

Reprinted from the *Journal of Environmental Quality*  
Vol. 9, no. 4, October-December 1980, Copyright © 1980, ASA, CSSA, SSSA  
677 South Segoe Road, Madison, WI 53711 USA

PURCHASED BY THE AGRICULTURAL  
RESEARCH SERVICE, U. S. DEPARTMENT  
OF AGRICULTURE FOR OFFICIAL USE

## **Picloram in Water and Soil from a Semiarid Pinyon-Juniper Watershed**

THOMAS N. JOHNSEN, JR.

# Picloram in Water and Soil from a Semiarid Pinyon-Juniper Watershed<sup>1</sup>

THOMAS N. JOHNSEN, JR.<sup>2</sup>

## ABSTRACT

A mixture of picloram (4-amino-3,5,6-trichloropicolinic acid) at 2.8 kg acid equivalent (ae)/ha and 2,4-D [(2,4-dichlorophenoxy) acetic acid] at 5.6 kg acid equivalent/ha was aerially applied onto 113 ha of a 146-ha pinyon-juniper watershed [*Juniperus osteosperma* (Torr.) Little and *Pinus edulis* Engelm., respectively] in north-central Arizona. Picloram residues in runoff water and soil were monitored. Picloram was detected in runoff water leaving the treated area for 30.5 months after application. The highest concentration, 320 ppbw, was in the initial runoff after treatment. A total of 1.1% of the picloram applied left the treated area in runoff water. Picloram was not detected farther than 5.6 km downstream. The picloram concentration was relatively constant during runoff events unless water from snow melt or from an untreated area mixed with the runoff from the treated area. Less picloram came from an area with individually treated trees than from an area with broadcast application. Dip (grab), single-stage flood, or splitter-box water samples all gave comparable picloram contents from the same location with the same runoff event. Picloram was detected in the soils for 44 months, mainly below the 45-cm depth down to bedrock at 122 cm.

**Additional Index Words:** pollution, herbicides, water quality, dissipation.

Johnsen, T. N., Jr. 1980. Picloram in water and soil from a semiarid pinyon-juniper watershed. *J. Environ. Qual.* 9:601-605.

Picloram (4-amino-3,5,6-trichloropicolinic acid) is very effective for controlling woody plants. It is potentially useful on semiarid rangelands to restore vegetation lost to woody-plant invasion of former grasslands and savannahs. However, the fate of picloram in such environments is largely unknown. Knowledge of its fate is needed to ensure the safe use of this herbicide in semiarid regions. It is water soluble and potentially mobile, but little is known about its movement off treated areas in this type of region. Information is also needed about the persistence and movement of this relatively long-lived herbicide in soils of semiarid regions.

This is a report of a study on the occurrence and persistence of picloram in runoff water and soil from a semiarid pinyon-juniper rangeland area in north-central Arizona.

<sup>1</sup>Contribution from Agric. Res., Sci. and Educ. Admin., USDA. Received 9 Oct. 1979.

<sup>2</sup>Research Agronomist, USDA-SEA-AR, 2000 East Allen Road, Tucson, AZ 85719.

## STUDY AREA DESCRIPTION

The study area, Watershed 3 (WS-3), is located approximately 56 km south of Flagstaff, Ariz., on the Beaver Creek Pilot Watershed in the Coconino National Forest. It is a 146-ha calibrated experimental watershed established by the Rocky Mountain Forest and Range Experiment Station in 1956. The area is on a westerly slope covered by pinyon-juniper woodland. The dominant tree is Utah juniper [*Juniperus osteosperma* (Torr.) Little] with pinyon (*Pinus edulis* Engelm.) as a minor component of the overstory. The understory before treatment was mainly broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britt. & Rusby] and annuals.

The elevational range of WS-3 is 1,515 to 1,679 m above sea level. The annual precipitation ranges from 30 to 60 cm, averaging 46 cm. Precipitation occurs in two distinct wet seasons, summer and winter, separated by dry springs and falls. Summer storms, averaging a total of 18 cm, are typically of high intensity, short duration, and localized, seldom wetting the soil deeper than 15 to 30 cm. Winter storms, averaging a total of 28 cm, generally are of low intensity, long duration, and are widespread, falling as either rain or snow. Winter storms often wet the entire soil profile. Stream flow is intermittent and irregular, usually occurring as runoff from snow melt in early spring or from severe summer thunderstorms.

