometer (Shimadzu Scientific Instruments, Columbia, MD, USA). Herbicide concentrations were analyzed by the GC/MS as a 1-μL injection of the supernatant flowing through a Shimadzu SHR5XLB 30 m × 0.25 mm × 0.25 μm column with helium carrier gas. Ion source and interface temperatures were both set at 260 C. The oven gradient temperature increased from 55 C to 260 C at a rate of 10 C min^{-1}. The oven was then maintained at 260 C until returning to 55 C for a total run time of 33 min. Masses were detected as single ion monitoring set to m/z 200 for atrazine (Dagnac et al. 2005), m/z 179.10 for pyroxasulfone (Westra et al. 2015), m/z 252 for pendimethalin (Hirahara et al. 2005), m/z 276 for ethalfluralin (Sanchez-Brunete et al. 1998), and 306 m/z for trifluralin (Hirahara et al. 2005). The concentration of each herbicide was quantified relative to a butylate standard (m/z 146).

Saflufenacil and imazethapyr were analyzed on a liquid chromatograph/mass spectrometer (LC/MS) consisting of a Nexera X2 ultra high performance liquid chromatograph (Shimadzu Scientific Instruments), with 2 LC-30AD pumps, a SIL-30ACMP autosampler, a DGU-20A5 prominence degasser, a CTO-30A column oven, and an SPD-M30A diode array detector coupled to an 8040 quadrupole mass spectrometer (Shimadzu Scientific Instruments, Columbia, MD, USA). Imazethapyr levels were detected in positive mode with a multiple reaction monitoring (MRM) of 290.10 > 177.1 (Sack et al. 2015). The mass spectrometer was set for a 100-ms dwell time with a Q1 prebias of −14.0 V, a collision energy of −30.0 V, and a Q3 prebias of −18 V. The samples were chromatographed on a 100 × 4.6 mm F5 2.6-μm column (Phenomenex, Torrance, CA, USA) maintained at 40 C. Saflufenacil levels were detected in positive mode with three product ions contributing approximately one-third of the total ion. The first product had an MRM of 501 > 197.5. The MS was set for a 100-ms dwell time with a Q1 prebias of −34 V, a collision energy of −48 V, and a Q3 prebias of −19 V. For the second product, the MRM was 501 > 349 with a 100-ms dwell time and a Q1 prebias of −24 V, a collision energy of −28 V, and a Q3 prebias of −24 V. For the third product, the MRM was 501 > 459 with a 100-ms dwell time and a Q1 prebias of −24 V, a collision energy of −16 V, and a Q3 prebias of −23 V. Samples were chromatographed on a biphenyl Kinetex® (Phenomenex) 2.6-μm, 100-Å, 100 × 4.6 mm column.

Solvents and flow rates for imazethapyr and saflufenacil both used the following protocol: solvent A consisted of water with 0.1% formic acid, and solvent B was methanol. Relative concentrations according to time (min) were 40% B at start, 95% B at 5 min, 95% B at 7 min, 40% B at 7.1 min, and 40% B at 12 min. Flow rate was set at 0.4 mL min^{-1}. Injection volume was 1 μL for both herbicides.

A protocol for extracting isoxaflutole and its diketonitrile metabolite was developed, but extractions were not performed because of poor and erratic recovery of the combined molecules. Although dimethenamid-P was applied in a mixture with saflufenacil in the field, dimethenamid-P degradation was not analyzed, as dimethenamid-P is labeled for use in the rotational crops used in this study.

Herbicide concentrations were adjusted for moisture and reported as herbicide concentration in nanograms per gram

https://doi.org/10.1017/wet.2023.85 Published online by Cambridge University Press

dry soil. Concentrations were then adjusted for their respective extraction efficiency (Table 3), which was determined by spiking clean soil with known amounts of analytical herbicide active ingredient and extracting with the same methods described earlier. Soil sampling dates selected for extraction depended on individual herbicides. Samples taken at time 0 and 28 DAA were analyzed first for all herbicides, then four to six other dates were selected for analysis to develop a useful regression to estimate soil half-life without expending excess time and resources to analyze all soil samples.

