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Tebuthiuron Persistence and Distribution in Some Semiarid Soils

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ABSTRACT

Tebuthiuron (*N*[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-*N*,*N*'-dimethylurea) is a soil-applied herbicide used on rangelands to control weeds and brush. This study was conducted at five previously treated semiarid rangeland locations in northcentral Arizona to determine how long tebuthiuron remains in the soil and to what depths it penetrates into the soil. Treatments were made from 1975 through 1979. Soils were collected from 1980 through 1986 at 0- to 7-cm, 7-to 15-cm, and successive 15-cm layers to bedrock or into caliche layers from the perimeter of 3- by 0.5-m trenches dug perpendicular to the long axis of the plots. Tebuthiuron was assayed using gas chromatography with flame photometric detection. Tebuthiuron was detected in soil 11 yr after application. Most of the tebuthiuron detected was in the surface 30 cm of soil during the first 5 yr, but small amounts were detected as deep as 105 cm 6 and 9 yr after treatment. After 9 yr from 55 to 73% of the tebuthiuron detected was at the depth of between 60 and 90 cm.

TEBUTHIURON , a soil-applied herbicide, is used to reduce woody plant and weed populations on rangelands (Scifres et al., 1979; Pettit, 1979; Meyer et al., 1983; Clary et al., 1985a; Herbel et al., 1985; McDaniel and Balliette, 1986). Tebuthiuron is effective on many woody plants because of its persistence.

Tebuthiuron concentration in the soil diminishes with time (Bovey et al., 1982). In southern Arizona, tebuthiuron was estimated to persist from 2.9 to 7.2 y following 0.84 kg a.i./ha application (Emmerich et al., 1984). However, in northern Mexico and southern Arizona, tebuthiuron may not be detectable after 2.6, 2.7, and 3.1 yr following 0.5, 1.0, and 1.5 kg a.i./ha applications, respectively (Ibarra and Morton, 1984). In Texas, tebuthiuron was found in soil 2 yr after 2.2 and 4.4 kg a.i./ha applications (Bovey et al., 1982). Sosebee et al. (1979) estimated that tebuthiuron could kill susceptible plants for 5 or more yr. In Utah, Clary et al. (1985b) reported tebuthiuron killed plants 4 yr after 0.7, 1.0, and 1.3 kg a.i./ha applications. However, no studies of tebuthiuron residues longer than 4 yr after application have been reported.

Tebuthiuron is found mainly in the surface 30 cm of soil, but small amounts have been reported from as deep as 61 cm (Garcia and Gontarek, 1975; Bovey et al., 1978). However, tebuthiuron attachment to clay particles and organic matter (Garcia and Gontarek, 1975; Chang and Stritzke, 1977; Duncan and Scifres, 1983) may delay or prevent its movement in the soil.

Because tebuthiuron is widely used, it is important to know its persistence and movement in various soil environments. The purposes of this study were to determine (i) how long tebuthiuron remains in soils on northcentral Arizona pinyon (*Pinus* spp.)-juniper (*Juniperus* spp.) rangelands, (ii) to what depths it penetrates into the soils, and (iii) if application amount or soil texture markedly affects tebuthiuron loss rates or penetration depth under semiarid conditions.

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MATERIALS AND METHODS

Study Locations

The study was conducted at five locations, three north of Prescott: Brushy Mountain, Drake, and Rio Verde; and two north of Flagstaff: Indian Flat and Red Mountain. Rainfall annual means for the locations are between 310 and 430 mm (Table 1). All locations have rainfall peak amounts in the summer and winter with late spring and early fall usually being dry periods.

Soil depths varied from 56 to 152 cm (Table 1). The Barkerville soil is underlain by granite, the others by basalt and cinders. The Tajo and Lynx soils contain caliche to 107 and 152 cm, respectively. Soil-water permeability is slow in the Springerville and Thunderbird soils, moderately slow in the Lynx and Tajo soils, and moderately rapid in the Barkerville soil (Wendt et al., 1976).