The predominant soil is Springville very stony clay, a fine, montmorillonitic, mesic Typic Chromusterts, which has a typical 112-cm profile with a clay texture throughout on an impervious bedrock of basalt. Almost all of the clay fraction is montmorillonite, which causes pronounced swelling and shrinking and with each wetting-drying cycle, resultant cracks open as much as 5 cm wide and 1 m deep. The dry surface forms a loose, porous mulch of small aggregate which slough into the cracks. Water entering the cracks, rather than percolating through the soil, often remoistens the subsoils. The alternate swelling and shrinking produces a churning action which mixes soils in the surface 1 meter. The area and its responses to the herbicide treatments have been described in more detail elsewhere (5).

## MATERIALS AND METHODS

Applications of 2.8 kg acid equivalent (ae) of picloram and 5.6 kg ae of 2,4-D [(2,4-dichlorophenoxy) acetic acid] as trisopropanolamine salts in 94 liters of water/ha were made onto 113 ha of WS-3 by helicopter on 21 and 22 Aug. 1968. High wind velocities limited spraying to a short time after sunrise each morning. The remaining 33 ha (Fig. 1) either were left untreated or individual trees were treated with the same herbicides with a backpack mist blower.

The duration and amount of water leaving WS-3 was measured with a stage recorder on a calibrated flume. This measurement and runoff-water sampling enabled determination of the total amount of picloram leaving the watershed in each runoff event and variations in picloram concentration during flow periods.

Samples of runoff water were collected from 10 different locations. The first two were on WS-3 (Fig. 1). Point 1 was just below a 4-ha sub-watershed of individually treated junipers; Point 2 was just below a similar area that had been aerially sprayed. Point 3 was at the flume at the bottom of WS-3.

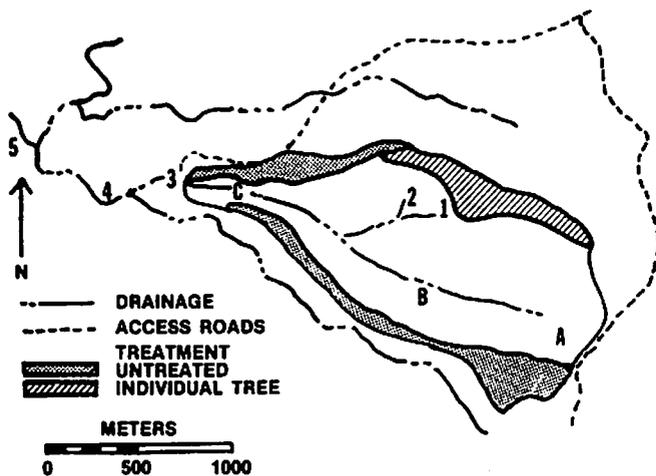


Fig. 1—Location of collecting sites for water (numbers) and soil (letters) on and just downstream from Watershed 3 for picloram determinations.

Points 4 through 10 were located downstream from WS-3 at the junctions of major drainages. Only Points 9 and 10 have perennial water flow. Samples were obtained from above and below the drainage junctions.

Point 4, 0.4 km downstream, was where drainage from the 146-ha study area at WS-3 joins the Round Mountain drainage which drains 692 ha. Point 5, 1.2 km downstream, was where the Round Mountain and Mullican drainages join. Mullican drains about 3,146 ha above this point. Point 5 was at the bottom of a narrow, steep-walled canyon, 150–245 m deep. Point 6, 3.2 km downstream, was in a canyon 245–395 m deep where the Mullican and Rarick drainages join. Point 7, 5.6 km downstream, was at the U.S.G.S. Red Tank Draw Gauging Station. Point 8, 11.3 km downstream, was where the Red Tank Draw and Dry Beaver Creek drainages join. Point 9, 22.5 km downstream, was at the junction of the Dry and Wet Beaver Creeks. Point 10, 30.6 km downstream, was just outside of Camp Verde, where the Wet Beaver Creek and Verde River join.

