Dissipation, Movement, and Environmental Impact of Herbicides on Texas Rangelands

A 25-Year Summary

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Dissipation, Movement, and Environmental Impact of Herbicides on Texas Rangelands — A 25-Year Summary

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Summary

Herbicides are necessary to control weeds and brush on rangelands. Safe and effective use of herbicides requires that their properties, behavior, and impact on the environment be thoroughly understood. Herbicides considered in this review are picloram, clopyralid, the phenoxys, dicamba, triclopyr, tebuthiuron, hexazinone, karbutilate, and glyphosate.

Picloram degrades within 3 to 6 months in Texas soils. Half-life of this herbicide varies widely depending upon rainfall and soil temperature. Picloram tends to leach to lower soil depths, but most remains in the upper meter of soil. Picloram may move in surface runoff water, but its removal from watersheds is usually less than 5% of the total amount applied. Picloram is degraded slowly by soil microorganisms and plant metabolism but is degraded rapidly by sunlight. Picloram is phytotoxic to a wide range of plants especially broadleaf plants, so care must be taken to limit its movement.

Clopyralid is chemically similar to picloram but has a shorter half-life in soil than does picloram and is subject to degradation by soil microbes. It resists degradation by sunlight. Clopyralid moves in water sources as does picloram but is not as phytotoxic to most plants as is picloram.

The phenoxy herbicides such as 2,4-D and 2,4,5-T are short lived in the southwestern U.S. environment and have limited mobility, so movement into groundwater is unlikely. Phenoxys are rapidly decomposed by soil microbes, sunlight, and plant metabolism. Phenoxy herbicides are generally less phytotoxic to broadleaf plants than is picloram. However, preventing spray drift or vapors to susceptible plants such as cotton is essential.

Dicamba, in moist, warm soil has a half-life of <14 days as a result of microbial degradation. Half-life in native grasses and litter is 3 to 4 weeks. Under simulated rainfall conditions, a maximum of 5.5% of dicamba applied to a watershed was removed in runoff water. Dicamba levels found in streams after application to large watersheds were several orders of magnitude below threshold response levels for fish and mammals.

In Texas, triclopyr persisted in soil for 3 months after summer application. Mode of breakdown in soils is by leaching, photodegradation, and microbial activity. Mobility in runoff water is similar to 2,4-D.

In semiarid and humid regions, tebuthiuron may persist for long periods. Tebuthiuron is readily adsorbed in soil having high organic matter or high clay content but may leach in soils low in organic matter or low clay content. Tebuthiuron content, however, in forage plants is typically well below legal residue limits when applied as pellets. Concentrations of tebuthiuron in runoff water decreased rapidly and was <0.05 ppm after 3 months from a watershed in central Texas. Tebuthiuron resists photodecomposition and volatilization, and breakdown by microbial activity is slow.

Hexazinone is mobile in runoff water and readily leaches in some soils. Spot-gun application to brush species indicated limited movement and transport from treated watersheds in stream discharge. Half-life varied from 1 to 6 months in soil depending upon location. Glyphosate is rapidly inactivated in soil by adsorption and microbial activity. Chance of environmental contamination is remote.

Introduction

Weeds and brush represent one of the most serious barriers to profitable livestock production on U.S. rangelands. Most of the 43 million hectares (ha) of grassland in Texas are infested with weeds and brush. In some areas, only one or two species are troublesome, but in others, several species are a problem. Weeds and brush reduce forage quantity and quality; deplete soil water and nutrients; harbor insects vectors and predators; and may be poisonous, unpalatable, or mechanically injurious to livestock. Dense stands of weeds increase difficulty of handling livestock and reduce land values. Loss of grass cover to brush and weeds encourages soil erosion.

Herbicides are an important means of selectively managing weeds and brush on rangelands and may be the only alternative where steep, rocky terrain limits mechanical methods or where inadequate fuel limits prescribed burning. Herbicides are also important in combination with fire, mechanical, or biological control measures in integrated management systems.

A variety of herbicides, herbicide formulations, and herbicide combinations are available commercially. Properties, behavior, and impact of herbicides on the environment must be thoroughly understood so they can be used safely and effectively.

This report summarizes and highlights data obtained on the behavior and fate of important herbicides used on Texas rangelands and includes an assessment of their effect on environmental quality. These herbicides are picloram, clopyralid, the phenoxys, dicamba, triclopyr, tebuthiuron, hexazinone, karbutilate, and glyphosate. See Table 1 for details on chemistry, formulations used, mode of entry, major uses and rates, water solubility,

Table 1: Herbicides used for weed and brush control on rangelands.[a]

Herbicide	Chemical name	Commercial formulation	Mode of entry	Major uses	Rates (kg/ha)	Water solubility (ppm)	Mammalian toxicity LD$_{50}$(mg/kg)	Test species
Clopyralid	3,6-dichloro-2-pyridine carboxylic acid	Monoethanolamine salt	Foliage and root	Broadleaf weeds and brush, effective on honey mesquite	0.06 to 4.5	1,000	5,000	Rat
Dicamba	3,6-dichloro-2-methoxybenzoic acid	Dimethylamine salt	Foliage and root	Weeds and brush	0.5 to 11	4,500	1,028	Rat
2,4-D	(2,4-dichlorophenoxy) acetic acid	Various salts and esters	Foliage	Broadleaf weeds, certain woody plants	0.25 to 2 (4 to 5 kg/1,000 L on certain woody plants)	900	300 to 1,000	Rat Guinea pig Rabbit
Glyphosate	N-(phosphonomethyl) glycine	Isopropylamine salt	Foliage	Broad spectrum, nonselective weed control	0.3 to 2	12,000	5,600	Rat
Hexazinone	3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H,3H)-dione	Soluble powder, miscible liquid or pellet	Root	Weed and brush control on noncrop areas, forest sites	2 to 12	33,100	1,690	Rat
Karbutilate[b]	3-[[(dimithylamino) carbonyl] amino] phenyl (1,1-dimethylethyl) carbamate	Wettable powder, pellets	Root	General weed control, woody plants, and noncrop areas	2 to 22	325	3,000	Rat
Picloram	4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid	Potassium or amine salts	Foliage and root	Weed and brush control on rangelands and noncrop areas	0.14 to 9	430	8,200	Rat
Tebuthiuron	N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N'-dimethylurea	Wettable powder and pellets	Root	Weed and brush control on rangelands; total vegetation control	0.6 to 4.2	2,300	644	Rat
2,4,5-T[c]	(2,4,5-trichlorophenoxy) acetic acid	Various salts and esters	Foliage	Weed and brush control on rangelands	0.5 to 2	238	500	Rat
Triclopyr	[(3,5,6-trichloro-2-pyridinyl)-oxy] acetic acid	Triethylamine salt and butoxyethyl ester	Foliage and root	Weed and brush control on forest, rangelands, and noncrop areas	0.28 to 10	430	713	Rat

[a] Many herbicides listed are also commercially available in mixtures with other herbicides. Some mixtures useful in weed and brush control include: clopyralid + triclorphyr; picloram +triclopyr; 2,4-D + picloram; 2,4-D + dicamba; and 2,4-D + triclopyr.

[b] Not commercially available.

[c] All uses of silvex and 2,4,5-T have been cancelled.

and mammalian toxicity. Most herbicides used on rangeland are of moderate to low toxicity. Some, however, are persistent and water soluble enough to move in soils and water. Foliar-applied herbicides such as clopyralid, 2,4-D, dicamba, picloram, and triclopyr may drift when sprayed. Such materials must be properly applied to prevent damage to nontarget susceptible vegetation. The potential of each herbicide to persistent in soil, vegetation, or water and to move to off-target areas in surface runoff and to groundwater will be discussed. Environmental problems, if any, will be indicated. This report is based on research conducted on Texas grazing lands. Data from outside Texas are included only to illustrate a point or to fill information gaps.

Picloram

The fate of picloram in grassland ecosystems was summarized (38) in 1971, but considerable data have been generated since. Picloram can control many broadleaf weed and brush species on grasslands (38). It has a very low order of toxicity to warm-blooded animals but is relatively persistent in the environment. Its persistence results in its effectiveness as an herbicide. If not photodecomposed, some picloram may move laterally on the soil surface or vertically through the soil profile to a limited degree. Biological breakdown of picloram by microbes or higher plants is slow, but dilution by runoff and dissipation in impounded water are important modes of dissipation. Environmental problems with picloram is related to susceptible plant life where contaminated runoff or irrigation water could result in damage or where spray drift injures vegetation.

Persistence in Soil

Subhumid Rangeland Sites

Bioassays 1 year after treatment have shown that <1 ppb of picloram was detected in soil at five Texas rangeland sites when applied at 1.1 to 4.5 kg/ha (38). However, the soils were sampled only once to a depth of 61 or 91 cm; thus the sampling did not account for possible leaching of herbicide beyond 91 cm.

In other studies, picloram was applied at 2.2 and 9 kg/ha on the Gulf Coast Prairie at Victoria on a Katy gravelly sandy loam (fine-loamy, siliceous, thermic Aquic Paleudalfs) and on the Post Oak Savannah at College Station on an Axtell fine sandy loam (fine, montmorillonitic thermic family of Udertic Paleustalfs) (72). Annual rainfall at both sites was 81 cm. Frequent sampling at Victoria and College Station has shown that 2.2 kg/ha of picloram disappeared from the top 61 cm of soil by 6 and 12 weeks after treatment, respectively. Picloram was not detected after 1 year, regardless of herbicide rate or sampling depth. Bioassays using field beans confirmed chemical analysis, indicating absence of detectable residues.

Additional studies at College Station were conducted to determine picloram residue levels to a depth of 2.4 m for 2 years after application of 1.12 kg/ha (8). Annual rainfall was 62 and 48 cm for year 1 and 2, respectively. After 30 days, residues were 93 ppb in the top 15 cm of the Axtell fine sandy loam soil and <5 ppb at a depth of 46 to 122 cm. After 6 months, residues were between 5 and 10 ppb to a depth of 183 cm and <5 ppb between 198 and 244 cm deep. Residues to depths of 244 cm were <5 ppb 1 year after treatment. Retreatment after 1 year did not cause picloram accumulation, and dissipation of picloram was similar for spray and granular formulations. Although picloram leached to the lower soil profile, concentrations detected were extremely low and would not likely contaminate the soil or groundwater.

Fallowed Areas and High Rates

Much of the picloram spray is intercepted by vegetation and plant litter. To investigate the magnitude of this effect, residues and leaching of picloram applied to bare soil was determined (25). Picloram was applied at 1.1, 3.4, and 10.1 kg/ha to a Erving clay loam and Lakeland sand at College Station and a Nipe clay, Fraternidad clay, and Catano sand near Mayagüez, Puerto Rico. Annual rainfall in Texas was 71 and 74 cm at the sand and clay sites, respectively, and 81, 175, and 196 cm, respectively, on the Fraternidad clay, Nipe clay, and Catano sand sites in Puerto Rico.

Texas Studies

Picloram was applied to dry soil that received <1 cm of rainfall during the first 6 weeks after treatment. Loss of picloram was rapid during this period (25), presumably by photodecomposition (71) because picloram was exposed to sunlight on bare soil. After 3 months, picloram applied at 1.1 kg/ha disappeared from sandy soil. Picloram concentrations in the sand and clay soils treated at all rates were considerably reduced; these soils received 23 and 30 cm of rainfall, respectively.

Six months after treatment at 1.1, 3.4, and 10.1 kg/ha, picloram was present in the upper 15, 30, and 91 cm of the clay soils, respectively (25). Picloram was detected at nearly all levels down to 122 cm in sand, but had dissipated at the 1.1-kg/ha rate. After 18 months, a small

amount of picloram (0.03 ppm) was found in only the top 15 cm of clay soil treated at 3.4 kg/ha.

Plots treated with 10.1 kg/ha had picloram residues in the top 91 cm of clay soil at 3 and 6 months after treatment but were found only in the top 61 cm of soil after 18 months (25). Picloram in the sandy soil was found at 122 cm deep at the 6- and 18-month sampling dates. Bioassay with 'Black Valentine' beans (*Phaseolus vulgaris* L.) 18 months after treatment detected no picloram residues where 1.1 kg/ha was applied on clay and sandy soils and in the sandy soil at 3.4 kg/ha. However, beans grown in clay soil from 0 to 15 or 15 to 30 cm deep treated with picloram at 3.4 kg/ha were injured. Greatest injury to beans occurred when grown in the top 60 cm of clay soil receiving 10.1 kg/ha of picloram. Some injury was also recorded from soil at depths of 91 to 122 cm. The greatest picloram injury to beans grown in sandy soil was at 91 to 122 cm deep probably because of leaching after receiving abundant rainfall on the site.