Pinyon-juniper is the dominant vegetation at all locations (Table 1). One-seed juniper [*J. monosperma* (Engelm.) Sarg.] dominates at Indian Flat and Red Mountain, where summer rains predominate, and Utah juniper [*J. osteosperma* (Torr.) Little] dominates at Brushy Mountain, Drake, and Rio Verde, where winter rains predominate. Black grama (*Bouteloua eriopoda* Torr.) is the predominate grass at Drake and Rio Verde and blue grama [*B. gracilis* (H.B.K.) Lag.] is the predominate grass at Brushy Mountain, Indian Flat, and Red Mountain.

Treatments

Tebuthiuron tablets at concentrations of 160, 320, and 470 g a.i./kg were applied to spots in 2.74-by 2.74-m grid patterns on nonreplicated 16.4- by 19.2-m plots in April 1975 at Drake at rates equivalent to 2.2, 4.5, and 6.7 kg a.i./ha, respectively.

Tebuthiuron pellets at a concentration of 100 g a.i./kg were hand-broadcast on 50-m^2 plots in randomized complete block studies with two replications at Drake, Indian Flat, and Red Mountain. At Drake, tebuthiuron was applied at 2.0 and 4.0 kg a.i./ha in September 1976, April 1977, and August 1977. At Indian Flat, tebuthiuron was applied at 4.0 kg a.i./ha in October 1976 and August 1977. At Red Mountain, tebuthiuron was applied at 4.0 kg a.i./ha in October 1976, May 1977, and August 1977.

Tebuthiuron pellets at a concentration of 200 g a.i./kg were aerially broadcast at Rio Verde and Brushy Mountain. At the Rio Verde location, tebuthiuron was applied November 1977 at 1.2 and 2.0 kg a.i./ha on nonreplicated 3.1-ha plots and 4.9 kg a.i./ha on a 2.6-ha plot. At Brushy Mountain, tebuthiuron was applied at 0.9, 1.8, and 4.6 kg a.i./ha on nonreplicated 8.1-ha plots in May 1979.

Soil Sampling

Soil sampling was initiated in 1980 and continued through 1986. Soil samples were collected from 0- to 1-, 1- to 6-, and 6- to 12-cm soil depths in June 1980 and from 0 to 1, 1 to 7, 7 to 15, and 15 to 30 cm in August 1980. Since tebuthiuron was detected in the 15- to 30-cm depth, sampling was done each fall between 1981 and 1986 to bedrock or caliche. Samples from 1981 to 1986 were collected at 0- to 7-, 7- to 15-, and 15- to 30-cm depths, and thereafter at 15-cm increments

Table 1. Study locations, elevation, annual rainfall, soils, and major plant species.

Location	Elevation	Annual rainfall	Soils				Main plant species†
			Series texture	Classification	Depth	Bulk density	
	m	mm			cm	g/cm³	
Brushy Mountain	1520	380	Barkerville, sandy loam	Loamy, mixed, mesic shallow Udorthentic Haplustolls Mollisols	91	1.66	Qutu, Juos Pied
Drake	1400	330	Springerville, clay	Fine, montmorillonitic, mesic Typic Chromusterts Vertisols	76	1.78	Juos, Bogr Bocu, Boer
			Tajo, loam	Fine-loamy, mixed, mesic Petrocalcic Paleustolls Mollisols	107	1.60	Juos, Boer Bocu, Bogr
Indian Flat	2220	430	Thunderbird, clay loam	Fine, montmorillonitic, mesic Aridic Argiustolls Mollisols	122	1.59	Jumo, Pied Bogr, Pipo
Red Mountain	1950	310	Thunderbird, clay loam	Fine, montmorillonitic, mesic Aridic Argiustolls Mollisols	117	1.57	Jumo, Pied Bogr
Rio Verde	1290	340	Barkerville, sandy loam	Loamy, mixed, mesic shallow Udorthentic Haplustolls Mollisols	56	1.66	Juos, Pied Boer, Bogr Bocu
			Lynx, loam	Fine-loamy, mixed, mesic Cumulic Haplustolls Mollisols	152	1.66	Juos, Pied Qutu, Bocu