Runoff water samples were obtained by dip (grab), single-stage (15), and splitter sampling (4). Composite dip samples of runoff were obtained by immersing a new 1-liter polyethylene bottle in the water, at least 3 times, filling the bottle. Dip samples were collected on each visit to a collection point during or after flow events for 4½ years. Single-stage flood water samples (15) obtained in a narrow-necked 1-liter polyethylene bottle placed with the top about 2 cm above the channel bottom in a protected location just downstream of a pooling area. Single-stage samples were collected as soon after a runoff event as possible at irregular intervals for 7½ years to insure that all picloram leaving the area would be detected. A sediment-measuring installation (4) with a series of splitters to collect a small, known, representative portion of water leaving the watershed at the WS-3 flume was also used to obtain water for picloram assays after each flow period for 4½ years. Water samples were sealed, stored at 0–5°C in the dark, and analyzed for picloram within 1–2 months.

Water samples were assayed for picloram with an electron-capture gas chromatograph by a commercial analytical laboratory using Dow Chemical Company's ACR 68.14 method (available from Dow Chemical Company, Midland, Mich.).<sup>3</sup> This method is sensitive to 0.4 ppbw picloram in water. Samples containing known amounts of picloram were used along with soybean biological-activity assays described below to confirm results. Assays for 2,4-D were not done.

Soil samples were collected from three locations within the treated portion of the watershed 1, 10, 22, 32, 44, 57, and 69 months after application (Fig. 1). Holes were dug to bedrock with a backhoe each time; the pit sides were cleaned to prevent contamination; and composite soil samples were taken from depths of 0 to 8, 8 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, and 90 to 122 cm at each location. Soils

<sup>3</sup>Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Table 1—Picloram concentration in runoff water collected on or downstream from Watershed-3.

Sample date and days after treatment	Picloram concentration at indicated collection point					
	1	2	3	4	6	7
ppbw						
1969 26 Jan. (157)	-	-	320	-	-	-
27 (158)	165	-	260	-	-	-
28 (159)	180	-	235	6	-	-
30 (161)	-	-	180	-	nd†	nd
14 Feb. (178)	nd	-	-	4	-	-
16 (178)	-	-	200	-	-	-
19 (181)	-	-	160	-	-	-
23 (185)	-	-	200	-	-	-
24 (186)	110	185	200	16	-	-
25 (187)	-	-	175	nd	nd	nd
5 March (195)	63	170	175	nd	-	-
6 (196)	-	-	175	2	-	-
12 (202)	-	-	98	-	-	-
13 (203)	-	-	135	21	3	1
14 (204)	-	-	130	-	-	-
15 (205)	-	-	94	-	-	-
17 (207)	52	180	135	nd	nd	nd
7 Aug. (350)	3	-	14	1	-	-
12 (356)	-	-	10	-	-	-
26 (369)	3	-	16	6	-	-
17 Sept. (391)	-	-	8	-	-	-
18 (402)	-	-	8	3	-	-
16 Nov. (451)	-	-	18	-	-	-
17 (452)	2	16	12	7	-	-
20 (455)	-	-	16	1	-	-
1970 2 March (557)	5	10	10	5	-	-
4 (559)	-	-	10	5	nd	nd
5 (560)	-	-	10	-	-	-
6 (561)	-	-	10	4	nd	nd
9 (564)	nd	-	11	1	-	-
11 (566)	-	-	10	4	-	-
13 (568)	4	7	7	1	-	-
6 Sept. (745)	-	-	2	-	-	-
8 (747)	1	3	3	nd	nd	nd
1971 23 Feb. (915)	2	11	7	1	-	-
14 Aug. (1087)	nd	1	nd	-	-	-
16 (1089)	-	-	nd	nd	-	-

† nd = no detectable picloram in the sample.

were collected directly into double-walled plastic bags, taken to the laboratory, air dried away from direct lighting, and analyzed as soon as possible. Soil moisture was determined with soil-moisture blocks (18) at each sampling depth at each soil-collection site.

Soils were assayed for picloram by use of soybean assays for biological activity. Soybeans were planted in polystyrene containers of sampled soils, grown for 2 weeks, and visually compared with soybeans grown at the same time in similar, but untreated soils containing known amounts of picloram. Soil dilutions were made as necessary by adding fine, washed quartz sand to the soil. All tests were done with at least four replications and were repeated when dilutions were made. The test readily detected 1–16 ppbw picloram with good repeatability between replications and separate tests. Results of exploratory tests indicated that 2,4-D at this concentration did not interfere with the picloram determinations.