Puerto Rican Studies

Three months after treatment, picloram was distributed throughout the upper 51 cm of soil profile in clay soils at all rates of treatment (25). Picloram residues increased as the rate was increased. Picloram at 3.4 and 10.1 kg/ha persisted in the Fratenidad clay soil for 1 year. Disappearance of picloram was related to soil type and rainfall. Picloram was most persistent in the Fraternidad clay where rainfall was lowest. Disappearance of picloram from the Catano sand was rapid, and no herbicide was detected 6 months after treatment in the upper 100 cm of soil. Rainfall of 122 cm on the Catano sand may have leached much of the picloram from the soil. By 1 year after treatment in the Nipe clay, picloram was detected only where 10.1 kg/ha had been applied, but detectable concentrations were <10 ppb. Use of picloram rates >1.1 kg/ha would be uncommon. At 1.1 kg/ha, picloram residues disappeared rapidly from the sandy soil but were detected at as much as 23 ppb in clay soils for at least 6 months. Bioassay and gas-liquid chromatographic (GLC) techniques were compared for Nipe and Fraternidad clay soils receiving 3.4 kg/ha of picloram (25). Both methods show similar trends in picloram concentrations at most depths of sampling, but for undetermined reasons, the bioassay consistently gave higher readings for the Fraternidad clay than did gas chromatography. Bioassay procedures with 'Puerto Rico 39' cucumbers (*Cucumis sativus* L.) are accurate and sensitive to 5 ppb of picloram. Other studies also showed close correlation between bioassay and GLC techniques (94).

Semiarid Sites

In the Rolling Plains of Texas, detectable picloram residues occurred in the upper 30 to 45 cm of soil after application of 0.28 kg/ha (95). Picloram was applied to sandy loam soils in June or July, and then soils were irrigated to cause leaching. After application of as much as 23 cm of irrigation water for 15 hours within 20 days after picloram treatment, residues were typically in the upper 45 cm of soil. On seven rangeland sites in the Rolling Plains, picloram at 0.28 kg/ha usually dissipated from the soil profile within 1 year after treatment.

Widely Diverse Locations

In studies at five diverse locations including east-central, south, and west Texas, picloram disappeared from soils by 1 year after application of 0.26 to 1.1 kg/ha regardless of cumulative rainfall or location (56).

Factors Affecting Soil Persistence

Soil Texture. As indicated in Texas and Puerto Rico, picloram disappeared more rapidly from sandy than from clay soils (25). Scifres et al. (99) found that picloram disappeared within 56 to 112 days after application from two watersheds on sandy soils in east-central Texas, and most picloram was restricted to the upper 15 cm of soil. No picloram was detected deeper than 60 cm. Bovey and Richardson (36) detected picloram as long as 181 days after application in Houston black clay, mostly in the upper 30 cm of soil. Application rate was 0.56 kg/ha in both studies.

Environment. Laboratory studies (71) indicated that dissipation of picloram was accelerated at high temperatures (38 °C versus 4 and 20 °C) and by leaching. Photodecomposition may be an important means of loss if the herbicide remains on the soil surface for several days. All these dissipation pathways have been documented (8, 25, 36, 38, 56, 72, 95, 99).

Effect of Repeated Treatment. Bovey et al. (23, 24) applied a 1:1 mixture of 2,4,5-T plus picloram at 1.1 kg/ha every 6 months for a total of five times on a native-grass pasture watershed and five times at 2.2 kg/ha every 6 months on an adjacent watershed. Herbicide content of the Houston black clay remained low (0 to 238 ppb) during the study. Picloram dissipated and did not accumulate at either soil site.

Effect of Picloram Soil Residues on Plant Growth

Picloram is widely used for weed and brush control in forage grass crops (32, 38, 39). In Puerto Rico, 'USDA-34' corn (*Zea mays* L.), 'Combine Kafir-60' sorghum (*Sorghum bicolor* L.), 'Mentana' wheat (*Triticum aestivum* L.), 'Taichung Native No. 1' rice *(Oryza sativa* L.), and 'Blightmaster' cotton (*Gossypium hirsutum* L.) could be grown without reduction in fresh weight as early as 3 months after application of 6.72 kg/ha. 'Clark' Soybean [*Glycine max* (L.) Merrill] were injured as long as 6.5 months after treatment of picloram at 6.72 kg/ha (35). Activated carbon applied at as much as 672 kg/ha in a Toa silty clay protected oats from picloram applied at 0.56 kg/ha but did not completely protect 'Ashly' cucumbers or 'Black Valentine' beans (33). At College Station, Texas, 'Tophand' sorghum was grown in Wilson clay loam 12 months after application of 1.12 kg/ha picloram without reduction in plant numbers, dry matter production, flowering, or germination (34). No picloram was detected in sorghum seed harvested from plants growing in picloram-treated soil as early as 6 month after application. 'Hill' soybean numbers per hectare and total dry matter production were slightly depressed 14 months after picloram application (34).

Ryegrass (*Lolium perenne* L. and *multiflorum* Lam.) could be grown as early as 75 days (and 16 cm rainfall) after application of picloram at 1.1 or 3.4 kg/ha as a spray or granule in a Wilson clay loam soil (5).

Scifres and Halifax (97) found that picloram did not influence germination but did affect range grass seedling growth. Radicle elongation of sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.], buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.], and switchgrass (*Panicum virgatum* L.) in petri dishes was reduced by 125 ppb picloram, whereas shoot elongation was not retarded by 1,000 ppb. Buffalograss, sideoats grama, and switchgrass seedlings germinated in soil containing 500 ppb picloram and were generally not reduced in topgrowth production. However, topgrowth production of Arizona cottontop [*Digitaria Californica* (Benth.) Henr.] and vine mesquite (*Panicum obtusum* H.B.K.) was reduced by 125 to 250 ppb of picloram in soil. Root production and root:shoot ratios of switchgrass seedlings were decreased when 1,000 or 2,000 ppb of picloram were placed on the soil surface or at 7.5 cm deep (98). Sideoats grama root production decreased by application of 1,000 ppb of picloram placed 2.5 cm deep, but production was increased in soil with 1,000 ppb of picloram placed 15 cm deep. Root:shoot ratios in picloram-treated soil were typically no different than those in untreated soil, but root growth pattern was affected.

Grain sorghum varieties varied in their response to pre- or postemergence irrigation and postemergence spray of various picloram concentrations (93). Significant increases in dry weight of Pioneer 820, RS-625, and PAG-665 occurred when treated preemergence with irrigation water containing 500, 1,000, and 2,000 ppb of picloram, whereas GA-615, RS-671, Tophand, and RS-626 were retarded by these concentrations. Dry weights of Pioneer 820 and RS-625 were increased by irrigation water containing 1 to 5 ppb of picloram applied postemergence or when treated with sprays containing 0.035 to 0.7 kg/ha.

Persistence in Plants

Herbaceous Plants

Getzenduner et al. (51) showed that picloram residues in grass collected from various U.S. locations generally degraded after 1 year, and residues were lower from granular than from liquid formulation. No bound form of picloram was found in grasses.

Semiarid Areas. Picloram dissipated from grass, primarily buffalograss, at rates of 2.5 to 3% per day after applications of 0.28 kg/ha for honey mesquite control (96). Thus more than 90% of the picloram dissipated from grasses and broadleaf herbs within 30 days after application. Dissipation of picloram from grasses was not affected by irrigation to surface runoff within 10, 20, or 30 days after application (96).

Hoffman (56) found that picloram disappeared from grasses in 3 to 6 months at more than 20 locations (mainly semiarid sites) in Texas. Picloram was applied with equal rates of 2,4,5-T for honey mesquite control. Rates of picloram varied from 0.28 to 0.84 kg/ha. If rates of picloram are from 2.24 to 4.48 kg/ha, persistence may be as long as 2 years after treatment of redberry juniper (*Juniperus pinchoti* Sudw.) with picloram granules (38). Predominant grasses in the study were little bluestem and sideoats grama.

Humid Areas. Dissipation of picloram in range grasses in humid areas was relatively rapid. Zero to small concentrations were detected 6 months after treatment (15, 16, 23, 24). Even when treatments were repeated every 6 months for a total of five applications at recommended (0.56 + 0.56 kg/ha) and at twice recommended rates of picloram and 2,4,5-T, picloram dissipated rapidly and did not accumulate in the grasses or environment (23, 24).

Woody Plants

Semiarid Areas. Honey mesquite leaves contained about 25 ppm of picloram the day of application of 0.28 kg/ha (96), but contained <1 ppm 23 days later. Picloram dissipated slower from sand shinnery oak leaves (*Quercus havardii* Rydb.) at the same site than from honey mesquite. Nearly 2 ppm were detected in the oak leaves after 60 days. Picloram in soil surface leaf litter dissipated after 120 days.

Humid Areas. Baur et al. (15) reported that the amounts of 2,4,5-T detected in live oak at Victoria, Texas, were greater when applied with either the potassium salt or isooctyl ester of picloram than when 2,4,5-T was applied alone. Most herbicide had dissipated from live oak stems 6 months after treatment. Less than 1 ppb of picloram was detected in yaupon (*Ilex vomitoria* Ait.) stems or roots 6 months after treatment or retreatment with 1.12 kg/ha of picloram (16).

Effect on Plants

Fourteen days after planting, aqueous picloram solutions were used to water plants growing in pots (11). Water containing 0.25 and 0.50 ppb stimulated fresh shoot weights of 'Texas No. 30' corn, 'ATX3197 MS Kafir 60' sorghum, 'Stoneville 213' cotton, 'Alabama Blackeye' cowpea [*Vigna unguicula* (L.) Walp.], and 'Lee' soybean 21 days after planting. It took 100 ppb to get the same effect in 'Milam' wheat. Significant stimulation in dry weight production occurred in corn, sorghum, cotton, and soybean at 0.25 ppb and cowpea at 1 ppb. Fresh and dry weight decreased in corn, wheat, and sorghum at 1,000 ppb and in all dicot species at 100 ppb. Picloram at levels as great as 1,000 ppb had no effect on dry weights of 'Bluebell' rice and wheat or fresh weight of rice. Picloram caused reductions in soluble protein concentrations in all monocot species and in 'HA-61' sunflower. Significant increases in soluble protein occurred at 0.25 and 1 ppb in cowpea and cotton, respectively.

In the field, picloram, tebuthiuron, and 2,4-D did not reduce protein concentration in kleingrass (*Panicum coloratum* L.), buffelgrass (*Cenchrus ciliaris* L.), and Coastal bermudagrass [*Cynodn dactylon* (L.) Pers.] but did reduce protein concentrations in a buffel X birdwood hybrid (*Cenchrus setigerus* Vahl.) (12). Glyphosate increased protein content in buffelgrass and kleingrass and sometimes reduced production of buffelgrass and buffelgrass X birdwood hybrid.

Factors Affecting Degradation

Concentrations as high as 70 ppm of picloram were detected on grasses 2 hours after foliar application of 0.56 kg/ha or 1.12 kg/ha each of picloram and 2,4,5-T (23, 24). Only 842 ppb of picloram at 0.56 kg/ha could be detected on grass after application of 3.8 cm simulated rainfall (24). Photodecomposition may also be important in loss of picloram from treated vegetation (13). Herbicide dilution and metabolism by plant growth also influences picloram loss.

Persistence and Movement in Water Sources

Movement of Picloram in Surface Water

Trichell et al. (109) determined movement of picloram in runoff water from small plots 24 hours after application. Loss of picloram was greater from sod than from fallow. The maximum loss obtained for picloram, dicamba, or 2,4,5-T was 5.5%, and the average was approximately 3%. The time interval from picloram application to the first rainfall determined the amount of picloram that moved into the soil profile and/or the amount that moved away from the point of application with surface runoff. Four months after application, picloram losses were <1% of that lost during the initial 24 hours after application.

Scifres et al. (95) indicated that picloram moved in surface runoff when 0.28 kg/ha was applied in the Rolling Plains of Texas for control of honey mesquite. Irrigation the first 10 days after application resulted in a concentration of 17 ppb of picloram in surface runoff. Irrigation at 20 or 30 days resulted in <1 ppb of picloram residue in runoff water. No more than 1 or 2 ppb picloram was detected after dilution of runoff water into ponds.