Field Bioassay

To determine the effects of SAH carryover, a field bioassay was performed. The field bioassay composed the second year of the field study for each repetition of the experiment. Following the application of herbicides and irrigation treatments from the previous year, rotational crops were planted in strips across the original plots. In plots receiving herbicides labeled for corn (atrazine, saflufenacil + dimethenamid-P, pyroxasulfone, isoxaflutole) in the previous year, rotational dry bean and sugar beet were planted. In plots receiving herbicides labeled for dry bean (imazethapyr, pendimethalin, ethalfluralin, trifluralin) in the previous year, rotational corn and sugar beet were planted. All plots were irrigated with the same ETc levels as in the previous year. Weeds were controlled with a preplant burndown of glyphosate (1.3 kg ae ha^{-1}) and hand weeding after crop emergence as needed. Mid-season, dry bean received one application of bentazon (0.9 kg ai ha^{-1}), sugar beet received one to two applications of glyphosate (1.3 kg ae ha^{-1}), and corn received one application of glyphosate (1.3 kg ae ha^{-1}) + fluroxypyr (0.2 kg ai ha^{-1}). Rotational crop yield was measured at physiological maturity by harvesting 3-m lengths of row in six locations per plot.

Statistical Analysis

Crop yield, as affected by irrigation level and herbicide, was analyzed using a linear mixed effects model in R 4.1.1 (Bates et al. 2015; R Core Team 2023), with herbicide treatment and irrigation level as fixed effects and block and study year as random effects. Means separation was performed using Tukey-adjusted pairwise comparisons at $\alpha = 0.05$ using the MULTCOMP and EMMEANS packages (Hothorn et al. 2008; Lenth 2022).

Herbicide degradation was analyzed as nonlinear regression using the DRC package version 3.0-1 in R (Ritz et al. 2015). The following nonlinear model was used to regress herbicide concentration over time as influenced by irrigation level:

$$C_t = C_0 \times \exp^{-t/k} \qquad [1]$$

where C_t is herbicide concentration (ng g^{-1} soil) at time t, t is time (d), C_0 is average herbicide concentration immediately after application (ng g^{-1} soil), and k is a rate constant (EPA 2023). To estimate the dissipation rate in the field, DT_{50} was estimated from the model using the method described by the EPA (2023):

$$DT_{50} = \log(2) \times k \qquad [2]$$

DT_{50} is defined as the time (d) when 50% of the initial herbicide concentration had dissipated. Because herbicides were applied at the same rate for all irrigation treatments, the C_0 parameter was fixed as the average soil herbicide concentration for all three irrigation treatments at 0 DAA. This avoided biasing herbicide dissipation half-life (DT_{50}) estimates resulting from measured differences in initial concentration due to inherent experimental variation. A 95% confidence interval of the fixed C_0 parameter was also calculated to visualize variation in initial herbicide concentration.

To determine the influence of irrigation level and study year on herbicide dissipation, analysis of variance was also performed on herbicide concentration with irrigation level, DAA, and study year as factors. If study year was a significant source of variation, nonlinear regression was performed separately for each study year. Similarly, if irrigation level was a significant model factor, nonlinear regression was performed separately for each irrigation level. Otherwise, nonlinear regression was performed on compiled data from all irrigation levels and study years for each herbicide.

Results and Discussion

For both study years, soil moisture status remained lower in the moderate and low irrigation treatments than the full irrigation treatment (Figure 1). Irrigation treatment targets were 100%, 85%, and 70% ETc; however, after adjusting for precipitation and actual sprinkler output, total water received by the moderate and low irrigation treatments was 87% and 78% of the full irrigation treatment in 2015, respectively, and 86% and 76% of the full irrigation treatment in 2016, respectively (Table 4). Corn and dry bean yields were significantly reduced in the 87% and 78% irrigation treatments in 2015, confirming that the applied irrigation treatments successfully impacted the biology of the system (Table 4). In 2015, corn ETc exceeded total irrigation + precipitation received by the full irrigation treatment, so in 2016, we increased irrigation rates to match corn ETc. In 2016, there was no significant difference in yield for corn and dry bean between the 100% and 86% irrigation treatments, but the 76% irrigation treatment reduced corn and dry bean yields compared to all other irrigation treatments (Table 4).