† Bocu = *Bouteloua curtipendula*; Boer = *B. eriopoda*; Bogr = *B. gracilis*; Jumo = *Juniperus monosperma*; Juos = *J. osteosperma*; Pied = *Pinus edulis*; Pipo = *P. ponderosa*; Qutu = *Quercus turbinella*.

to bedrock or into caliche. At each depth 100-g samples were taken with a small, clean trowel from 10 to 15 points at least 30-cm apart around the trench perimeter starting with the lower layers, first removing the exposed soil surface to reduce chances of cross contamination. Samples were composited by layers for each plot. The composite samples were placed in plastic bags, transported to the laboratory, air-dried, passed through a 2-mm sieve, thoroughly mixed and stored at room temperature. All soil samples were taken from randomly located 0.5- by 3.0-m trenches dug perpendicular to the plot's long axis. Collections were taken from one trench on hand-treated plots and from two trenches on aerially treated plots. In order to minimize the disturbance effect of the trench on the remainder of the plot, excavated soil was placed on plastic sheets, and, after sampling, returned to the trench and compacted by layers.

Laboratory Analyses

Tebuthiuron and its metabolites were extracted from 20-g subsamples with acidified methanol (Loh et al., 1980), transferred into ethyl acetate by liquid-liquid partition, and placed on an alumina column. Tebuthiuron was eluted from the column with a 99:1 mixture of acetonitrile isopropanol, and the metabolites were eluted from the column with a 98:2 mixture of methanol water (Loh et al., 1980). The column fractions were quantified with a Tractor Model 222[1] gas chromatograph equipped with a flame photometric detector. Tebuthiuron, metabolite I , and metabolite II were quantified by gas chromatograph equipped with a borosilicate column (122—by 0.3-cm) containing 50 g/kg Carbowax 20M on Chromosorb HP. Column, injector, and detector temperatures were 215, 300, and 190°C, respectively. Metabolite III was quantified using a borosilicate column (60- by 0.3-cm) containing 10 g/kg Carbowax 20M on Chromosorb HP with column, injector, and detector temperatures of 195, 270, 190°C, respectively. A Spectra Physics Minigrator was used to quantify tebuthiuron and its metabolites.

Tebuthiuron and metabolite standards at concentrations ranging from 0 to 2.5 mg/L were used to quantify all unknown samples. Samples were diluted when necessary to attain this concentration range. Tebuthiuron and metabolite standards were added to the various soils to determine recovery rates. The detection limit for tebuthiuron and its metabolites in soil was 0.05 mg/kg. The recovery of tebuthiuron from soil averaged 82% of that added to the soil, recovery of metabolites I and II averaged 75% of that added, and recovery of metabolite III averaged 60% of that added.

[1]Mention of companies or commercial product does not imply recommendation or endorsement by the USDA over others not mentioned.

Calculations and Statistical Analyses

Tebuthiuron concentrations (mg/kg) in the soil were converted to kilograms per hectare for the soil profile using soil bulk densities (Table 1) derived from soil descriptions (Wendt et al., 1976) or field determinations from the sand cone excavation method (Blake, 1965). To provide a common basis to compare tebuthiuron loss rates from different application rates, data were converted to the percentage of tebuthiuron recovered from what was applied. Results are presented for each year after application sampled, and as means and standard deviation from the mean for each year to indicate dissipation trends and the variability associated with these trends. Nonparametric rank sum tests comparing each observation relative to every other observation (Huntsberger and Billingsley, 1981) were used to determine differences ($P = 0.05$) of the ratios of tebuthiuron recovered between soil textures, application rates, soil depths, and years after application. Regression analyses were used to determine the relationship of time after application and the amount of tebuthiuron remaining in the soil.

Soil texture effects on tebuthiuron persistence were examined on loam (Barkerville, Lynx, and Tajo) and clay (Springerville and Thunderbird) soils that had been treated with 4.0 and 4.9 kg a.i. tebuthiuron/ha.