Baur et al. (14) studied picloram residues from a 6.1-ha watershed treated with the potassium salt of picloram at 1.12 kg/ha near Carlos, Texas, on an Axtell fine sandy loam soil. Samples were collected directly below the treated area and in streams below the plots after each heavy rainfall. Within 4 days after treatment, picloram residues in runoff water ranged from 9 to 168 ppb after heavy rainfall. After 3 months, concentrations of 5 ppb or less of picloram were found in runoff water. After 1.5 weeks with initial treatments in April, no picloram was found in streams from 0.8 to 3.2 km from the treated area. After a 6.1-cm rainfall 10 months after treatment, no picloram was detected in runoff water regardless of sampling location.

Research shows that herbicide residues can occur in surface runoff water if heavy rainfall occurs soon after treatment. When pelleted picloram was applied at 2.24 kg/ha to a 1.3-ha rangeland watershed, surface runoff of 1.5 cm from a 2.1-cm rain received 2 days after treatment contained an average of 2.8 ppm of picloram (37). However, picloram content declined rapidly in each successive runoff event, and runoff water contained <5 ppb by 2.5 months after application. Loss of the potassium salt of picloram from grassland watersheds in surface runoff water was similar whether the picloram was applied as aqueous sprays or as pellets on a Houston black clay soil. Picloram plus 2,4,5-T at 0.56 kg/ha each were applied May 4, 1970, December 4, 1970, May 4, 1971, and October 8, 1971 (24). No runoff event occurred until July 25, 1971, 72 days after the third herbicide treatment. Concentration of 2,4,5-T and picloram averaged 7 and 12 ppb, respectively, in runoff water and <5 ppb during subsequent runoff events. Data indicated that picloram or 2,4,5-T content was typically <5 ppb in runoff if major storms occurred 1 month or longer after treatment on the Houston black clay.

On sandy soils, Scifres et al. (99) found only trace amounts of picloram or 2,4,5-T, which had been applied at 0.56 kg/ha each, in surface runoff water following storms about 30 days after application.

Mayeux et al. (69) found that maximum concentrations of picloram were 48 and 250 ppb in initial runoff from an 8-ha area treated with 1.12 kg/ha in 1978 and 1979, respectively. Herbicide concentration decreased with distance from the treated area in proportion to the size of adjacent, untreated watershed subunits that contributed runoff water to streamflow. About 6% of the applied picloram was lost from the treated area during active transport.

Movement of Picloram in Subsurface Water

Bovey et al. (23) conducted an investigation to determine the concentration of 2,4,5-T and picloram in subsurface water after spray applications to the surface of a seepy area watershed and lysimeter site in the Blacklands of Texas. A 1:1 mixture of the triethylamine salts of 2,4,5-T plus picloram was sprayed at 2.24 kg/ha every 6 months on the same area for a total of five applications. Seepage water was collected on 36 different dates, and 1 to 6 wells in the watershed were sampled at 10 different dates during 1971, 1972, and 1973. Concentration of 2,4,5-T and picloram in seepage and well water from the treated area was extremely low (<1 ppb) during the 3-

year study. No 2,4,5-T was detected from 122 drainage samples from a field lysimeter at another site sampled for 1 year after treatment with 1.12 kg/ha of a 1:1 mixture of the triethylamine salt of 2,4,5-T plus picloram. Picloram at levels of 1 to 4 ppb was detected in lysimeter water from 2 to 9 months after treatment. Supplemental irrigation in addition to a total of 85.5 cm natural rainfall was used to leach picloram into the subsoil.

In another study, Bovey and Richardson (36) found that picloram and clopyralid remained in the uppermost 30 cm of a Houston black clay soil. The herbicides were sprayed at 0.56 kg/ha each on the same area in 1988 and 1989 on a seepy site overlying a shallow, perched water table. No herbicide was detected in subsurface water from the area in 1988, but concentrations of <6 ppb of both herbicides were detected in subsurface water collected 11 days and from 41 to 48 days after treatment in 1989.

Dissipation of Picloram from Impounded Water Sources

Research conducted in semiarid and subhumid environments have shown that most picloram was dissipated from impounded, natural water sources within a month to 6 weeks after introduction (53). However, concentrations of picloram from 1 to 2 ppb were detectable a year after application of 1.1 kg/ha to these ponds. In no case did treated areas adjacent to domestic water wells that were 9 to 46 m deep result in picloram residues in wells. Once picloram moved into water catchments in the Rolling Plains, residues were detected for at least a year after treatment (95).

Dilution is important in the dissipation of picloram from impounded water. Photodecomposition is also important in reducing picloram concentration in water. In the photolysis of picloram, certain levels of light energy are necessary for degradation of each molecule. Assuming light energy is randomly dispersed, then interception of photons by picloram molecules would be a random occurrence. In such a system, degradation of picloram would be expected to occur rapidly at first, then decrease as fewer molecules were available for light interception. Such dissipation curves were reported by Haas et al. (53), who found that most rapid dissipation occurred within the first 3 to 4 weeks after application of picloram to impounded water. In such a concentration-dependent system, more energy must be applied for degradation of the remaining herbicide molecules than required at higher picloram concentrations (13).

Clopyralid

Clopyralid is included next because it is chemically closely related to picloram but reacts differently to certain weed species and is less persistent in the environment (3). Clopyralid is less effective than picloram on most broadleaf species but is highly effective against certain broadleaf weeds such as those in the Polygonaceae, Compositae, and Leguminosae families. It has little or no activity against grasses or crucifers. Mixtures of clopyralid with other growth regulator-type herbicides extends the spectrum of species controlled. Differing from picloram, clopyralid is resistant to photodecomposition but is more susceptible to degradation by microbes (3). In a wide range of soils across the United States, clopyralid degrades at a medium to fast rate. It has a half-life ranging from of 12 to 70 days (3).

Persistence in Soil and Movement in Water Sources

A 1:1 mixture of the monoethanolamine salts of clopyralid and the tri-isopropanolamine salt of picloram was applied at 0.56 kg/ha each in May 1988 and June 1989 to the same area (36). Approximately 90 days after treatment, >99% of the clopyralid as compared with 92% of the picloram had dissipated. Most herbicide was detected in the upper 30 cm of soil. Neither herbicide was detected after 1 year.

Neither herbicide was detected in subsurface water from the treated area in 1988, but concentrations of <6 ppb of clopyralid or picloram were detected in subsurface water collected 11 days and from 41 to 48 days after treatment in 1989. The study represents a worst case scenario because the herbicides were applied twice to bare soil and were disked into the soil to prevent loss from photodegradation. Under normal practices, the herbicides may be applied once every 5 to 20 years to weeds and brush and are not protected from photodegradation by disking.

Persistence in Plants

See triclopyr section on persistence in plants.

Phenoxys

Persistence in Soil

For more than 40 years, many investigators have recognized that 2,4-D was rapidly inactivated in moist soil (40). Warm, moist soil accelerates degradation of phenoxy herbicides by stimulating microbial activity. After application in three Oklahoma soil types, Altom and Stritzke (2) found that the average half-life of the diethanolamine salts of 2,4-D, dichlorprop [(±)-2-(2,4-dichlorophenoxy) propanoic acid], silvex [(2,4,5-trichlorophenoxy) propanoic acid], and 2,4,5-T were 4, 10, 17, and 40 days, respectively.

In Texas, Bovey and Baur (20) applied the propylene glycol butyl ether esters of 2,4,5-T at 0.56 and 1.12 kg/ha to soils at five locations. After 6 weeks, 2,4,5-T had disappeared from all locations. At three different locations on sandy soils in central Texas, Scifres et al. (99) found that 2,4,5-T was reduced to trace levels of <10 ppb in 7, 28, and 56 days. Residues of 2,4,5-T were not detected below 15 cm and generally remained in the upper 2.5 cm of soil.

Influence of High Rates

Early work by Crafts (45) and others indicated that 2,4-D typically did not persist from one growing season to another even at high rates, largely because of microbial breakdown. Work by Bovey et al. (35) in Puerto Rico indicated that corn, sorghum, wheat, rice, soybean, and cotton could be grown in soils 3 months after application of a 1:1 mixture of the n-butyl esters of 2,4-D plus 2,4,5-T at 26.9 kg/ha without reduction in fresh weight. Except for soybean, which was sensitive to picloram residues, similar results were obtained with these crops for a 2:2:1 mixture of 2,4-D plus 2,4,5-T plus picloram at 16.8 kg/ha. Young et al. (117) reported that 2,4-D and 2,4,5-T were applied at massive doses to three areas at Eglin Air Force Base in Florida in the 1960's. Chemical analysis of soil cores collected in 1970 from the treated area indicated that the herbicides had degraded.

Effect of Repeated Treatment

Gas chromatographic analysis of Canadian soils indicated no residual amounts of 2,4-D and MCPA after 40 and 34 annual treatments, respectively (105). Under laboratory conditions, the breakdown of 2 kg/ha of (^{14}C)2,4-D or (^{14}C)MCPA [(4-chloro-2-methlyphenoxy) acetic acid] was slightly faster in soils that had received continuous applications with the appropriate herbicide, which suggests that soil microbial populations adapted in response to repeated long-term use.

In two separate studies in Texas, Bovey et al. (23, 24) found that 2,4,5-T did not accumulate in soils when applied five times at 0.56 or 1.12 kg/ha every 6 months on the same area. In plots receiving 0.56 and 1.12 kg/ha of 2,4,5-T, average concentration did not exceed 95 and

144 ppb, respectively, and most herbicide was confined to the upper 15 cm of soil and generally disappeared by the time of retreatment.

Modes of Breakdown in Soil

As indicated, soil microorganisms contribute greatly to the detoxification of phenoxy herbicides (40). Other means of degradation include chemical decomposition, thermal loss and volatilization, absorption in soils, and photodegradation. Temperature of the soil surface may easily reach 60 °C in the summer. Baur et al. (13) found 55% loss of 2,4,5-T as the free acid exposed to 60 °C but no loss at 30 °C after 2 days. The K^+ salt of 2,4,5-T adjusted to pH 7 showed 30% loss at both 30 and 60 °C after 7-day exposure. Baur and Bovey (9) exposed dry preparations of 2,4-D to 60 °C, which resulted in 75% loss of 2,4-D within 1 day after treatment. Herbicides 2,4-D and 2,4,5-T were also subject to breakdown by long-wave ultraviolet (356 nm) irradiation (9, 13). Therefore, 2,4-D or 2,4,5-T on soil and plant surfaces would be subject to loses by ultraviolet, thermal, and volatility in the field.

Persistence in Plants

Over a 3-year period, Morton et al. (76) studied the disappearance of 2,4-D, 2,4,5-T, and dicamba from pastures containing silver beardgrass (*Andropogon saccharoides* Swartz), little bluestem (*A. scoparius* Michx.), dallisgrass (*Paspalum dilatatum* Poir.), and sideoats grama. No important differences were found in persistence of different herbicides. The half-life of 2,4-D, 2,4,5-T, and dicamba in green tissue was from 2 to 3 weeks after application. Half-life in grass litter was slightly longer (3 to 4 weeks) than in green tissue. Shorter half-life of herbicides in green tissues was attributed to dilution by growth. Rainfall was important in hastening herbicide disappearance.

Baur et al. (15) applied 2.24 kg/ha of the 2-ethylhexyl ester of 2,4,5-T alone and with 0.56, 1.12, and 2.24 kg/ha of the potassium salt or isooctyl ester of picloram to pastures supporting infestations of live oak (*Quercus virginiana* Mill.). Grass species indigenous to the site were little bluestem, brownseed paspalum (*Paspalum plicatulum* Michx.), and indiangrass (*Sorghastrum* spp.). Recovery of 2,4,5-T acid and ester from woody and grass tissues was greatest when applied with picloram. Herbicide recovery in all treatments, however, were generally <10 and 0.1 ppm, 1 and 6 months, respectively, after application.

Bovey and Baur (20) analyzed forage grasses from five locations in Texas comprising different grass species, soils, and climate that had been treated with the propylene glycol butyl ether esters of 2,4,5-T at 0.56 and 1.12 kg/ha. Six weeks after treatment, an overall average of 98% of the 2,4,5-T had been lost from all treated areas. After 26 weeks, the herbicide levels in grass were very low, ranging from 0 to 51 ppb.

In two separate studies, Bovey et al. (23, 24) applied a 1:1 mixture of the triethylamine salts of 2,4,5-T and picloram at a total of 1.12 and 2.24 kg/ha to the first and second experiment, respectively, on pasture land in central Texas. Repeat treatments were made every 6 months to the same area for a total of five applications. Herbicide content on native grass was high (28 to 113 ppm) immediately after spraying but degraded rapidly after each treatment and disappeared before new applications were made. There was no accumulation of 2,4,5-T in soils or vegetation.