Although we successfully induced yield-reducing drought stress to crops in both years of the study, in all cases but one, dissipation of SAHs was not significantly slower in reduced irrigation treatments compared to fully irrigated treatments ($P > 0.05$; Figures 2 and 3). This is contrary to the general expectation of slower dissipation in drier soil conditions (Colquhoun 2006; Curran 2016). Irrigation level was a significant model factor in only two instances: for imazethapyr dissipation in 2015 and 2016 ($P = 0.04$), as well as pyroxasulfone dissipation in 2015 ($P = 0.02$). Imazethapyr DT_{50} increased with decreasing irrigation level (Table 5); however, unexpectedly, DT_{50} of pyroxasulfone in 2015 was longest in the fully irrigated treatment compared to the reduced irrigation treatments (Table 5).

Rotational crop responses supported the results of the measured herbicide dissipation rates, as there was never a significant interaction ($P > 0.05$) between herbicide and irrigation level. Instead, rotational crop response was determined by the inherent persistence of the individual herbicide and its toxicity to specific rotational crops. For rotational corn, no herbicide reduced yield (Table 6). For rotational sugar beet, imazethapyr reduced yield, but trifluralin, pendimethalin, ethalfluralin, isoxaflutole, pyroxasulfone, saflufenacil, and atrazine did not (Table 6). For rotational dry bean, saflufenacil, pyroxasulfone, and atrazine had no effect, whereas isoxaflutole reduced yields (Table 6). For isoxaflutole, we were unable to compare this effect with modeled soil dissipation because of our inability to detect isoxaflutole's diketonitrile metabolite in the soil.

https://doi.org/10.1017/wet.2023.85 Published online by Cambridge University Press

Table 4. Yield of dry bean and corn for three irrigation treatments in 2015 and 2016 in the year of herbicide application.[a,b]

Target irrigation level	Actual irrigation level		Dry bean		Corn	
	2015	2016	2015	2016	2015	2016
% ETc	——— % ETc ———		——— kg ha^{-1} ———		——— kg ha^{-1} ———	
100	100	100	2,220 a[a]	4,430 A	7,150 a	7,850 a
85	87	86	1,230 b	3,980 A	4,680 a	7,570 a
70	78	76	520 c	2,200 B	2,600 a	5,360 a

[a]Abbreviaton: ETc, estimated crop evapotranspiration.
[b]Means within a column followed by the same letter are not statistically different according to Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