Application rates were compared by mean rate classes of 1.1, 2.0, and 4.4 kg a.i./ha, with ranges of 0.9 to 1.2, 1.8 to 2.2, and 4.0 to 4.9 kg a.i./ha, respectively. Only data from plots with loam soils (Barkerville, Lynx, and Tajo) were used to compare rates, as these soils received a wider range of application rates than clay soil.

The maximum depths of penetration, and relative amounts and distribution of tebuthiuron in the soil are expressed as the average gram a.i. tebuthiuron per hectare in

Table 2. Percent recovery from the soil profile of tebuthiuron applied at five north central Arizona locations.

Location	Year treated	Rate	Years after application†										
			1	2	3	4	5	6	7	8	9	10	11
		kg/ha	%										
Brushy Mountain	1979	0.9	89‡	82	11	4	5	1	–	–	–	–	–
		1.8	19‡	19	27	1	6	0	0	–	–	–	–
		4.6	58‡	8	17	2	4	0	0	–	–	–	–
Drake	1975	2.2	–	–	–	–	–	3	1	9	17	38	15
		4.5	–	–	–	–	–	9	10	7	6	28	42
		6.7	–	–	–	–	–	14	7	2	2	0	8
	1976	2.0	–	–	–	–	0	–	–	–	–	–	–
	1977	2.0	–	–	5‡	5	–	–	–	–	–	–	–
		2.0	–	–	48‡	–	–	–	–	–	–	–	–
Indian Flat	1976	4.0	–	–	–	–	–	–	21	0	2	0	–
	1977	4.0	–	–	–	–	12	–	–	–	–	–	–
		4.0	–	–	–	75	13	25	2	4	0	–	–
Red Mountain	1976	4.0	–	–	–	–	–	11	2	4	19	0	–
		4.0	–	–	–	–	49	23	–	–	–	–	–
	1977	4.0	–	–	–	80	7	–	–	–	–	–	–
		4.0	–	–	–	–	0	9	5	0	0	–	–
		4.0	–	–	–	–	–	14	–	–	–	–	–
Rio Verde	1977	1.2	–	–	–	15	–	–	–	–	–	–	–
		2.0	–	–	–	19	0	11	1	0	0	–	–
		4.9	–	–	–	1	2	3	0	0	–	–	–

† – Indicates not sampled.
‡ Sample from surface 30 cm of soil only.

each layer of soil at yearly intervals. The averages are based on all samples of the same depth taken the same time after application, regardless of rate, location, or year of application.

RESULTS AND DISCUSSION

Persistence

The first year after application, the percentage of tebuthiuron detected in the soil at Brushy Mountain averaged 55% of that applied (Table 2). Even though the percentage of tebuthiuron recovered varied between treatments at a location and between similar treatment rates at different locations (Table 2), the percentages of tebuthiuron found during Years 1 through 4 are similar to those reported by others (Emmerich et al., 1984; Ibarra and Morton, 1984). Therefore, the average percentages seem to be representative of the percentage of tebuthiuron found in semiarid soils 1 to 4 yr after application.

The average percentage of tebuthiuron recovered in soils continued to decline for about 8 yr and then increased during Years 9, 10, and 11 (Fig. 1). The large standard deviations of each mean indicate that apparent differences between some means may not be real. Nonetheless, the overall average percentage of tebuthiuron recovered at Drake the 11th yr was significantly ($P = 0.5$) greater than those recovered in the 5th through 9th yr. Tebuthiuron recovered on a plot treated with 4 kg a.i./ha at Red Mountain also