Baur et al. (15) found that most of the 2,4,5-T applied at 2.24 kg/ha as the 2-ethylhexyl ester to live oak disappeared in 6 months. However, they detected small amounts of both the acid (93 ppb) and ester (233 ppb) of 2,4,5-T. At 1 and 6 months, more 2,4,5-T was found in live oak tissue at the top of the plant than at the middle and lower stem because the top portion intercepts more spray than do lower regions. In live oak, more 2,4,5-T was found when combined with picloram than was 2,4,5-T alone at equivalent rates.

Brady (41) indicated that radioactive 2,4,5-T persisted three to seven times longer in treated woody plants as in forest soils. The half-life of 2,4,5-T was 5.5, 5.8, 6.7, and 12.4 weeks in loblolly pine (*Pinus taeda* L.), post oak (*Quercus stellata* Wangenh.), sweetgum (*Liquidambar styraciflua* L.), and red maple (*Acer rubrum* L.), respectively. All four species decarboxylated 2,4,5-T and released CO_2 with no significant difference among species or doses.

Modes of Breakdown in Plants

Basler et al. (4) established that the 2,4-D and 2,4,5-T breakdown in excised blackjack oak (*Quercus marilandica* Muenchh.) leaves was 50% or more in 24 hours. Morton (74) showed that approximately 80% of the 2,4,5-T absorbed by mesquite leaves was metabolized in 24 hours. Numerous other investigations also have shown the importance of metabolism in detoxification and loss of phenoxy herbicides in many plant species (40).

9

Leaves and stems of plants are main receptors of foliar-applied herbicides. Aside from their function in decarboxylation, breakdown, and conjugation of the herbicide, leaves and plant parts may abscise or abort from the plant and fall to the soil, where the tissue and any residual herbicide may weather and decay. Aerial parts of plants may be removed by mowing machines or clipped and consumed by grazing animals. If the herbicide does not kill or stop growth of the plant, such as happens in many grasses, the herbicide will be diluted by growth.

On plant surfaces, phenoxy herbicides are lost by photodegradation and volatilization in a manner similar to loss from soils. Rainfall is also reported as an important means of accelerating herbicide loss from litter and plant surfaces (23, 24, 76).

Persistence and Movement in Water Sources

Trichell et al. (109), using gas chromatographic and bioassay detection techniques, investigated the loss of 2,4,5-T, dicamba, and picloram from bermudagrass and fallow plots of 3 and 8% slope. When determined 24 hours after application of 2.24 kg/ha, a maximum of about 2, 3, and 5 ppm picloram, 2,4,5-T, and dicamba, respectively, were found in runoff water after 1.3 cm of simulated rainfall. Losses of dicamba and picloram were greater from sod than from fallow plots, whereas 2,4,5-T losses were approximately equal. Four months after application, picloram, 2,4,5-T, and dicamba concentration in runoff water from sod plots had diminished to 0.03, 0.04, and 0 ppm, respectively. Maximum loss of any herbicide from the treated area was 5.5% and averaged 3%.

Bovey et al. (24) sprayed a 1:1 mixture of the triethylamine salts of 2,4,5-T plus picloram at 1.12 kg/ha every 6 months on a native-grass watershed for a total of five treatments. Plant "wash-off" was the main source of herbicide detected in runoff water. Concentrations of both herbicides was moderately high (400 to 800 ppb) in runoff water if 3.8 cm of simulated rainfall was applied immediately after herbicide application. If major natural storms occurred 1 month or longer after herbicide treatment, concentration in runoff water was <5 ppb.

Norris and Moore (86) and Norris (83) indicated that concentration of 2,4-D, 2,4,5-T, picloram, and amitrole seldom exceeds 0.1 ppm in streams adjacent to carefully controlled forest spray operations in Oregon. Concentrations exceeding 1 ppm have never been observed and are not expected to occur. Chronic entry of these herbicides into streams did not occur for long periods after application.

Impounded Water

Bovey and Young (40) summarized the literature on the fate of 2,4-D and other phenoxys in impounded water. In general, phenoxy decompose rapidly, especially if adapted microorganisms are present. Photodegradation of phenoxys in impounded water is also an important means of breakdown.

Groundwater

Wiese and Davis (116) applied 500 ml of water to wet tubes (7.6 x 61 cm) of dry Pullman silty clay loam topsoil to a depth of 56 cm. The diethylamine salts of 2,3,6-TBA (2,3,6-trichlorobenzoic acid) and PBA (chlorinated benzoic acid) leached to about 51 cm, while the amine salt of 2,4-D and the sodium salt of fenac (2,3,6-trichlorobenzeneacetic acid) leached to 38 cm. The amine salts of silvex and 2,4,5-T leached to approximately 23 cm. Esters of silvex, 2,4,5-T, and 2,4-D remained in the top 8 cm of soil. When excessive water (34.4 cm) was used to wet soil in the tubes, all herbicides could be detected in the leachate except monuron (N'-(4-chlorophenyl)-N,N-dimethylurea) and the ester formulation of 2,4,5-T.

O'Connor and Wiergenga (87) in New Mexico studied degradation and movement of 64 kg/ha of 2,4,5-T in lysimeter columns in the greenhouse. They concluded that pollution of groundwater from normal application rates of less than 2 kg/ha of 2,4,5-T is unlikely because of its relatively slow rate of movement in soil and its rapid biological detoxification.

Edwards and Glass (48) applied 11.2 kg/ha 2,4,5-T (excessively high rate) to a large field lysimeter in Coshocton, Ohio. The total amount of 2,4,5-T found in percolation water intercepted at 2.5 m deep for as long as 1 year after application was insignificant.

Bovey and Baur (20) found little or no 2,4,5-T 12 weeks after treatment in soils at five widely separated locations in Texas after treatment with the propylene glycol butyl ether esters of 2,4,5-T at 0.56 and 1.12 kg/ha.

Bovey et al. (23) conducted an investigation to determine the concentration of 2,4,5-T and picloram in subsurface water after spray applications of the herbicides to the surface of a seepy area watershed and lysimeter in the Blacklands of Texas. A 1:1 mixture of the triethylamine salts of 2,4,5-T plus picloram was sprayed

at 2.24 kg/ha every 6 months on the same area for a total of five applications. Seepage water was collected at 36 different dates, and 1 to 6 wells in the watershed were sampled at 10 different dates during 1971, 1972, and 1973. Concentration of 2,4,5-T and picloram in seepage and well water from the treated area was extremely low (<1 ppb) during the 3-year study. No 2,4,5-T was detected from 122 drainage samples from a field lysimeter at another site sampled for 1 year after treatment with 1.12 kg/ha of a 1:1 mixture of the triethylamine salt of 2,4,5-T plus picloram. Picloram was detected in lysimeter water at only 1 to 4 ppb during 2 to 9 months after treatment. Supplemental irrigation in addition to 85.5 cm natural rainfall leached 2,4,5-T and picloram into the subsoil.

Surveys

An extensive analysis of surface waters of Texas in 1970 for 2,4-D, 2,4,5-T, and silvex revealed zero or trace levels of these herbicides (47). Hectares of brush sprayed with 2,4,5-T annually in the 1960's was generally less than 0.4 million. Out of a total of 43 million ha of range and pasturelands, approximately 0.8 million ha of pasture weeds were sprayed annually with 2,4-D in Texas (111). Some herbicide was introduced into the environment each year but did not contaminate surface waters.

Mode of Breakdown in Water

Phenoxy herbicides do not persistent in water sources, and significant concentrations, if found, occur within a short time after treatment (40). Loss of herbicides from treated areas by movement in runoff water is a very small percentage of the total amount applied even under intensive natural or simulated rainfall. Phenoxy herbicides rapidly dissipate in streams and are not detected downstream from points of application. In impounded water, phenoxys decompose rapidly, especially if adapted microorganisms are present. Even under large-scale applications to surface water sources, 2,4-D disappeared rapidly after application, and concentrations remained low or undetectable. In surveys of major river systems in the United States, 2,4-D appeared infrequently and in minute concentrations.

Spray Drift Potential

Maybank and Yoshida (68) indicated that a typical droplet-size distribution produced by herbicide spray nozzles using water diluent contained droplets of <100 μm in diameter that were subject to drift. This could amount to 20% of the total spray volume, depending upon the type of nozzles and pressures used. Smith and Wiese (106) found that application of 2,4-D at 0.05 to 0.1 kg/ha to cotton caused significant yield loss. The earlier the cotton was sprayed, the more severe the damage. Studies by Maybank and Yoshida (68) indicated that drift of herbicide at 0.04 kg/ha approached those concentrations causing injury to cotton. If precautionary measures are not taken, spray droplets of <100 μm may drift several hundred meters, and application rates of 2,4-D at 0.5 kg/ha or higher may damage adjacent sensitive crops.

At four locations in Texas, Behrens et al. (17) found that 2,4-D caused more leaf malformation in cotton than did 2,4,5-T and MCPA. Silvex did not cause leaf malformations. Similarly, 2,4-D caused greatest reduction in cotton yield followed by 2,4,5-T and MCPA. Silvex caused the least reduction in yield. Smith and Wiese (106) compared 2,4-D to dicamba, picloram, bromoxynil (3,5-dibromo-4-hydroxybenzonitrile), and 2,3,6-TBA. The order of damage to cotton was 2,4-D ester > 2,4-D amine >> dicamba > MCPA > picloram >> bromoxynil >> 2,3,6-TBA. Sprays of 2,4-D, dicamba, or MCPA at 0.1 kg/ha reduced lint yields from 20 to 97%. Yield losses were most severe when cotton was sprayed before blooming. However, lint quality (micronaire and length) was not affected by these herbicides. 'Tamcot' cotton seedlings were injured by foliar sprays of 2,4,5-T, triclopyr, and clopyralid at 0.03 kg/ha in the greenhouse (29). No new growth occurred when cotton was treated with 0.14 or 0.56 kg/ha of 2,4,5-T or triclopyr. Clopyralid was less injurious to cotton than were triclopyr and 2,4,5-T, and only slight leaf malformations occurred at clopyralid rates of 0.03 kg/ha or less. Because clopyralid has shown excellent control of honey mesquite (Prosopis glandulosa Torr.) in Texas, damage from spray drift of this herbicide should be minimal.

Methods to control spray drift and volatility of 2,4-D and other herbicides are discussed elsewhere (115). Injury of cotton and other crops from 2,4-D has occurred in Texas. Such residues in soils or plants are short lived but can cause significant injury the season of application.

Dicamba

Persistence in Soil

Scifres and Allen (91) indicated that dicamba applied at 0.28 kg/ha dissipated from grassland soils of Texas in

4 weeks and in 9 to 16 weeks at 0.56 kg/ha. Dicamba residues were generally detected no deeper than 120 cm in clay or sandy loam soils. However, dicamba residues were detected at 120 cm deep 53 weeks after application of granules at 1.68 or 2.24 kg/ha to sand in semiarid grassland. Under moist, warm soil conditions, dicamba has a half-life of <14 days (103) as a result of microbial degradation (62). Dicamba readily converts through microbial activity to 3,6-dichlorosalicyclic acid (DCSA) (103,104). DCSA can undergo breakdown but breakdown has been reported to be slower than for dicamba (103,104). DCSA adsorption to soils is significant (79). Although dicamba is minimally adsorbed to soils, its residues are short lived and unlikely to become a problem in groundwater.

Modes of Breakdown in Soil

Microbial degradation is highly important in disappearance of dicamba (62, 103, 104). Bacteria that utilize dicamba have been isolated and identified (62).

Persistence in Plants

Herbaceous Plants

Morton et al. (76) studied the disappearance of 2,4-D, 2,4,5-T, and dicamba over a 3-year period from a pasture containing silver beardgrass, little bluestem, dallisgrass, and sideoats grama. No important differences were found in persistence of different herbicide formulations. The half-life of 2,4-D, 2,4,5-T, and dicamba in green tissue was from 2 to 3 weeks after application. Half-life in grass litter was 3 to 4 weeks. The short residual of herbicides in green tissues was attributed to dilution by growth. Rainfall hastened herbicide disappearance.

Effect on Forage Grasses and Cotton

Vine mesquite tolerated 0.28 kg/ha dicamba applied preemergence (54). After emergence, 'Premier' sideoats grama tolerated 0.56 kg/ha dicamba. Pre- or postemergence applications of 1.12 and 2.24 kg/ha severely retarded shoot production of all species including 'Blackwell' switchgrass. All species germinated and grew without reduction in shoot production in soil containing as much as 63 ppb of dicamba.