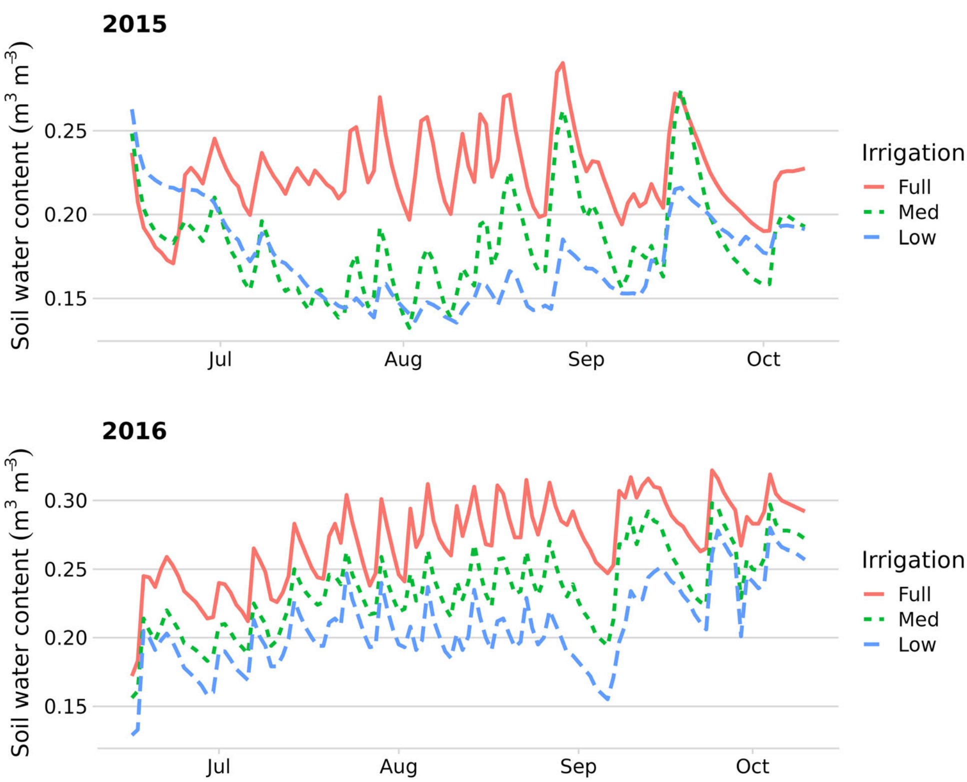

Figure 1. Volumetric soil water content during 2015 and 2016 for three irrigation treatments: low (70% ETc), medium (85% ETc), and high (100% ETc).

Although the majority of herbicides in this study dissipated more quickly than commonly reported values (Shaner 2014), most are realistic given the variable nature of dissipation rates reported in the literature. For example, Westra et al. (2014) reported pyroxasulfone half-lives ranging from 47 to 134 d in Colorado, encompassing our measured half-lives ranging from 49.8 to 119.3 d (Table 5). Alister et al. (2009) found pendimethalin half-lives to range from 10 to 32 d over 4 yr, with other studies reporting 3 to 7 d (Barrett and Lavy 1983), supporting our measured half-life of 10.3 d. Reviews of ethalfluralin and trifluralin fate (Grover et al. 1997; Wolt 1997) reported field half-lives of 1 to 146 d for ethalfluralin and 19 to 173 d for trifluralin. In this study, trifluralin and ethalfluralin both dissipated relatively quickly, with a half-life of 4.5 and 3.4 d, respectively. This may be related to the influence of incorporation rather than season-long soil moisture. Saflufenacil half-lives have been reported to range from 1 to 36 d (Mueller et al. 2014; Papiernik et al. 2012; Shaner 2014), encompassing our measurement of 8.7 d. Finally, even the relatively rapid dissipation of atrazine ($DT_{50} = 21.1$ d) and imazethapyr ($DT_{50} = 22.9$ to 33.2 d) observed in this study is reasonable considering other dissipation mechanisms, such as soil preconditioning, local conditions (Shaner and Henry 2007; Shaner and Wiles 2009), and the relatively high soil pH of this study (Loux and Reese 1993).

Our results suggest that SAH carryover risk in reduced irrigation cropping systems is influenced primarily by inherent chemistry rather than irrigation level. Herbicides with recropping intervals of 1 yr or less, such as ethalfluralin, trifluralin, pendimethalin, and saflufenacil + dimethenamid-P, did not injure rotational crops even in reduced irrigation treatments, whereas those with greater recropping intervals, such as isoxaflutole, injured sensitive crops regardless of irrigation level. Both imazethapyr and atrazine were included in this study as positive controls because of their documented persistence and acute toxicity to certain crops in low doses. The results of this study support the high carryover risk of imazethapyr (Moyer and Esau 1996); however, they do not support carryover risk of atrazine. The lack of observed atrazine carryover to rotational dry bean and sugar beet contradicts the 24-mo recropping interval. However, this is not a novel observation, as some regional results suggest that atrazine may not be as persistent as traditionally thought, even in

https://doi.org/10.1017/wet.2023.85 Published online by Cambridge University Press

Table 5. Half-life (DT_{50}) of seven soil-applied herbicides under three irrigation treatments in 2015 and 2016.[a]

Herbicide[b]	Irrigation P-value[c]	DT_{50} Target irrigation level 100% ETc	85% ETc	70% ETc	Combined[d]
		d			
Atrazine	0.467	25.4	19.3	18.8	21.1
Ethalfluralin	0.424	4.4	1.6	3.2	3.4
Imazethapyr	0.037	22.9	27.0	33.2	27.4
Pendimethalin	0.770	13.0	1.0	10.6	10.3
Pyroxasulfone 2015	0.016	119.3	56.6	59.1	77.5
Pyroxasulfone 2016	0.775	69.4	57.5	49.8	58.4
Saflufenacil	0.804	0.1	5.8	10.1	8.7
Trifluralin	0.869	3.8	5.3	4.4	4.5