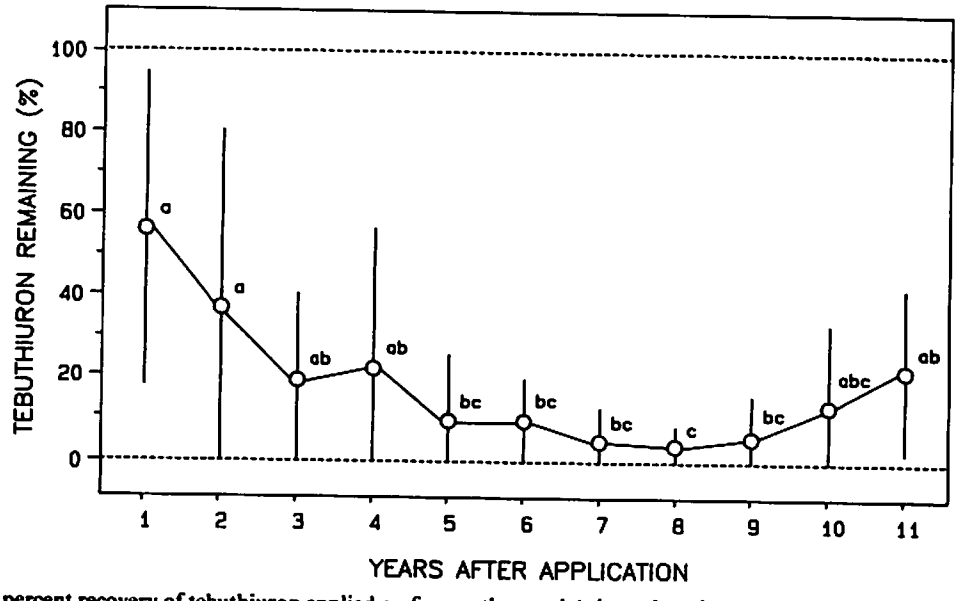

Fig. 1. Annual mean percent recovery of tebuthiuron applied on five northcentral Arizona locations. Vertical lines indicate standard deviations. Means followed by the same letter are not significantly different ($P = 0.05$) according to paired rank sum tests.

increased markedly 9 yr after treatment, but that increase was not apparent the following year (Table 2).

Tebuthiuron metabolites were not found in any soil samples, suggesting little or no degradation in the soil. Tebuthiuron is not lost by volatilization at normal soil temperatures and is not decomposed by sunlight (Beste, 1983). Tebuthiuron may be lost from soils by microbial decomposition, leaching, and uptake by plants. Microbial decomposition of tebuthiuron occurs, but is not considered a predominant mode of degradation (Beste, 1983). Moisture often does not wet the entire soil profile, limiting tebuthiuron penetration in semiarid regions, so little tebuthiuron would be leached out of the soil profile. The uptake by plants depends on absorption of soil moisture and movement of tebuthiuron in soil-water. Thus, tebuthiuron would be lost very slowly from soils under semiarid conditions.

The apparent increase in tebuthiuron found a decade after application is likely due to tebuthiuron bound to soil particles and organic matter being moved deeper into the soil rather than being an increase in the amount of tebuthiuron. Particles of clay or organic matter on which tebuthiuron is tightly held could be moved downward and accumulate at the depth moisture penetrates, and increase concentrations detected at those depths. Also, small amounts of tebuthiuron could be released with each wetting-drying cycle, and after release, leached deeper into the soil, being released and absorbed repeatedly over time without being detected until detectable quantities accumulated at the maximum depths to which rainfall penetrated. Chang and Stritzke (1977) extracted tebuthiuron from soils with water six successive times and removed <40% of the amount of tebuthiuron in a loam soil. We were unable to extract an average of 18% of the amount tebuthiuron in the soil, this 18% could account for the magnitude of the increase in tebuthiuron recovered during the 9th, 10th, and 11th yr after application. The increased amount of tebuthiuron detected would also be available for absorption by plant roots and cause damage to susceptible plants.

Garcia and Lee (1979) observed cyclic increases in the amount of tebuthiuron in soils and theorized that tebuthiuron was released from the decomposing litter from treated plants. In open areas between trees and bushes, such as we sampled, litter is scarce so little tebuthiuron would be cycled through litter. But in semiarid regions, woody plant roots occupy the open areas between plants. Thus, decomposing roots of woody plants killed by tebuthiuron could be a source of tebuthiuron in the soil. But, if we assume 20 000 kg/ha of roots in the soil (Johnsen, 1962; Young et al., 1984) containing an unlikely high amount of 20 mg/kg tebuthiuron, only 0.4 kg a.i./ha can be accounted for, an amount much less than the 1.88 kg a.i./ha measured after 11 yr on the plot treated with 4.5 kg a.i./ha at Drake (Table 2). In addition, decomposing woody juniper roots would release both tebuthiuron and its breakdown products, but breakdown products were not found. Therefore, most of the tebuthiuron found in the 11th yr probably came from tebuthiuron released from soil particles and soil organic matter.