## RESULTS AND DISCUSSION

### Runoff Water

Runoff water samples were collected at the WS-3 flume (collection point 3) on 68 different days; picloram was present only the first 34 collecting days. The first runoff, 157 days after treatment, contained the highest picloram concentration found, 320 ppbw (Table 1). This is similar to the concentrations found by Davis and Ingebo (6) from a chaparral watershed in central

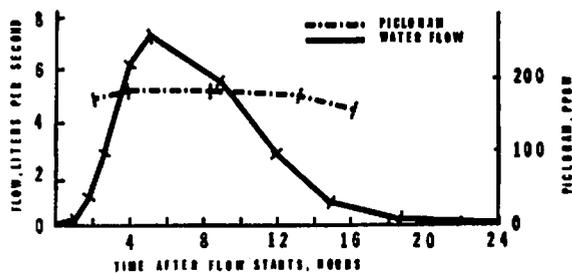


Fig. 2—Relationship of picloram concentration in runoff sampled by dip collection and by paired single-stage flood or splitter collection. The solid line represents the dip concentrations.

Arizona, but much lower than the 2.8 ppm reported in surface runoff by Bovey et al. (2) in mesquite in central Texas.

The last picloram detected leaving WS-3 at point 3, 7 ppbw, was collected 30 months after treatment and after a total of 114 cm of precipitation. The last detection of picloram at a water-sampling point was at a concentration of 1 ppbw on the treated area at Point 2, 35.5 months after treatment. Davis and Ingebo (6) found picloram for only 16 months after application, during which time a total of 102 cm of precipitation was received. They also found the highest concentrations of picloram during the initial runoff periods.

Nine days of winter runoff were not sampled. The picloram contents of these runoffs were estimated by comparing the picloram contents of samples collected during the same flow period among themselves and with those of single-stage and splitter samples. Almost all of the missing samples were from low-volume flows of <math> < 100 \text{ m}^3/\text{day}</math> that occurred during flow periods with volumes totaling from 2,000  $\text{m}^3$  to >7,000  $\text{m}^3$ .

In collections from the same location and runoff event, picloram content was comparable in runoff sampled by dip, single-stage, and splitter-box collection (Fig. 2). Picloram concentration tended to be slightly higher in single-stage samples than in 15 paired dip samples, and slightly lower in splitter-box samples than in 11 paired dip samples. In either comparison, differences were small and inconsistent. Each collection system gave usable results for the small, intermittent streams sampled. It is not known whether all collection systems would serve equally well for other types of streams or in more humid regions.

The year after the herbicide application very little sediment, only 1,520 kg, came off WS-3s 146 ha (4). Because so little sediment left the watershed and picloram is readily soluble in water, very little picloram was assumed to have left the watershed in sediment.

An estimated total of 3.33 kg of picloram, 1.1% of that applied, left the watershed in a total runoff of 57,684  $\text{m}^3$ . Of this amount, an estimated 2.98 kg left during the first year's spring runoff, which totaled 17,272  $\text{m}^3$  in five runoff periods. Only 0.35 kg of picloram left after the initial spring. This loss of picloram is lower than losses reported by others. Trichell et al. (19) reported that as much as 5.5% of the picloram applied to small plots in central Texas was lost in surface runoff 24 hours after application. Davis and Ingebo (6) reported the loss of 4.5% of the picloram applied at 10.4 kg/ha on 0.8 ha of an 18.8-ha chaparral

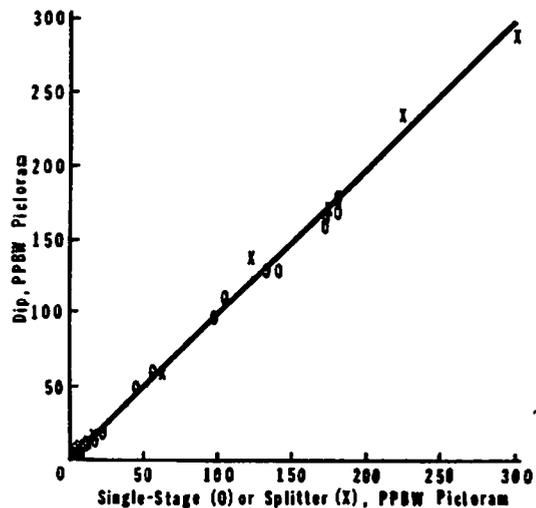


Fig. 3—Relationship of runoff volume and picloram concentration at the Watershed 3 flume, 5-6 Feb. 1969. Cross marks on the lines indicate measurement and sampling times.

watershed in central Arizona. Both these areas receive more rainfall than WS-3 and have soils different from that of WS-3, which may explain the differences in the total amount of picloram moving off the areas and the apparent longer persistence of picloram on WS-3. In addition, 157 days passed before the first runoff event in this study.