In greenhouse studies, dicamba applied preemergence and postemergence at 0.14 to 2.24 kg/ha injured seedling kleingrass (21). Mature plants of kleingrass, buffelgrass, King Ranch bluestem [*Bothriochloa*

ischaemum (L.) var. *Songarica* (Rupr) Celarier & Harlan], green sprangletop (*Leptochloa dubia* H.B.K.), sideoats grama, common bermudagrass [*Cynodon dactylon* (L.) Pers.], and plains bristlegrass (*Setaria macrostachya* H.B.K.) tolerated dicamba and 2,4-D at rates as much as 2.24 kg/ha. Rates of 2,4-D at 1.12 kg/ha injured buffelgrass, which tolerated dicamba (21).

In the field, dicamba, 2,4-D, or 2,4,5-T generally did not reduce vegetative production of common, Coastal, or coastcross-1 bermudagrass when applied in spring or fall (31). In central Texas, herbage production of native forage grass was increased when whitebrush [*Aloysia gratissima* (Gillies & Hook.) Troncoso] was controlled by dicamba or picloram plus dicamba (32).

Smith and Wiese (106) indicated that sprays of 2,4-D, dicamba, or MCPA at 1.12 kg/ha reduced lent yields of cotton from 20 to 97%. Yield losses were most severe when cotton was sprayed before blooming. However, these herbicides did not affect lint quality (micronaire and length).

Modes of Breakdown in Plants

Dissipation of dicamba from plants can occur by exudation through roots into the surrounding soil, by metabolism within the plant, or by loss from leaf surfaces (3). Loss by ultraviolet light is also suggested (13).

Persistence and Movement in Water Sources

Trichell et al. (109) studied dicamba runoff from sloping sod plots in Texas. They found that as much as 5.5% of the applied dicamba was recovered in runoff water when 1.3 cm artificial rain was applied 24 hours after herbicide application. No dicamba was found in runoff water from a similar artificial rain application 4 months later after a 21.6-cm natural rainfall event. Approximately 8% of the artificial rain was recovered as runoff.

Norris (84) found maximum dicamba levels of 37 ppb about 5.2 hours after treatment at 1.3 km from the point where the sample stream entered the treatment unit in Oregon. Dicamba residues detected the first 30 hours after application resulted from drift and direct application to exposed surface water. By 37.5 hours, residue levels had declined to background levels; no dicamba residues were found more than 11 days after application. Dicamba levels found in streams were several orders of magnitude below threshold response levels for fish and mammals.

In 1984, Muir and Grift (78) sampled the Ochre and Turtle Rivers which flow into Dauphin Lake in western Manitoba, Canada, to determine levels of MCPA, diclofop {(±)-2-[4-(2,4-dichlorophenoxy) phenoxy] propanoic acid}, dicamba, bromoxynil, 2,4-D, triallate [s-(2,3,3-trichloro-2-propenyl)bis(1-methylethyl)carbamothioate], and trifluralin [2,6-dinitro-$\underline{N},\underline{N}$-dipropyl-4-(trifluoromethyl)benzenamine], which were used widely in each watershed. Dicamba and 2,4-D were detectable throughout most of the sampling period in both rivers at low levels of <1 ppb. Levels of <6 ppb of dicamba and 2,4-D were detected in water from the Turtle River before a high-water event, possibly from sprayed ditches or rights-of-way near the river. Even so, discharges of all herbicides monitored in the study were <0.1% of the amounts used in each watershed. Levels of dicamba and 2,4-D in June were still far below toxic levels for fish or fish food organisms and below levels affecting water quality standards.

Impounded Water

Dicamba dissipated most rapidly from water under non-sterile, lighted conditions (92). Pond sediment evidently contained microbial populations capable of decomposing the herbicide. Temperature was crucial in dicamba dissipation, especially in the presence of sediment. In some cases, influence of sediment on dissipation rate of dicamba was apparently augmented by light. Under summer conditions, dicamba at 4.4 kg/ha/surface area of ponds dissipated at about 1.3 ppm/day. Dicamba dissipated as a logarithmic function of concentration with time.

Influence of Dicamba in Irrigation Water on Seedling Crops

Crops varied in their response to one irrigation of water containing dicamba (92). 'Dunn' was the most susceptible cotton cutlivar. Fresh weights of Dunn seedlings were reduced at 100 ppb of dicamba, whereas concentrations of 500 ppb were required for weight reduction in 'Paymaster'. 'Blightmaster' was the most tolerant cultivar studied. 'Pioneer 820' and 'RS-626' grain sorghums seedlings also tolerated all dicamba treatments. RS-626 at 500 ppb showed increased fresh weight. 'Straight-eight' cucumber seedlings tolerated irrigation water containing as much as 50 ppb dicamba but were injured or killed by 100 and 500 ppb, respectively. Crop tolerance to dicamba in irrigation water from greatest to least were sorghum > cotton > cucumber.

Triclopyr

Relatively little research has been done with triclopyr in Texas because of preoccupation with other herbicides and because studies on triclopyr residues were being done at other locations.

Persistence in Soil

In Texas, Moseman and Merkle (77) determined that triclopyr when applied in the fall persisted about 6 months in a Miller clay soil but dissipated 3 months after summer application. Jotcham et al. (61) in Canada indicated that triclopyr was slightly less persistent than 2,4,5-T but neither herbicide was biologically active during the next season. In four different soils, triclopyr and 2,4-D had similar mobilities as determined by soil TLC. Schubert et al. (90) reported that triclopyr residues in soil decreased from a maximum of 18 to 0.1 ppm in 166 days in a West Virginia watershed.

At two sites in Oregon, Norris et al. (85) found that triclopyr and its metabolites persisted for 1 year or more in small concentrations. They speculated that dry summers in Oregon may retard dissipation of triclopyr compared with West Virginian summers. Triclopyr residues were confined to the top 30 cm of soil. Newton et al. (82) in Oregon also found that triclopyr persisted in small amounts for 1 year in soil after aerial application. However picloram, triclopyr, and 2,4-D residues decreased rapidly after application, leveled off 79 days after treatment, and then began a period of slow loss that continued until the following summer. Newton et al. (82) found that picloram was lost quicker than triclopyr or 2,4-D as contrasted to results reported by Norris et al. (85), who observed that picloram persisted longer than 2,4-D. Norris et al. (85) was working in a nearby but drier area. Newton et al. (82) suggested that triclopyr is similar to 2,4-D in movement and persistence.

Mode of Breakdown in Soils

Leaching, photodegradation, and microbes degrade triclopyr (3).

Persistence in Plants

Bovey et al. (28) found more picloram than triclopyr in greenhouse-grown huisache [*Acacia farnesiana* (L.) Willd.] 0, 3, 10, and 30 days after treatment with foliar sprays, soil application, or soil-plus-foliar treatments. In field-grown honey mesquite, more clopyralid and piclo-

ram than triclopyr or 2,4,5-T was detected in honey mesquite stem tissue (27). Triclopyr and 2,4,5-T residues were generally <2 ppm by 3 days after application, whereas picloram and clopyralid residues were as high as 11 and 22 ppm, respectively. Concentrations of triclopyr and picloram recovered from honey mesquite stems were about 25% greater at 3 than at 30 days after treatment, whereas concentrations of 2,4,5-T and clopyralid were about 50% greater at 3 than at 30 days after application. Concentrations of 2,4,5-T in standing dead stems were 0.2 and 0.4 ppm dry weight in upper stem phloem and upper stem xylem, respectively, 20 months after application (27). Phloem and xylem tissue taken from the base of dead stems had <0.01 ppm of 2,4,5-T and had little or none in live resprouts. Concentrations of triclopyr in dead stems ranged from 0.06 to 0.9 ppm, but generally the herbicide could not be detected in live resprouts.

After 22 to 26 months, as much as 0.4 and 0.9 ppm of 2,4,5-T and triclopyr could be detected in dead honey mesquite stems that had fallen to the soil surface. Thorns also contained detectable concentrations of 0.1 ppm each of 2,4,5-T and triclopyr.

In comparison, concentrations of picloram ranged from 0.3 to 1.3 ppm dry weight 20 to 26 months after treatment in dead honey mesquite stems—standing or fallen on the soil (27). Concentrations of clopyralid in the same tissues ranged from 0.7 to 3.3 ppm. No clopyralid was detected in treated live stems, but concentrations of 0 to 0.04 ppm of picloram were detected. Picloram and clopyralid, at 0.3 and 0.8 ppm, respectively, were detected in thorns from several dead stems.

Norris et al. (85) found that triclopyr decreased rapidly from grasses in Oregon. Initial average concentrations of 527 ppm immediately after treatment were reduced to <0.3 ppm by 158 days after treatment. Newton et al. (82) found that 2,4-D, triclopyr, and picloram persisted in evergreen foliage and twigs for nearly 1 year. Crowns and browse layers showed similar rates of loss, but browse layer concentrations of 2,4-D and triclopyr were only about one-third of those in crown foliage. Despite shading, picloram decreased to low levels before rainfall and remained low but detectable. Salt formulations of the herbicides were lost faster than ester formulations, and herbicide residues decreased rapidly in litter and soil.

Whisenant and McArthur (114) showed the dissipation of triclopyr from several herbaceous and woody species in northern Idaho. Triclopyr concentrations in foliage varied among species at two sites. The highest concentration of 362 ppm occurred in shinyleaf ceano-

thus (*Ceanothus velutinus* Dougl. ex. Hook.) 1 day after treatment, but by 365 days more than 98% of the triclopyr had dissipated from all species. Triclopyr residue data from the study and large herbivore toxicological data from other studies indicate that toxicity from proper use of triclopyr is unlikely.

Effect on Plants

Triclopyr was generally more phytotoxic to seedling '5855X127C' corn, 'TAM 0312' oat, 'MS 398' grain sorghum, and 'Selection 75' kleingrass than was either 2,4,5-T or clopyralid (29). 'Caddo' wheat tolerated triclopyr at 0.56 kg/ha. Triclopyr and clopyralid caused greater injury to 'Florrunner' peanuts than did 2,4,5-T, whereas 2,4,5-T and triclopyr were more damaging to 'Tamcot' cotton and 'Liberty' cucumber than was clopyralid. All three herbicides at 0.14 and 0.56 kg/ha killed 'Gail' soybean. Kleingrass was not affected by any rate of clopyralid.

Factors Affecting Degradation

Triclopyr is lost from grasses because of metabolism, growth dilution, wash-off, volatilization, and photodegradation (85).

Persistence and Movement in Water Sources

Surface Runoff Water

Schubert et al. (90) using a helicopter treated the upper part of a watershed in West Virginia with 11.2 kg/ha triclopyr. Two streams transversed the treated area. Movement of triclopyr residues in soil and water downslope from the treated area was insignificant.

Maximum concentration of triclopyr in stream water was 95 ppb the first 20 hours after application, similar to that observed for other herbicides applied to forest streams (85). Reduction in concentration the first 20 hours after application was attributed to photodecomposition. In September during the first significant rains after application in May, maximum triclopyr residues of 12 ppb were found in a small pond at the site. A 6-cm rain on November 9, causing a 6,500-L stream discharge, increased triclopyr concentrations to 15 ppb, but after November 11 no more triclopyr was detected.

Groundwater

Triclopyr was applied in both ester and amine formulations on October 24, 1986, to Coastal Plain flatwood

watersheds near Gainesville, Florida (43). Panicum grasses (*Panicum* spp. and *Dichanthelium* spp.), wiregrass (*Arietida stricta*), gallberry (*Ilexglabra*), and most herbaceous plant species were controlled by both formulations. Triclopyr application resulted in a shift toward a bluestem-dominated understory. Triclopyr residues were detected at trace levels of 1 to 2 ppb in storm runoff during the first runoff event after application. No triclopyr residues were detected in subsequent runoff events or in any groundwater wells for 6 months after application.

Impounded Water

Examination of triclopyr and by-product 3,5,6-trichloro-2-pyridinol (TCP) residue dissipation following application of the triethylamine salt of triclopyr at prescribed rates showed that no adverse effects should be produced on the aquatic environment (52). The results showed that detectable triclopyr levels in water were variable from 3 to 21 days, residue half-life being less than 4 days. Residue accumulation in sediment, plants, and fish was negligible. TCP concentrations and persistence were transitory. However, results of crayfish evaluation indicated prolonged persistence of triclopyr and TCP. Further evaluation of triclopyr and TCP accumulation in clams and crayfish, separating the edible parts of the crayfish from the nonedible parts, must be accomplished before a tolerance level can be established.