Application Rate

Application rates did not affect rapidity of tebuthiuron loss from the soil (Fig. 2). Therefore, if the application date is known, the percentage of tebuthiuron present in the soil at any given time should be predictable and quantifiable. Emmerich et al. (1984) and Ibarra and Morton (1984) made estimates based on linear regression equations calculated from data obtained in studies of < 4 yr duration. Neither accurately predicted the amounts of tebuthiuron recovered from the plots in this study > 4 yr after application. Attempts to develop a prediction formula

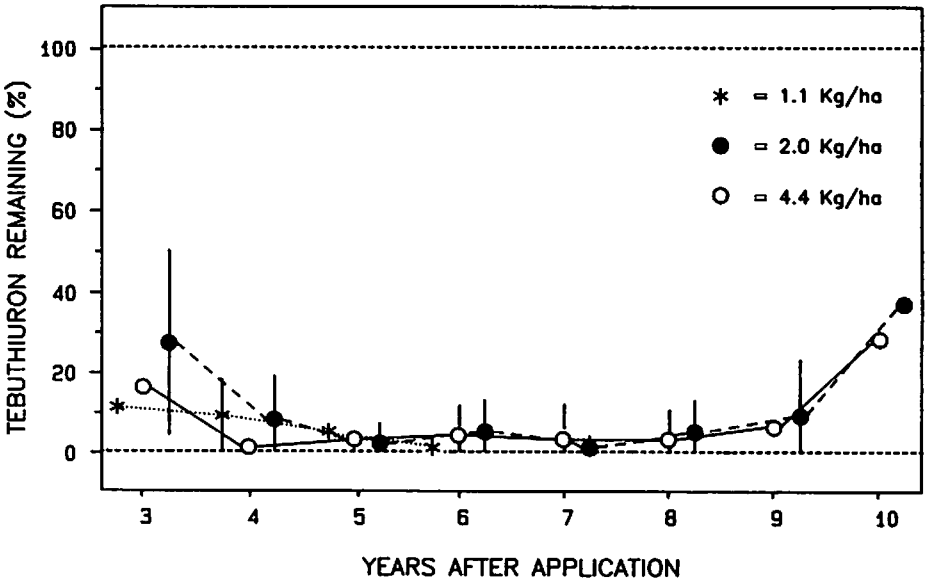

Fig. 2. Application rate effect on the average percent of applied tebuthiuron recovered from loam soils at yearly intervals after application at five northcentral Arizona locations. Points for rates are offset at the year intersects to aid comparison. Vertical lines indicate standard deviation.

Table 3. Persistence of tebuthiuron in soils by depth and years after application. Average amounts (g/ha) of all soil samples taken from five locations in north central Arizona.