Usually water from WS-3 did not flow very far below Point 4 before disappearing into the sand and gravel beds, unless water was flowing in the Round Mountain channel. Picloram was not detected below Point 7, 5.6 km downstream. Picloram was detected only once at Point 6 (3 ppbw) and 7 (1 ppbw) and then only in single-stage samples taken upstream from the stream junctions on 13 March 1969. Unfortunately, Point 5, 1.2 km downstream and very hazardous to reach, was sampled only twice, on 16 March and 17 Nov. 1969. No picloram was found.

There was always less picloram in the water from the individual tree treatment area (Point 1) than there was from the small broadcast treatment area (Point 2) (Table 1). Picloram from the individual tree treatment area was also detected for a shorter period of time.

Dip samples collected throughout flow events at the WS-3 flume showed that picloram concentrations usually remained relatively constant during a given winter runoff event. This uniformity is illustrated by the flow of 5-6 Feb. 1969, after a typical winter rainstorm (Fig. 3). The runoff came from 1.3 cm of rain that fell onto patches of snow on wet soil. During this runoff period picloram concentrations ranged only from 155 to 175 ppbw. Also picloram concentrations measured during similar flows on 28 Jan. 1969, 5 March 1969, and 11 March 1970, were relatively constant for each runoff event, although picloram concentrations differed between sampling dates.

Samples obtained on 16 Feb. 1969, showed the effect of increasing the rate of snow melt during a runoff event. The day was overcast but warm, melting the snow cover. The flow volume peaked shortly after 1200 hours and began to recede. Then the cloud cover broke and the flow rate increased for about 1 hour before subsid-

PICLORAM, KG/HA, INDICATED MONTHS AFTER TREATMENT

	1	10	22	32	44	57
0-8	1.11	0.02	0.03	0.03	ND	ND
8-15	0.08	0.06	0.02	0.02	ND	ND
15-30	0.02	0.06	0.07	0.01	ND	ND
30-45	ND	0.12	0.10	0.04	ND	ND
45-60	ND	0.56	0.62	0.07	T	ND
60-90	ND	0.23	0.10	0.64	0.01	ND
90-122	ND	2.06	1.52	0.13	T	ND
TOTAL PICLORAM	1.21	3.11	2.46	0.94	0.01	ND
TOTAL RAINFALL, CM	168	359	779	117.2	154.2	171.7

Fig. 4—Picloram content in Watershed 3 soils.

ing again. The picloram concentrations were initially between 220–240 ppbw. When the flow rate increased after 1200 hours, the picloram concentration fell to 160 ppbw. Within 1 hour the flow rate again subsided, and the picloram concentrations rose to 220–220 ppbw and remained there until the flow stopped.

Summer flows were difficult to sample because of their short duration, their rapid rise and fall, and our inability to predict their occurrence. The findings for samples obtained from peak and recession flows combined with those for single-stage samples indicated that the summer runoff events also seemed to have relatively constant picloram concentrations. However, the picloram contents of the water first coming through the flume were highly variable.

These results differ from those reported by Davis and Ingebo (6), who stated that picloram concentrations fell as surface flow receded. However, they were working on a watershed with a small stream that had a base flow to which the surface flow was added. Thus, as the surface flow receded, the base flow more effectively diluted the incoming surface water, reducing the picloram concentration in the stream. The present report is concerned with the effects of intermittent surface-runoff events without any base flow. Therefore, there was no dilution except from precipitation or other incoming surface flow further downstream during runoff events. Also, the soils on WS-3 are fine-textured clays and clay loams, while those in the chaparral were gravelly loams.

#### Channel Dilution

The picloram contents of water samples collected at the WS-3 flume were compared with those of samples collected about 0.4 km downstream, above and below the junction of the WS-3 and Round Mountain drainages. The channel below WS-3 is very narrow, with an impervious rock bottom and little sand or gravel in the channel. Little overland flow enters from the sides of this channel, so that little dilution occurs until the WS-3

drainage enters the Round Mountain drainage. For example, a sample of water leaving WS-3 after a thunderstorm contained 14 ppbw picloram. Just before the WS-3 drainage entered Round Mountain drainage the picloram content of the former was still 14 ppbw, but 0.1 km after it entered Round Mountain picloram was barely detectable, 0.6 ppbw, in the combined flow.