[a]Abbreviation: ETc = estimated crop evapotranspiration.
[b]If year is specified, year was a significant model factor ($\alpha < 0.05$) and DT_{50} was calculated separately for 2015 and 2016. If year is not specified, DT_{50} values were calculated using the combined data from both years.
[c]If irrigation P-value is significant ($\alpha < 0.05$), the DT_{50} value was statistically different between target irrigation levels.
[d]Model half-life value using data from all target irrigation levels.

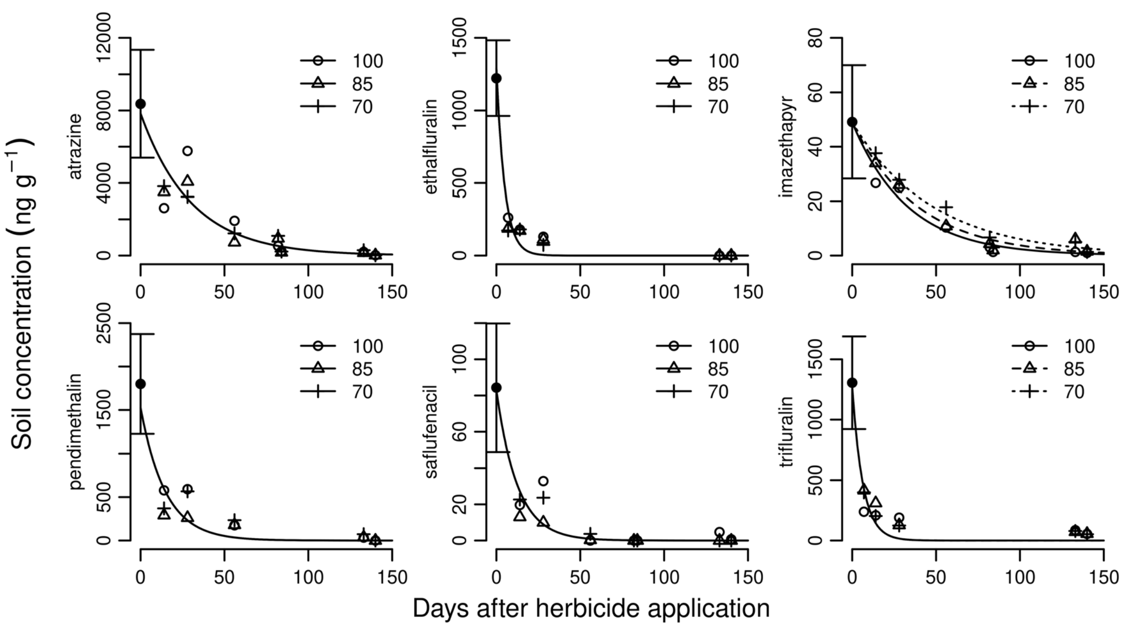

Figure 2. Dissipation of six soil-applied herbicides in response to three target irrigation treatments: low (70% ETc), medium (85% ETc), and high (100% ETc). Data are a combination of 2015 and 2016, as year was not a significant model factor ($\alpha < 0.05$). For plots with only one degradation curve, irrigation rate was not a significant model factor ($\alpha < 0.05$). Error bars represent the 95% confidence interval of initial soil herbicide concentration following application.