Mode of Breakdown in Water

Photodegradation is a major means of triclopyr decomposition in water (3).

Tebuthiuron

Persistence in Soil

Pelleted tebuthiuron was applied aerially on duplicate plots at 2.2 and 4.4. kg/ha in spring, summer, fall, and winter of 1978 and 1979 for mixed brush control (30). Soil was predominantly an Axtell fine sandy loam (Udertic Paleustalfs). Tebuthiuron persisted for more than 2 years in the Claypan Resource Area of Texas at depths of 0 to 15 cm and 15 to 30 cm as determined by 'Tamcot' cotton and 'Caddo' wheat bioassays. Tebuthiuron content ranged from 0.08 to 0.49 ppm. Deeper soil depths were not sampled. On a Houston Black clay (Udic Pellustert), pellets were broadcast and applied in bands at 2.24 kg/ha (22). Tebuthiuron was also detected to depths of 46 to 61 cm but not at 76 to 91 cm deep. After 6 months, most tebuthiuron was found in the 0- to 15-cm soil layer. Whether tebuthiuron leached deeper after 6 months is unknown. Tebuthiuron applied as a broadcast spray also resided mainly in the 0- to 15-cm layer. In another study, tebuthiuron at 2.24 kg/ha persisted in the 0- to 15-cm and 15- to 30-cm layers of soil for 25 months on a Lufkin fine sandy loam (Vertic Albaqualfs) but not in a Wilson Clay loam (Vertic Ochraqualfs) (73). The Lufkin fine sandy loam, however, was underlain by a claypan at 15 to 30 cm deep, whereas the Wilson clay loam was more permeable. All studies mentioned are in an area with approximately 75 to 90 cm or more annual rainfall.

In semiarid rangeland soils in north central Arizona, Johnsen and Morton (59) detected most tebuthiuron in the surface 30 cm of soil during the first 5 years after treatment, but small concentrations were detected as deep as 105 cm 6 and 9 years after treatment. After 9 years, from 55 to 75% of the tebuthiuron detected was at the depth of 60 to 90 cm.

Factors Affecting Dissipation and Leaching

Tebuthiuron has a half-life of 12 to 15 months in areas receiving 100 to 150 cm rainfall annually (3). Photodecomposition and volatilization loss from soil is negligible. Some microbial breakdown occurs, but the half-life of tebuthiuron is considerably greater in low rainfall areas and in soils of high organic matter regardless of rainfall. Chang and Stritzke (44) found that after six successive desorption extractions, 40% of the tebuthiuron was adsorbed to soil with 4.8% organic matter, but less than 1% was adsorbed to soil with 0.3% organic matter. Soil mobility of tebuthiuron was greater in soil with low organic matter and low clay content. Greater dissipation occurred at 15% soil moisture and 30 °C than at lower moisture and temperature levels. Baur (6) also found that leaching of tebuthiuron was inversely related to clay content of soil and directly related to rate of application. Tebuthiuron is more phytotoxic in soils low in clay and/or organic matter (44, 46). Therefore for these reasons, one could expect greater tebuthiuron persistence in semiarid soils than soils in humid areas, as discussed by Johnsen and Morton (59).

Distribution and Dissolution of Pellets

Whisenant and Clary (113) indicated that using a 40% active extruded pellet at 0.6 and 1.1 kg/ha left residues of 9 to 21% and 17 to 38% of the treated areas, respectively. The lower percentages were from a soil with 47 g/kg soil organic carbon (OC), and higher percentages were on loam soils with 17 and 18 g/kg OC.

Van Pelt and West (110) placed large tebuthiuron briquettes of 1.8 g, 13% active ingredient (a.i.) beneath pinyon pine trees at the dripline, midcrown, and stem base. Residues analysis indicated that overland runoff, wind, and animals did not move briquettes.

Effect on Plant Growth

Greenhouse. Baur and Bovey (10) compared the growth inhibition of five herbicides by applying 1.4 to 1,434 μg/plant to one unifoliolate leaf of 'Southern blackeye' cowpea and the partly unfurled true leaf of 'Topland' sorghum seedlings. The order of decreasing effectiveness for growth and herbicidal effectiveness for cowpea and sorghum was paraquat (1,1'-dimethyl-4,4'-bipyridinium ion), glyphosate, tebuthiuron, 2,4-D, and endothall (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid). Tebuthiuron and glyphosate had little inhibitory effect on germination of sorghum, cowpea, or 'Era' wheat.

Tebuthiuron applied preemergence or early postemergence at 0.6 kg/ha injured buffelgrass (26). Buffelgrass became more tolerant with age to as old as 150 days, but plants were still injured at 1.1.kg/ha of tebuthiuron applied as foliar sprays to plants growing in pots. Buffelgrass [*Pennisetum ciliare* (L.) Link] shoot and root weights were reduced by 2 to 4 ppm of tebuthiuron placed 0 to 3, 8 to 11, or 15 to 18 cm deep in soil columns 30 days after emergence (89). Plains bristlegrass seedling shoot weights were not reduced when 2 ppm of tebuthiuron were placed 8 to 11 cm deep or deeper.

Field. Common bermudagrass and kleingrass tolerated March and April applications of tebuthiuron at 2.2 kg/ha using an 80% wettable powder formulation, but June applications reduced production (12). Buffelgrass and buffelgrass X birdwood hybrid tolerated tebuthiuron at 0.4, 1.1, and 2.2 kg/ha with March, April, and June applications. Coastal bermudagrass tolerated March but not April or June treatments. Tebuthiuron had little effect on protein concentrations of common or Coastal bermudagrass, buffelgrass, and kleingrass but reduced protein concentrations in the buffel X birdwood hybrid.

Masters and Scifres (67) reported that application of tebuthiuron pellets (20% a.i.) at rates as much as 2.2 kg/ha did not affect in vitro digestible organic matter of little bluestem, Bahiagrass (*Paspalum notatum* Flügge), Bell rhodesgrass (*Chloris gayana* Kunth), and green sprangletop but did increase foliar crude protein concentrations of little bluestem the growing season of application. In the South Texas Plains, tebuthiuron pellets (20% a.i.) at rates as much as 2.2 kg/ha at three locations did not significantly decrease buffelgrass standing crop or foliar cover compared with untreated areas (55).

Natural Areas. In the Texas Post Oak Savannah during spring, aerial application of tebuthiuron pellets (20% a.i.) at 2.2 and 4.4 kg/ha to heavy brush cover increased grass production the second growing season after application (102). Treated native-grass stands consisted of a higher proportion of perennial species of good-to-excellent grazing value than stands on untreated rangeland.

Aerial application of tebuthiuron pellets at 2.2 kg/ha to mixed brush in south Texas significantly increased grass standing crop at 1, 2, and 3 years after treatment (100). Overall grazing of the grass stand was improved, but forb production and diversity were decreased where 1 kg/ha or more of herbicide was applied. Forage stand recovered after 3 years regardless of herbicide rate used.

Reseeding on Treated Areas

In January 1976, Baur (7) treated areas in the Texas Claypan Resource area near Leona, Texas, with 1.1 or 2.2 kg/ha of tebuthiuron using the wettable powder as a spray or 20% a.i. pellets. Tebuthiuron at 1.1 kg/ha suppressed weed cover and produced a 71% kleingrass cover. Tebuthiuron at 2.2. kg/ha prevented kleingrass establishment. In 1977, kleingrass production in plots treated with 1.1 kg/ha tebuthiuron the same year exceeded untreated areas, but 2.2 kg/ha of tebuthiuron markedly reduced kleingrass production. No Coastal bermudagrass survived in tebuthiuron-treated areas on the deep sand.

In other work, Baur (5) showed that annual ryegrass could not be established until 261 days and 68 cm of rainfall after treatment of 1.1 kg/ha of tebuthiuron as either spray or granule. Rates of 3.4 kg/ha prevented revegetation by johnsongrass on 95% of the area after 499 days on the black clay loam soil.

Persistence in Plants

Herbaceous Plants

Concentration of tebuthiuron in Coastal bermudagrass was 438 ppm from spray applications of 2.2 kg/ha but was <1 ppm from broadcast- or band-applied pellets at 2.2 kg/ha (22). Low concentrations are desirable in forage because livestock or wildlife may graze treated areas immediately after treatment. Tebuthiuron concentrations in forage from sprays decreased rapidly with time, and residues from sprays or pellets were <2 ppm

within 3 months after treatment in the Texas Blacklands prairie.

In semiarid areas, tebuthiuron or its metabolites persisted as long as 11 years after treatment (60). Tebuthiuron was detected in sideoats grama and blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Griffiths] 10 years after application of 6.7 kg/ha. Metabolites of tebuthiuron were detected in blue grama 11 years after applications of 2.2, 4.5, and 6.7 kg/ha. Highest concentrations of tebuthiuron plus metabolites were 25 ppm in blue grama 10 years after application of 4.5 kg/ha and 21 and 23 ppm in sideoats grama 9 and 10 years, respectively, after applications of 6.7 kg/ha. Only these 3 samples of 120 samples exceeded legal limits of 20 ppm of tebuthiuron plus metabolites in forage plants. No samples from plots treated with 4 kg/ha or less exceeded 10 ppm of tebuthiuron plus metabolites, and only 10% of them exceeded 5 ppm.

Woody Plants

Foliage, twigs, stems, and litter from recently killed Utah juniper [*Juniperus osterosperma* (Torr.) Little] trees averaged 13.3, 0.4, 0.4, and 4.0 ppm of tebuthiuron plus its metabolites, respectively (58). Dead stems averaged 0.5 ppm in sapwood, 0.1 ppm in heartwood, and 0.4 ppm in bark 3 to 9 years after treatment. Root bark averaged 1.1 ppm and root wood averaged 0.5 ppm. The investigator concluded that residues have little potential harm when used as firewood or fenceposts.

Persistence and Movement in Water Sources

Surface Runoff Water

Pelleted tebuthiuron was applied at 2.24 kg/ha to a 1.3-ha rangeland watershed. A 2.8-cm rain, 2 days after application, produced 0.94 cm of runoff, which contained an average of 2.2 ppm of tebuthiuron (22). Tebuthiuron concentration decreased rapidly with each subsequent runoff event. After 3 months, tebuthiuron concentration was <0.05 ppm; none was detected in runoff water 1 year after treatment. Concentration of tebuthiuron, applied as a spray at 1.12 kg/ha, decreased to <0.01 ppm in runoff within 4 months from a small plot receiving simulated rainfall. On 0.6-ha plots, mean tebuthiuron concentration from sprays and pellets was 0.50 ppm or less in water when the first runoff event occurred 2 months after application. Concentrations of tebuthiuron in soil and grass from pellet applications were <1 ppm and decreased with time.

Tebuthiuron applied at 1 kg/ha as 20% a.i. pellets to dry Hathaway gravelly, sandy loam soil in the spring diminished by 5% at the first simulated rainfall event, 37 mm, in runoff water and sediment (75). The second and third simulated rainfall events, 22 and 21 mm, respectively, removed an additional 2% of tebuthiuron. When tebuthiuron was applied to wet soil in the spring, the initial simulated rainfall events, totaling 42 mm, removed 15% of the tebuthiuron. When tebuthiuron was applied to wet soil in the fall, the initial rainfall events, totalling 40 mm, removed 48% of the tebuthiuron in runoff water and sediment. No significant differences were found in the total amount of tebuthiuron within the soil profile after application to dry and wet soils. More than half of the tebuthiuron had moved into the upper 7 cm 1 day after application. Tebuthiuron was not detected below 90 cm after 165 mm of simulated rainfall and 270 mm of natural rainfall.

Hydrologic Effects

Selected hydrologic variables were evaluated after conversion of heavily wooded sites to open grassland with a herbicide-prescribed burning treatment sequence in east central Texas (66). Terminal infiltration rates and sediment production 3 years after aerial application of tebuthiuron pellets at 2.2 kg/ha for brush management differed little from values for untreated woody areas.

Hexazinone

Although hexazinone is used as a spot-soil treatment in Texas for control of honey mesquite and other woody plants (112), little work has been done in Texas on its residues in soils, plants, and water sources.