Findings in other studies have indicated that picloram was very quickly diluted after it left treated areas (3, 6, 17). These studies were done in more humid areas with live water streams and additional off-site surface runoff entering the stream channels. In arid and semiarid regions, picloram concentration may not be reduced through downstream dilutions, especially with localized summer storms. This lack of dilution might affect the use of runoff water close to picloram-treated areas. However, the findings of this study indicate that lack of dilution is a localized problem, since runoff usually occurs when overland flow is widespread and additional water is in the stream channels to dilute the picloram to an undetectable level within a short distance downstream of the treated area. At other times, the runoff water would not flow very far downstream before it was lost in sand and gravel beds. The effect of subsequent flows on the picloram carried by water lost in this manner is unknown.

#### Soil Residues

Picloram was last detected in soils collected 44 months after application. This persistence time agrees with the estimated 42 months predicted by the method developed by Hamaker et al. (13). The length of time that picloram persisted in soils in other studies varied from 7 weeks to 4.3 years, with the longest persistence being under the more arid conditions (1, 9, 17).

One month after application, 92% of the herbicide recovered was in the surface 8 cm of soil (Fig. 4). The picloram concentration in the soil at that time (1.21 kg/ha) was less than that applied (2.8 kg/ha), presumably because of interception by vegetation and rocks which had not been washed off by rain into the soil. Moisture from summer storms seldom wet the soil more than 15–30 cm in this region.

Nine months later, 66% of the picloram found was in the 90- to 122-cm depth, just above the impervious bedrock. Since these soils have little organic matter, picloram moves readily in them throughout the soil profile (8, 10). There is more herbicide further into the soil profile 10 months after application than might have been expected from the 1 month results (Fig. 4). The 10-month collections followed the initial winter. In this region, winter storms wet soils more efficiently than summer storms, and thus, would move water-soluble materials further into the soils than summer storms with similar amounts of rainfall. Also, since these soils crack and churn, even with partial drying and wetting, picloram in surface aggregate and in surface runoff water would enter the soil cracks and rapidly move deeply into the soil profile. The two zones of higher picloram concentration at 45–60 cm and 90–122 cm in the 10- and 22-month determinations, respectively, (Fig. 4) rather than a single zone may also be a result of the soil mixing. The depth of the churning would depend, in

part, on the depths of wetting and drying. Variations in soil mixing, combined with soil water movement, may account for differences in the depths of higher picloram concentrations observed in the 10- and 22-month and 32- and 44-month determinations (Fig. 4).

The average total amount of picloram in the 10-month samples (Fig. 4), 3.11 kg/ha, is higher than the average amount applied, 2.8 kg/ha, but within the expected variation for areas treated aerially (7). However, the amount of picloram may be higher due to an overestimate of picloram in the 90- to 122-cm layer. Safflower and soybean are very sensitive to low concentrations of picloram, directly determining concentrations up to 20 ppbw, but determinations of higher concentrations require dilutions. The more dilution needed, the greater the chance of error. Thus, high picloram concentrations in the surface 0- to 8-cm depth at 1 month and the 90- to 122-cm depth at 10 and 22 months after treatment may not be accurate. However, this does not change results indicating detection of picloram at lower concentrations or the determinations of how long picloram was biologically active in the soil.

Most of the herbicide was found below 45 cm in samples taken after the initial month. Plant development indicated this also. For example, sunflowers (*Helianthus annuus* L.) grew well early in the growing season, but as the plant root system extended deeper, shortening of internodes, cupping of leaves, and death of growing tips indicated the effects of picloram. Such symptoms were seen during the first three growing seasons after treatment, occurring later and less severely each year. Such effects were not seen in the fourth growing season, although the herbicide was found near the limits of detection in the soil. Picloram has been reported not to leach very deeply, usually not more than 60-90 cm (9, 16, 17). However, as in the present study, more picloram was found in the susoils 1, 2, and 3 years after application than during the initial year (16).

A total of 154 cm of precipitation was received by the time the last detectable picloram was collected from the soil, 44 months after application. However, leaching and runoff losses do not account for the disappearance of picloram from the soil. The soils lay over impervious bedrock. Only 3.3 kg of the 290.5 kg of picloram applied apparently left the area in runoff. Other modes of loss would include metabolism by microorganisms, absorption by plants, and breakdown by sunlight on the soil surface or in plant litter (3).