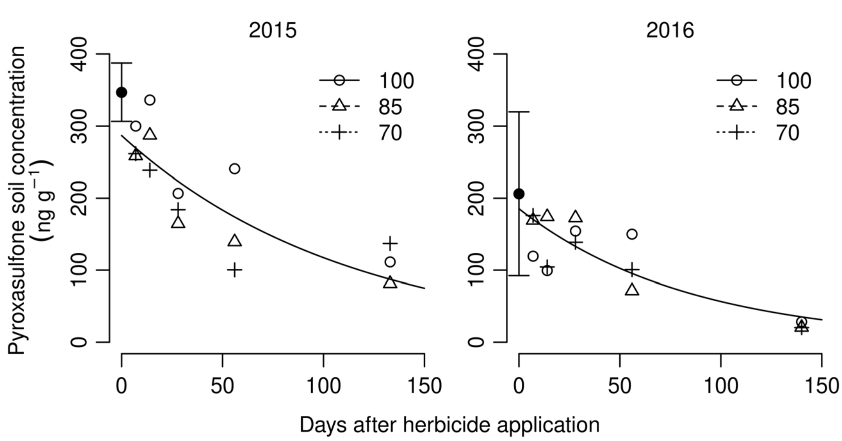

Figure 3. Dissipation of pyroxasulfone in response to three target irrigation treatments for 2015 and 2016: low (70% ETc), medium (85% ETc), and high (100% ETc). Irrigation rate was not a significant model factor ($\alpha < 0.05$) in either 2015 or 2016, so the degradation curves are a combination of all irrigation treatments. Error bars represent the 95% confidence interval of initial soil herbicide concentration following application.

Table 6. Rotational crop yield planted 1 yr after application of eight soil-applied herbicides.[a,b]

Herbicide	Rotational crop yield		
	Dry bean	Sugar beet	Corn
	kg ha^{-1}		
Corn			
Atrazine	2,700 a	47,900 a	—[b]
Isoxaflutole	980 b	44,000 a	—
Pyroxasulfone	2,680 a	52,200 a	—
Saflufenacil + dimethenamid-P	2,470 a	52,400 a	—
Control	2,390 a	48,500 a	—
Dry bean			
Ethalfluralin	—	53,600 a	6,230 a
Imazethapyr	—	0 b	5,530 a
Pendimethalin	—	48,300 a	5,990 a
Trifluralin	—	42,700 a	6,140 a
Control	—	48,500 a	5,700 a

[a]Rotational crop yields were not measured for herbicides registered for that crop.
[b]Means within a column followed by the same letter are not significantly different according to Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

limited irrigation systems (Shaner and Henry 2007; Shaner and Wiles 2009).

The lack of differences in dissipation rate as affected by irrigation levels is likely a result of the relatively small reductions in seasonal water application common to reduced irrigation systems. As opposed to potentially large variation in precipitation encountered during extreme drought events in rain-fed systems, reduced irrigation systems consistently supply enough water to produce an economically viable crop. Typically, deficit irrigation systems require reductions to at least 60% of a crop's ETc needs (Fereres and Soriano 2007). The lowest irrigation treatment of this study received 76% as much water as the full irrigation treatment, which did not cause acute drought capable of affecting herbicide persistence or carryover.

Practical Implications

Although agriculture will continue to face water stress in the near future due to changing demand and climatic patterns (Barnett et al. 2004; Pendergrass et al. 2017; Sabo et al. 2010), because of the need to produce an economically viable yield, it is unlikely that future irrigation practices will reduce levels beyond those of this study. Therefore increased persistence of SAHs should not be expected as long as irrigation is sufficient to produce agronomically and economically sustainable levels. Herbicide persistence and carryover should be considered a major concern only in instances of acute drought in rain-fed systems (Hayden and Smith 1980; Moyer et al. 2010; Mueller et al. 2014; Mueller and Steckel 2011).

Acknowledgments. This research was supported in part by the U.S. Department of Agriculture, National Institute of Food and Agriculture, through Hatch Project no. WYO-552-515, Accession no. 1005893. We thank UW PREC, Powell, WY, for providing resources and support to conduct this study. The authors declare no conflicts of interest.