Depth	Years after application										
	1	2	3	4	5	6	7	8	9	10	11
cm	g/ha										
0–7	16 ± 28† (3)	184 ± 227 (3)	42 ± 68 (11)	103 ± 193 (10)	21 ± 39 (14)	23 ± 36 (13)	16 ± 42 (12)	4 ± 12 (9)	2 ± 7 (10)	1 ± 4 (5)	0 ± 0 (3)
7–15	196 ± 270 (3)	160 ± 37 (3)	50 ± 104 (11)	70 ± 152 (10)	88 ± 199 (14)	16 ± 24 (13)	19 ± 37 (12)	8 ± 13 (9)	8 ± 23 (10)	10 ± 22 (5)	0 ± 0 (3)
15–30	1056 ± 979 (3)	55 ± 14 (3)	113 ± 286 (11)	307 ± 691 (10)	127 ± 257 (14)	142 ± 182 (13)	60 ± 132 (12)	31 ± 53 (9)	14 ± 31 (10)	31 ± 62 (5)	0 ± 0 (3)
30–45	–‡	48 ± 48 (3)	41 ± 70 (3)	125 ± 211 (9)	46 ± 106 (11)	106 ± 130 (13)	24 ± 36 (12)	31 ± 46 (8)	14 ± 24 (10)	48 ± 74 (5)	0 ± 0 (3)
45–60	–	65 ± 74 (3)	0 ± 0 (1)	41 ± 43 (8)	0 ± 0 (9)	48 ± 82 (11)	9 ± 31 (10)	12 ± 22 (8)	29 ± 48 (10)	53 ± 94 (5)	343 ± 300 (3)
60–75	–	–	0 ± 0 (1)	154 ± 271 (5)	0 ± 0 (6)	17 ± 34 (8)	46 ± 101 (8)	31 ± 58 (8)	96 ± 221 (9)	161 ± 324 (5)	473 ± 818 (3)
75–90	–	–	0 ± 0 (1)	41 ± 84 (4)	0 ± 0 (3)	62 ± 84 (7)	0 ± 0 (6)	0 ± 0 (5)	0 ± 0 (8)	233 ± 401 (3)	336 ± 0 (1)
90–105	–	–	–	0 ± 0 (1)	–	96 ± 137 (2)	0 ± 0 (2)	0 ± 0 (3)	10 ± 31 (7)	0 ± 0 (2)	0 ± 0 (1)
105–120	–	–	–	–	–	–	0 ± 0 (1)	0 ± 0 (2)	0 ± 0 (5)	0 ± 0 (1)	–

† Values are means derived from all locations ± standard deviations, no. in parentheses are no. of samples in mean.
‡ – Indicates not sampled.

using data from the present study failed because of the large variations and limited data from soils collected 9 or more yr after application.

Soil Texture

Tebuthiuron persistence in the soils was not markedly influenced by the different soils (Fig. 3). However, at Drake a lower percentage of tebuthiuron was found in clay soils than in loam soils 8 or more yr after application even though the application rate was higher on the clay soil (Tables 1 and 2). Furthermore, at Rio Verde, herbicide in the higher application rate plot may have leached into the weathered granite, underlying the shallow Barkerville soil. Such movement of tebuthiuron could account for the low amounts of tebuthiuron found on this plot compared to those on the lower rate plots on the deeper Lynx soil (Table 2).

Penetration Depths

The deepest penetration of tebuthiuron in the soil, 105 cm (Table 3), was on clay soil at Indian Flat, the wettest location. Tebuthiuron was found as deep as 60, 90, and 105 cm in the soil 2, 4, and 6 yr after application, respectively (Table 3). Previously, tebuthiuron had been reported as not being deeper than 61 cm in the soil (Bovey et al., 1978; Garcia and Gontarek, 1975; Garcia and Lee, 1979; Emmerich et al., 1984; Ibarra and Morton, 1984). However, these reports were based on studies of 2- or 3-yr duration or of limited sampling depths. Tebuthiuron may not at-