Persistence in Soil

The mobility of hexazinone in runoff water and its leachability in soil is well documented (1, 18, 49, 50, 63, 118). Hexazinone movement downslope in runoff water can sometimes injure nontarget vegetation remote from the point of application (1). The high water solubility of hexazinone in water (3.3 g/100 g) contributes to its leaching potential. However, Prasad and Feng (88) found that after 1 year, hexazinone residues were reduced to 1% at the treated spot and did not move laterally beyond 0.5 m on a sandy loam in Canada.

Greenhouse studies in silt and sandy loam soils showed that half-life of hexazinone was 4 to 5 months (3). Under field conditions, half-life varied from 1 to 6 months depending upon location. Microbial breakdown

contributes to decomposition in soil (3). Hexazinone photodegrades on the soil surface, but volatilization losses are negligible.

Persistence in Plants

Hexazinone and tebuthiuron were rapidly taken up by roots of seedling winged elm (*Ulmus alata* Michx.), bur oak (*Quercus macrocarpa* Michx.), black walnut (*Juglans nigra* L.), eastern redcedar (*Juniperus virginiana* L.), and loblolly pine (70). Four hours later, ^{14}C was detected in all parts of winged elm treated with ^{14}C-tebuthiuron and ^{14}C-hexazinone. Root and foliar absorption varied with herbicide and species. However, the results indicated that selectively of tebuthiuron and hexazinone can be attributed to amount of intact herbicide translocated to the foliage. Loblolly pine and eastern redcedar prevented accumulation of the parent compound in the foliage within 24 hours. Demethylation was the primary detoxification mechanism of tebuthiuron by eastern redcedar, loblolly pine, and bur oak. Loblolly pine, a hexazinone-resistant species degraded hexazinone rapidly into three unknown degradation products, thereby preventing its accumulation in foliage.

Jensen and Kimball (57) using whole-plant metabolism studies with pear [*Pyrus melanocarpa* (Michx.) Willd.] and bristly dewberry *(Rubus hispidus* L.) found no difference in ^{14}C accumulation in leaves but found a greater formation of the mono demethylated metabolite, B,[3-cyclohexyl-6-methylamino-1-methyl-1,3,5-triazine-2,4-dione] in the more tolerant *P. melanocarpa*.

Effect on Plants

Hexazinone controls many annual and biennial weeds, woody vines, and most perennial weeds and grasses, except johnsongrass (3). Hexazinone promises control of aquatic weeds and selective weeds in crops such as alfalfa, cacao, coffee, oil palm, pecans, sugarcane, rubber trees, tea, and certain conifers.

Persistence and Movement in Water Sources

Lavy et al. (63) found relatively small amounts of hexazinone in runoff water from a spot-gun application to a forest floor in Arkansas. Forest litter was highly effective in absorbing surface applications of hexazinone. In another study, maximum concentration of hexazinone was 14 ppm in the stream that drained a 11.5-ha watershed treated with 2 kg/ha (18). Hexazinone residues of <3 ppm were detected in stream discharge for 1

year after application. The amount of hexazinone transported from the watershed in stream discharge represented only 2 to 3% of the amount initially applied.

Neary et al. (81) found only 0.53% loss of hexazinone in streamflow of the applied herbicide in Georgia. Residues in streamflow peaked at 442 ppb in the first storm but declined rapidly and disappeared within 7 months. Total sediment yield increased by a factor of 2.5 because of increased runoff associated with site preparation using herbicide and salvage logging. However, sediment loading remained below those produced by mechanical techniques, and overall water quality changes were small and short lived. Leitch and Flinn (65) applied hexazinone at 2 kg/ha from a helicopter to a 46.4-ha catchment. Only 6 of 69 samples analyzed contained hexazinone, which was well below maximum allowable concentration of 600 μg/L for potable water.

Aquatic Environment

Polyethylene exclosures were located in a typical bog lake in north-eastern Ontario (107). Triclopyr, 2,4-D, and hexazinone were applied at 0.3 and 3, 1 and 2.5, and 0.4 and 4 kg/ha, respectively. Less than 5% of the triclopyr and 2,4-D remained in water after 15 days. As much as 25% of the 2,4-D absorbed to the side of the corrals. Triclopyr could not be detected after 42 days. At 0.3, 0.4, and 4 kg/ha, hexazinone could not be detected by 21 and 42 days after application. Hexazinone dissipated more rapidly than 2,4-D and was not absorbed to sediments.

Karbutilate

Karbutilate is no longer available, but two papers demonstrate the fate of pelleted herbicides used in brush control. Karbutilate spheres containing 0.76 g a.i., were monitored in the Texas Post Oak Savannah soils (80). Karbutilate residues (1.1 ppm) were detected after 194 days in clay loam to 90 cm deep directly below the point of impact of the spheres. Vertical movement through the soil profile was more evident than lateral displacement. After 191 days, about twice as much karbutilate was detected in the upper 30 cm of a clay loam than detected in a loamy sand. Scifres et al. (101) applied karbutilate formulated as a ball 1.34 cm in diameter to brush-infested rangeland by aircraft and by hand in a grid pattern with 1.83-m spacing. The karbutilate balls eliminated all vegetation in a 24- to 45-cm diameter circle the year of application. Treated areas revegetated within 2 years after treatment of 2.24 kg/ha in the Post Oak Savannah but required 32 months in the Rolling

Plains in sandy loam in sodgrasses such as tobosa [*Hilaria mutica* (Buckl.) Benth.] and buffalograss.

Glyphosate

Glyphosate controls many herbaceous and woody plants (19). It is recommended that spray drift or mist of glyphosate not be allowed to contact green foliage, green bark, or suckers of desirable plants.

Glyphosate has limited use on rangelands. Torstensson (108) indicated that glyphosate is rapidly adsorbed on soil. Adsorption occurs through the phosphoric acid moiety that competes for binding sites with inorganic phosphates. Glyphosate is virtually immobile in soils. Half-life ranges from a few days to several months and is correlated with microbial activity of soils. Inactivation of glyphosate through soil adsorption is important.

Brønstand and Friestad (42) concluded that regular use of glyphosate in agriculture or forestry allowed only very remote chances of contaminating the aquatic environment. The compound dissipates by microbial degradation, adsorption to sediments, and by photolysis.

Literature Cited

1. Allender, W.J. 1991. Movement of bromacil and hexazinone in a municipal site. Bull. Environ. Contam. Toxicol. 46:284-291.

2. Altom, J.D., and J.F. Stritzke. 1973. Degradation of dicamba, picloram and four phenoxy herbicides in soils. Weed Sci. 21:556-560.

3. Anonymous. 1989. Herbicide handbook of the Weed Science Society of America. 6th Ed. Herbicide Handbook Comm., N.E. Humbury, Chairman, WSSA. Champaign, IL. 301 p.

4. Basler, E., C.C. King, A.A. Badiei, and P.W. Santelmann. 1964. The breakdown of phenoxy herbicides in blackjack oak. Proc. South. Weed Conf. 17:351-355.

5. Baur, J.R. 1978. Effects of picloram and tebuthiuron on establishment and ryegrass winter pasture. J. Range Manage. 31:450-455.

6. Baur, J.R. 1978. Movement in soil of tebuthiuron from sprays and granules. Texas Agri. Exp. Sta. PR-3524. 14 p.

7. Baur, J.R. 1979. Establishing kleingrass and bermudagrass pastures using glyphosate and tebuthiuron. J. Range Manage. 32:119-122.

8. Baur, J.R., R.D. Baker, R.W. Bovey, and J.D. Smith. 1972. Concentration of picloram in the soil profile. Weed Sci. 20:305-309.

9. Baur, J.R., and R.W. Bovey. 1974. Ultraviolet and volatility loss of herbicides. Arch. Environ. Contam. Toxicol. 2:275-288.

10. Baur, J.R., and R.W. Bovey. 1975. Herbicidal effect of tebuthiuron and glyphosate. Agron. J. 67:547-553.

11. Baur, J.R., R.W. Bovey, and C.R. Benedict. 1970. Effect of picloram on growth and protein levels in herbaceous plants. Agron J. 62:627-630.

12. Baur, J.R., R.W. Bovey, and E.C. Holt. 1977. Effect of herbicides on production and protein levels in pasture grasses. Agron. J. 69:846-851.

13. Baur, J.R., R.W. Bovey, and H.G. McCall. 1973. Thermal and ultraviolet loss of herbicides. Arch. Environ. Contam. Toxicol. 4:289-302.

14. Baur, J.R., R.W. Bovey, and M.G. Merkle. 1972. Concentration of picloram in runoff water. Weed Sci. 20:309-313.

15. Baur, J.R., R.W. Bovey, and J.D. Smith. 1969. Herbicide concentration in live oak treated with mixtures of picloram and 2,4,5-T. Weed Sci. 17:567-570.

16. Baur, J.R., R.W. Bovey, and J.D. Smith. 1972. Effect of DMSO and surfactant combinations on tissue concentrations of picloram. Weed Sci. 20:298-302.

17. Behrens, R., W.C. Hull, and C.E. Fisher. 1955. Field responses of cotton to four phenoxy-type herbicides. Proc. South. Weed Conf. 8:72-75.

18. Bouchard, D.C., T.L. Lavy, and E.R. Lawson. 1985. Mobility and persistence of hexazinone in a forest watershed. J. Environ. Qual. 14:229-233.

19. Bovey, R.W. 1985. Efficacy of glyphosate in non-crop situations. *In* E. Grossbard and D. Atkinson (eds.), The herbicide glyphosate. Butterworth & Co., Ltd. U.K. pp. 435-448.

20. Bovey, R.W., and J.R. Baur. 1972. Persistence of 2,4,5-T in grasslands of Texas. Bull. Environ. Contam. Toxicol. 8:229-233.

21. Bovey, R.W., J.R. Baur, and E.C. Bashaw. 1979. Tolerance of kleingrass to herbicides. 32:337-339.

22. Bovey, R.W., E. Burnett, R.E. Meyer, C. Richardson, and A. Loh. 1978. Persistence of tebuthiuron in surface runoff water, soil, and vegetation in the Texas Blacklands Prairie. J. Environ. Qual. 7:233-236.

23. Bovey, R.W., E. Burnett, C. Richardson, J.R. Baur, M.G. Merkle, and D.E. Kissel. 1975. Occurrence of 2,4,5-T and picloram in subsurface water in the Blacklands of Texas. J. Environ. Qual. 4:103-106.

24. Bovey, R.W., E. Burnett, C. Richardson, J.R. Baur, M.G. Merkle, and W.G. Knisel. 1974. Occurrence of 2,4,5-T and picloram in surface runoff water in the Blacklands of Texas. J. Environ. Qual. 3:61-64.

25. Bovey, R.W., C.C. Dowler, and M.G. Merkle. 1969. The persistence and movement of picloram in Texas and Puerto Rican soils. Pest. Monit. J. 3:177-181.

26. Bovey, R.W., H. Hein, Jr., and R.E. Meyer. 1984. Effect of herbicides on the production of common buffelgrass (*Cenchrus ciliaris*). Weed Sci. 32:8-12.

27. Bovey, R.W., H. Hein, Jr., and R.E. Meyer. 1986. Concentration of 2,4,5-T, triclopyr, picloram and clopyralid in honey mesquite (*Prosopis glandulosa*) stems. Weed Sci. 34:211-217.

28. Bovey, R.W., M.L. Ketchersid, and M.G. Merkle. 1979. Distribution of triclopyr and picloram in huisache (*Acacia farnesiana*). Weed Sci. 27:527-531.

29. Bovey, R.W., and R.E. Meyer. 1981. Effects of 2,4,5-T, triclopyr and 3,6-dichloropicolinic acid on crop seedlings. Weed Sci. 29:256-261.

30. Bovey, R.W., R.E. Meyer, and H. Hein, Jr. 1982. Soil persistence of tebuthiuron in the clay resource area of Texas. Weed Sci. 30:140-144.

31. Bovey, R.W., R.E. Meyer, and E.C. Holt. 1974. Tolerance of bermudagrass to herbicides. J. Range Manage. 27:293-296.

32. Bovey, R.W., R.E. Meyer, and H.L. Morton. 1972. Herbage production following brush control with herbicides in Texas. J. Range Manage. 25:136-142.

33. Bovey, R.W., and F.R. Miller. 1969. Effect of activated carbon on the phototoxicity of herbicides in a tropical soil. Weed Sci. 17:189-192.

34. Bovey, R.W., F.R. Miller, J.R. Baur, and R.E. Meyer. 1975. Growth of sorghum and soybeans in picloram-treated soil. Agron. J. 67:433-436.