References

Adee E, Roozeboom K, Balboa GR, Schlegel A, Ciampitti IA (2016) Drought-tolerant corn hybrids yield more in drought-stressed environments with no penalty in non-stressed environments. Front Plant Sci 7:1–9

Alister C, Gomez P, Rojas S, Kogan M (2009) Pendimethalin and oxyfluorfen degradation under two irrigation conditions over four years application. J Environ Sci Health 44:337–343

Allen RG, Pereira LS, Raes D, Smith M (1998) FAO Irrigation and Drainage Paper 56. Irrigat Drain 300:1–333

Barnett T, Malone R, Pennell W, Stammer D, Semtner B, Washington W (2004) The effects of climate change on water resources in the west: introduction and overview. Clim Change 62:1–11

Barrett MR, Lavy TL (1983) Effects of soil water content on pendimethalin dissipation. J Environ Qual 12:504–508

Bates D, Machler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using LME4. J Stat Softw 67:1–48

Colquhoun J (2006) Herbicide persistence and carryover. Univ Wisc Extens Bull A3819:1–12

Curran WS (2016) Persistence of herbicides in soil. Crop Soils 49:16–21

Dagnac T, Bristeay S, Jeannot R, Mouvet C, Baran N (2005) Determination of chloroacetanilides, triazines, and phenylureas and some of their metabolites in soils by pressurized liquid extraction, GC-MS/MS, LC-MS and LC-MS/MS. J Chromatogr A1067:225–233

DaSilva A, Garretson C, Troiano J, Ritenour G, Krauter C (2003) Relating simazine performance to irrigation management. Weed Technol 17:330–337

[EPA] U.S. Environmental Protection Agency (2023) Degradation kinetics equations. https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/degradation-kinetics-equations. Accessed: August 21, 2023

Fait G, Balderacchi M, Ferrari F, Ungaro F, Capri E, Trevisan M (2010) A field study of the impact of different irrigation practices on herbicide leaching. Eur J Agron 32:280–287

Fereres E, Soriano MA (2007) Deficit irrigation for reducing agricultural water use. J Exp Bot 58:147–159

Flint JL, Witt WW (1997) Microbial degradation of imazaquin and imazethapyr. Weed Sci 45:586–591

Grover R, Wolt JD, Cessna AJ, Schiefer BH (1997) Environmental fate of trifluralin. Rev Environ Contam Toxicol 153:1–64

Hayden BJ, Smith AE (1980) Comparison of the persistence of ethalfluralin and trifluralin in Saskatchewan field soils. Bull Environ Contam Toxicol 25:508–511

Helling CS, Zhuang W, Gish TJ, Coffman BC, Isensee AR, Kearney PC, Hoagland DR, Woodward MD (1988) Persistence and leaching of atrazine, alachlor, and cyanazine under no-tillage practices. Chemosphere 17:175–187

Hirahara Y, Kimura M, Inoue T, Uchikawa S, Otani S, Haganuma A, Matsumoto N, Hirata A, Maruyama S, Izuka T, Ukyo M, Ota M, Hirose H, Suzuki S, Uchida Y (2005) Validation of multiresidue screening methods for the determination of 186 pesticides in 11 agricultural products using gas chromatography (GC). J Health Sci 51:617–627

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biometrical J 50:346–363

Jensen CR, Ørum JE, Pedersen SM, Andersen MN, Plauborg F, Liu F, Jacobsen SE (2014) A short overview of measures for securing water resources for irrigated crop production. J Agron Crop Sci 200:333–343

Lenth RV (2022) EMMEANS: estimated marginal means, aka least-squares means. R package version 1.4.6. https://CRAN.R-project.org/package=emmeans. Accessed: March 25, 2023

Loux MM, Reese KD (1993) Effect of soil type and pH on persistence and carryover of imidazolinone herbicides. Weed Technol 7:452–458

Moyer JR, Coen G, Dunn R, Smith AM (2010) Effects of landscape position, rainfall, and tillage on residual herbicides. Weed Technol 24:361–368

Moyer JR, Esau R (1996) Imidazolinone herbicide effects on following rotational crops in southern Alberta. Weed Technol 10:100–106

Mueller TC, Boswell BW, Mueller SS, Steckel LE (2014) Dissipation of fomesafen, saflufenacil, sulfentrazone, and flumioxazin from a Tennessee soil under field conditions. Weed Sci 62:664–671

Mueller TC, Senseman SA (2015) Methods related to herbicide dissipation or degradation under field or laboratory conditions. Weed Sci 63:133–139