Measurements of soil moisture showed that the soil below 30 cm did not become dry (15 bars or more) for 7 years after the trees were killed, whereas soils in untreated areas dried out to bedrock each spring. Moist subsoil favors activity of microorganisms (11) and growth of plants. Also, the moist subsoil favors the movement of picloram to the soil surface (12, 14) during wetting-drying cycles because less rainfall is required to

wet the soil profile. Thus, small amounts of picloram might move to the soil surface by capillary action and be exposed to direct sunlight and destroyed during each wetting-drying cycle of the soil (1).

## ACKNOWLEDGMENTS

I thank those who helped with this study, especially Reynaldo M. Madrigal, Gerald L. Mundell, and Robert E. Warden. The Rocky Mountain Forest and Range Experiment Station provided the runoff data. The Dow Chemical Company provided the herbicide and water analysis.

## LITERATURE CITED

1. Bovey, R. W., C. C. Dowler, and M. G. Merkle. 1969. The persistence and movement of picloram in Texas and Puerto Rican soils. *Pestic. Monit. J.* 3:177-181.
2. Bovey, R. W., C. Richardson, E. Burnett, M.G. Merkle, and R. E. Meyer. 1978. Loss of spray and pelleted picloram in surface runoff water. *J. Environ. Qual.* 7:178-180.
3. Bovey, R. W., and C. J. Scifres. 1971. Residual characteristics of picloram in grassland ecosystems. *Tex. Agric. Exp. Stn. Bull.* B-1111. 24 p.
4. Brown, H. E., E. A. Hansen, and N. E. Champagne, Jr. 1970. A system for measuring total sediment yield from small watersheds. *Water Resour. Res.* 9:818-826.
5. Clary, W. P., M. B. Baker, Jr., P. F. O'Connell, T. N. Johnsen, Jr., and R. E. Campbell. 1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona U.S. *For. Serv. Res. Pap.* RM-128. 28 p.
6. Davis, E. A., and P. A. Ingebo. 1973. Picloram movement from a chaparral woodland. *Water Resour. Res.* 9:1304-1313.
7. Eaton, B. J., H. M. Elwell, and P. W. Santelmann. 1970. Factors influencing commercial aerial application of 2,4,5-T. *Weed Sci.* 18:37-41.
8. Farmer, W. J., and Y. Aochi. 1974. Picloram sorption by soils. *Soil Sci. Soc. Am. Proc.* 38:418-423.
9. Fryer, J.D., P. D. Smith, and J. W. Ludwig. 1979. Long-term persistence of picloram in a sandy loam soil. *J. Environ. Qual.* 8: 83-86.
10. Grover, R. 1968. Influence of soil properties on phytotoxicity of 4-amino-3,5,6-trichloropicolinic acid (picloram). *Weed Res.* 8: 226-232.
11. Grover, R. 1972. Effect of picloram on some soil microbial activities. *Weed Res.* 12:112-114.
12. Grover, R. 1973. Movement of picloram in soil columns. *Can. Soil Sci.* 53:307-314.
13. Hamaker, J. W., C. R. Youngson, and C. A. Goring. 1968. Rate of detoxification of 4-amino-3,5,6-trichloropicolinic acid in soil. *Weed Res.* 8:46-57.
14. Merkle, M. G., R. W. Bovey, and F. S. Davis. 1967. Factors affecting the persistence of picloram in soil. *Agron. J.* 59:413-415.
15. Rainwater, F. H., and L. L. Thatcher. 1960. Methods for the collection and analysis of water samples. U.S. Geol. Surv. *Water-Supply Paper* no. 1454.
16. Scifres, C. J., O. C. Burnside, and M. K. McCarty. 1969. Movement and persistence of picloram in pasture soils of Nebraska. *Weed Sci.* 17:486-488.
17. Scifres, C. J., H. G. McCall, R. Maxey, and H. Tai. 1977. Residual properties of 2,4,5-T and picloram in sandy rangeland soils. *J. Environ. Qual.* 6:36-42.
18. Taylor, S. A., D. D. Evans, and W. D. Kemper. 1961. Evaluating soil water. *Utah Agric. Exp. Stn. Bull.* 426. 67 p.
19. Trichell, D. W., H. L. Morton, and M. G. Merkle. 1968. Loss of herbicides in runoff water. *Weed Sci.* 16:447-449.