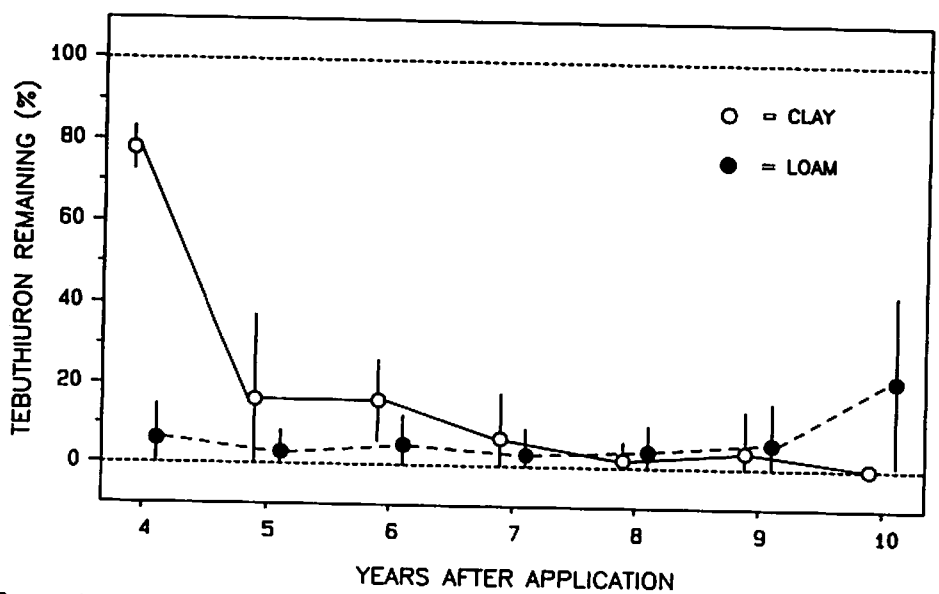

Fig. 3. Soil texture effect on the average percent of tebuthiuron recovered at yearly intervals when applied at 4.0 to 4.9 kg a.i./ha to loam and clay soils at five northcentral Arizona locations. Points for soils are offset at the year intercepts to aid comparisons. Vertical lines indicate standard deviations.

tain maximum penetration within 2 to 3 yr, especially in arid or semiarid climates.

The first year after application, 80% of the tebuthiuron found was detected in the surface 15 to 30 cm of soil (Table 3). Bovey et al. (1978) found most of the tebuthiuron in the surface 15 cm of soil 0.5 yr after application. Emmerich et al. (1984) found no tebuthiuron below 15 cm at 0.7 and 1.5 yr after application. Schultz and Whitesides (1985) found tebuthiuron in soil 30 cm deep after 25 cm of rainfall in greenhouse studies. Whisenant and Clary (1987) found tebuthiuron 30 cm deep 40 d after application. These reports indicated that depth of penetration may vary widely, especially in arid and semiarid regions.

During the first 5 yr after application, half or more of the tebuthiuron was found in the surface 60 cm of soil, mainly in the 7 to 30 cm layers (Table 3). Six to 8 yr after applications most of the tebuthiuron found was in the surface 45 cm of soil. Nine to 11 yr after applications, half or more of the herbicide found was in the 60- to 90-cm soil layer.

Small amounts of tebuthiuron were detected in the surface 7 cm of soil up to 10 yr after application (Table 3). Seeds are planted in this layer, so establishment of susceptible plants could be affected. If susceptible plants are established on herbicide-free surface soils, damage could occur when their roots grow into deeper soils containing tebuthiuron. Nevertheless, tolerant grasses would establish and grow on the same soils (Baur, 1979).

Long-term penetration of tebuthiuron in soil was not affected by application rate. For example, the mean maximum penetration depth was 53 ± 11 cm for 1.1 kg a.i./ha, 64 ± 27 cm for 2.0 kg, and 71 ± 22 cm for 4.4 kg. Penetration depths, however, may have been limited by soil depth and small amounts of rainfall typical in semiarid regions.

Tebuthiuron mean maximum penetration did not differ significantly between clay and loam soils, with mean maximum penetrations of 75 ± 21 and 61 ± 21 cm, respectively (data not shown). At Drake, where clay and loam soils occurred side by side, tebuthiuron penetrated more deeply in the loam, 90 cm, than the clay, 75 cm. In addition, mean maximum penetration depths did not differ significantly between locations: Brushy Mountain, 51 ± 5; Drake, 63 ± 25; Indian Flat, 76 ± 30; Red Mountain, 74 ± 20; and Rio Verde, 66 ± 23 cm (data not shown).

Tebuthiuron should not contaminate groundwater on semiarid upland sites. The limited downward movement of tebuthiuron in the soil, the relatively shallow soils, and the deep water tables on upland sites would combine to minimize the probability of groundwater contamination on these sites.

The persistence and penetration depth are the longest and deepest reported for tebuthiuron to date, but they could be common in arid and semiarid regions. These results demonstrate the need for long-term studies of herbicide persistence and penetration in soils under a variety of conditions.

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