Mueller TC, Steckel LE (2011) Efficacy and dissipation of pyroxasulfone and three chloroacetamides in a Tennessee field soil. Weed Sci 59:574–579

Papiernik SK, Koskinen WC, Barber BL (2012) Low sorption and fast dissipation of the herbicide saflufenacil in surface soils and subsoils of an eroded prairie landscape. J Agric Food Chem 60:10936–10941

Pendergrass AG, Knutti R, Lehner F, Deser C, Sanderson BM (2017) Precipitation variability increases in a warmer climate. Sci Rep 7:1–9
Pereira LS (2017) Water, agriculture and food: challenges and issues. Water Resour Manag 31:2985–2999
R Core Team (2023) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/
Reinhardt CF, Nel PC (1993) The influence of soil type, soil water content and temperature on atrazine persistence. S Afr J Plant Soil 10:45–49
Ritz C, Baty F, Streibig J, Gerhard D (2015) Dose–response analysis using R. PLoS ONE 10:e0146021
Rosa L, Chiarelli DD, Rulli MC, Dell'Angelo J, D'Odorico P (2020) Global agricultural economic water scarcity. Sci Adv 6:1–11
Sabo JL, Sinha T, Bowling LC, Schoups GHW, Wallender WW, Campana ME, Cherkauer KA, Fuller PL, Graf WL, Hopmans JW, Kominoski JS, Taylor C, Trimble SW, Webb RH, Wohl EE (2010) Reclaiming freshwater sustainability in the Cadillac Desert. Proc Natl Acad Sci U S A 107:21263–21270
Sack C, Vonderbrink J, Smoker M, Smith R (2015) Determination of acid herbicides using modified QuEChERS with fast switching ESI+/ESI-LC-MS/MS. J Agric Food Chem 63:9657–9665
Sanchez-Brunete C, Perez R, Miguel D, Tadeo J (1998) Multiresidue herbicide analysis in soil samples by means of extraction in small columns and gas chromatography with nitrogen-phosphorus and mass spectrometric detection. J Chromatogr A 823:17–24
Shaner DL, ed (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America. 513 p
Shaner DL, Henry WB (2007) Field history and dissipation of atrazine and metolachlor in Colorado. J Environ Qual 36:128–134
Shaner DL, Wiles L (2009) Behavior of atrazine in limited irrigation cropping systems in Colorado: prior use is important. J Environ Qual 38:1861–1869
Stickler RL, Knake EL, Hinesly TD (1969) Soil moisture and effectiveness of preemergence herbicides. Weed Sci 17:257–259
Van Eerd LL, Hoagland RE, Zablotowicz RM, Hall JC (2003) Pesticide metabolism in plants and microorganisms. Weed Sci 51:472–495
Vencill WK, Nichols RL, Webster TM, Soteres JK, Mallory-Smith C, Burgos NR, Johnson WG, McClelland MR (2012) Herbicide resistance: toward an understanding of resistance development and the impact of herbicide-resistant crops. Weed Sci 60:2–30
Westra EP, Shaner DL, Barbarick KA, Khosla R (2015) Evaluation of sorption coefficients for pyroxasulfone, *S*-metolachlor, and dimethenamid-P. Air Soil Water Res 8:9–15
Westra EP, Shaner DL, Westra PH, Chapman PL (2014) Dissipation and leaching of pyroxasulfone and *S*-metolachlor. Weed Technol 28:72–81
Wilhelmi OV, Wilhite DA (2002) Methodology for assessing vulnerability to agricultural drought: a Nebraska case study. Nat Haz 25:37–58
Wolfe LN, Mingelgrin U, Miller GC (1990) Abiotic transformations in water, sediments, and soil. Pages 103–168 *in* Cheng H, ed. Pesticides in the Soil Environment: Processes, Impacts, and Modeling. Madison, WI: Soil Science Society of America
Wolt JD (1997) Environmental fate of ethalfluralin. Rev Environ Contam Toxicol 153:65–90
Yaron B, Gerstl Z, Spencer W (1985) Behavior of herbicides in irrigated soils. Adv Soil Sci 3:121–211
Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Sci 20:301–307