35. Bovey, R.W., F.R. Miller, and J. Diaz-Colon. 1968. Growth of crops in soils after herbicidal treatments for brush control in the tropics. Agron. J. 60:678-679.

36. Bovey, R.W., and C.W. Richardson. 1991. Dissipation of clopyralid and picloram in soil and seep flow in the Blacklands of Texas. J. Environ. Qual. 20:528-531.

37. 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.

38. Bovey, R.W., and C.J. Scifres. 1971. Residual characteristics of picloram in grassland ecosystems. Texas Agri. Exp. Sta. B-1111. 24 p.

39. Bovey, R.W., A.F. Wiese, R.A. Evans, H.L. Morton, and H.P. Alley. 1984. Control of weeds and woody plants on rangelands. USDA and Univ. of Minnesota. AD-BU-2344. 16 p.

40. Bovey, R.W., and A.L. Young. 1980. The science of 2,4,5-T and associated phenoxy herbicides. John Wiley and Sons. NY. 462 p.

41. Brady, H.A. 1973. Persistence of foliar-applied 2,4,5-T in woody plants. Proc. South. Weed Sci. Soc. 26:282.

42. Brønstad, J.O., and H.O. Friestad. 1985. Behavior of glyphosate in the aquatic environment. *In* E. Grossbard and D. Atkinson (eds.), The herbicide glyphosate. Butterworth and Co., Ltd. U.K. pp. 200-205.

43. Bush, P.B., D.G. Neary, and J.W. Taylor. 1988. Effect of triclopyr amine and ester formulations on groundwater and surface runoff water quality in the Coastal Plain. Proc. South. Weed Sci. Soc. 41:226-232.

44. Chang, S.S., and J.F. Stritzke. 1977. Sorption, movement and dissipation of tebuthiuron in soils. Weed Sci. 25:184-187.

45. Crafts, A.S. 1949. Toxicity of 2,4-D in California soils. Hilgardia. 19:141-158.

46. Duncan, K.W., and C.J. Scifres. 1983. Influence of clay and organic matter of rangeland soils on tebuthiuron effectiveness. J. Range Manage. 36:295-297.

47. Dupuy, A.J., and J.A. Schulze. 1972. Selected water-quality records for Texas surface waters. 1970 water year. Texas Water Development Board and U.S. Geological Survey Rpt. 149. 211 p.

48. Edwards, W.M., and B.L. Glass. 1971. Methoxychlor and 2,4,5-T in lysimeter percolation and runoff water. Bull. Environ. Contam. Toxicol. 6:81-84.

49. Feng, J.C. 1987. Persistence, mobility and degradation of hexazinone in forest silt loam soils. J. Environ. Sci. Health. B22(2):221-233.

50. Feng, J.C., S.S. Sidhu, C.C. Feng, and V. Servant. 1989. Hexazinone residues and dissipation in soil leachates. J. Environ. Sci. Health. B24(2):131-143.

51. Getzenduner, M.E., J.L. Herman, and B. VanGiessen. 1969. Residues of 4-amino-3,5,6-trichloropicolinic acid in grass from application of Tordon herbicides. Agri. Food Chem. 17:1251-1256.

52. Green, W.R., H.E. Westerdahl, J.C. Joyce, and W.T. Haller. 1989. Triclopyr (Garlon 3A) dissipation in Lake Seminole, Georgia. Misc. Paper A-89-2 Dept. Army, U.S. Army Corps Eng., Washington, D.C. Final Report. 19 p.

53. Haas, R.H., C.J. Scifres, M.G. Merkle, R.R. Hahn, and G.O. Hoffman. 1971. Occurrence and persistence of picloram in natural water sources. Weed Res. 11:54-62.

54. Halifax, J.C., and C.J. Scifres. 1972. Influence of dicamba on development of range grass seedlings. Weed Sci. 20:414-416.

55. Hamilton, W.T., and C.J. Scifres. 1983. Buffelgrass (*Cenchrus ciliaris*) responses to tebuthiuron. Weed Sci. 31:634-638.

56. Hoffman, G.O. 1971. Practical use of Tordon 225 mixture herbicide on Texas rangelands. Down to Earth 27:17-21.

57. Jensen, K.I.N., and E.R. Kimball. 1990. Uptake and metabolism of hexazinone in *Rubus hispidus* L. and *Pyrus melanocarpa* (Michx.) Willd. Weed Res. 30:35-41.

58. Johnsen, T.N. Jr. 1992. Observations: potential long-term environmental impact of tebuthiuron and its metabolites in Utah juniper trees. J. Range Manage. 4:167-170.

59. Johnsen, T.N., Jr., and H.L. Morton. 1989. Tebuthiuron persistence and distribution in some semiarid soils. J. Environ. Qual. 18:433-438.

60. Johnsen, T.N., Jr., and H.L. Morton. 1991. Long-term tebuthiuron content of grasses and shrubs on semiarid rangelands. J. Range Manage. 44:249-253.

61. Jotcham, J.R., D.W. Smith, and G.R. Stephenson. 1989. Comparative persistence and mobility of pyridine and phenoxy herbicides in soil. Weed Technol. 3:155-161.

62. Krueger, J.P., R.G. Butz, Y.H. Atallah, and D.J. Cork. 1989. Isolation and identification of microorganisms for the degradation of dicamba. J. Agric. Food Chem. 37:534-538.

63. Lavy, T.L., J.D. Mattice, and J.N. Kochenderfer. 1989. Hexazinone persistence and mobility of a steep forested watershed. J. Environ. Qual. 18:504-514.

64. Leasure, J.K. 1964. Bioassay methods for 4-amino-3-5,6-trichloropicolinic acid. Weeds. 12:232-233.

65. Leitch, C.J., and D.W. Flinn. 1983. Residues of hexazinone in streamwater after aerial application to an experimental catchment planted with radiata pine. Aust. For. 46:126-131.

66. Lloyd-Reilley, J., C.J. Scifres, and W.H. Blackburn. 1984. Hydrologic impacts of brush management with tebuthiuron and prescribed burning on post oak savannah watersheds, Texas. Agri. Ecosystems and Environ. 11:213-223.

67. Masters, R.A., and C.J. Scifres. 1984. Forage quality responses of selected grasses to tebuthiuron. J. Range Manage. 37:83-87.

68. Maybank, J., and K. Yoshida. 1969. Delineation of herbicide drift hazards on the Canadian prairies. Trans. Am. Soc. Agri. Eng. 12:759-762.

69. Mayeux, H.S., Jr., C.W. Richardson, R.W. Bovey, E. Burnett, M.G. Merkle, and R.E. Meyer. 1984. Dissipation of picloram in storm runoff. J. Environ. Qual. 13:44-49.

70. McNeil, W.K., J.F. Stritzke, and E. Basler. 1984. Absorption, translocation and degradation of tebuthiuron and hexazinone in woody species. Weed Sci. 32:739-743.

71. Merkle, M.G., R.W. Bovey, and F.S. Davis. 1967. Factors affecting the persistence of picloram in soil. Agron. J. 59:413-414.

72. Merkle, M.G., R.W. Bovey, and R. Hall. 1966. The determination of picloram residues in soil using gas chromatography. Weeds. 14:161-164.

73. Meyer, R.E., and R.W. Bovey. 1988. Tebuthiuron formulation and placement effects on response of woody plants and soil residue. Weed Sci. 36:373-378.

74. Morton, H.L. 1966. Influence of temperature and humidity on foliar absorption, translocation and metabolism of 2,4,5-T by mesquite seedlings. Weeds. 14:136-141.

75. Morton, H.L., T.N. Johnsen, Jr., and J.R. Simanton. 1989. Movement of tebuthiuron applied to wet and dry rangeland soils. Weed Sci. 37:117:122.

76. Morton, H.L., E.D. Robison, and R.E. Meyer. 1967. Persistence of 2,4-D, 2,4,5-T and dicamba in range forage grasses. Weeds. 15:268-271.

77. Moseman, T.E., and M.G. Merkle. 1977. Analysis, persistence and activity of triclopyr. Proc. South. Weed Sci. Soc. 30:64.

78. Muir, D.C.G., and N.P. Grift. 1987. Herbicide levels in rivers draining two prairie agricultural watersheds (1984). J. Environ. Sci. Health. B22:259-284.

79. Murray, M.R., and J.K. Hall. 1989. Sorption-desorption of dicamba and 3,6-dichlorosalicylic acid in soils. J. Environ. Qual. 18:51-57.

80. Mutz, J.L., C.J. Scifres, S. Selm, and R.F. Cook. 1978. Movement and persistence of karbutilate in rangeland soils. Weed Sci. 26:179-181.

81. Neary, D.G., P.B. Bush, and M.A. Grant. 1986. Water quality of ephemeral forest streams after site preparation with the herbicide hexazinone. Forest Ecology and Manage. 14:23-40.

82. Newton, M., F. Roberts, A. Allen, B. Kelpsas, D. White, and P. Boyd. 1990. Deposition and dissipation of three herbicides in foliage, litter and soil of brushfields of southwest Oregon. J. Agri. Food Chem. 38:574-583.

83. Norris, L.A. 1971. The behavior of chemicals in the forest. Pesticides, pest control and safety on forest range lands. Proc., short course for pesticidal application. Oregon State Univ., Corvallis. pp. 90-106.

84. Norris, L.A., and M.L. Montgomery. 1975. Dicamba residues in streams after forest spraying. Bull. Environ. Contam. Toxicol. 13:1-8.

85. Norris, L.A., M.L. Montgomery, and L.E. Warren. 1987. Triclopyr persistence in western Oregon hill pastures. Bull. Environ. Contam. Toxicol. 39:134-141.

86. Norris, L.A., and D.G. Moore. 1970. The entry and fate of forest chemicals in streams. Proc. Symposium, Forest land uses and stream environment. Oregon State Univ., Corvallis. pp. 138-158.

87. O'Connor, G.A., and P.J. Wiergenga. 1973. The persistence of 2,4,5-T in greenhouse lysimeter studies. Soil Sci. Soc. Am. Proc. 37:398-400.

88. Prasad, R., and J.C. Feng. 1990. Spotgun-applied hexazinone: release of red pine (*Pinus resinosa*) from quaking aspen (*Populus tremuloides*) competition and residue persistence in soil. Weed Technol. 4:371-575.

89. Rasmussen, C.A., R.P. Smith, and C.J. Scifres. 1985. Seedling growth responses of buffelgrass (*Pennisetum ciliare*) to tebuthiuron and honey mesquite (*Prosopis glandulosa*). Weed Sci. 34:88-93.

90. Schubert, D.E., R.L. McKellar, L.P. Stevens, and B.C. Byrd. 1980. Triclopyr movement on a small watershed. Abstract No. 105, Weed Sci. Soc. Am. p. 50.

91. Scifres, C.J., and T.J. Allen. 1973. Dissipation of dicamba from grassland soils of Texas. Weed Sci. 21:393-396.

92. Scifres, C.J., T.J. Allen, C.L. Leinweber, and K.H. Pearson. 1973. Dissipation and phytotoxicity of dicamba residues in water. J. Environ. Qual. 2:306-309.

93. Scifres, C.J., and R.W. Bovey. 1970. Differential responses of sorghum varieties to picloram. Agron. J. 62:775-777.

94. Scifres, C.J., R.W. Bovey, and M.G. Merkle. 1972. Variation in bioassay attributes as quantitative indices of picloram in soils. Weed Res. 12:58-64.

95. Scifres, C.J., R.R. Hahn, J. Diaz-Colon, and M.G. Merkle. 1971. Picloram persistence in semi-arid rangeland soils and water. Weed Sci. 19:381-384.

96. Scifres, C.J., R.R. Hahn, and M.G. Merkle. 1971. Dissipation of picloram from vegetation of semi-arid rangelands. Weed Sci. 19:329-332.

97. Scifres, C.J., and J.C. Halifax. 1972. Development of range grass seedlings germinated in picloram. Weed Sci. 20:341-344.

98. Scifres, C.J., and J.C. Halifax. 1972. Root production of seedling grasses in soil containing picloram. J. Range Manage. 25:44-46.

99. 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.

100. Scifres, C.J., and J.L. Mutz. 1978. Herbaceous vegetation changes following applications of tebuthiuron for brush control. J. Range Manage. 31:375-378.

101. Scifres, C.J., J.L. Mutz, and C.H. Meadors. 1978. Response of range vegetation to grid placement and aerial application of karbutilate. Weed Sci. 26:139-144.

102. Scifres, C.J., J.W. Stuth, D.R. Kirby, and R.F. Angell. 1981. Forage and livestock production following oak (*Quercus* spp.) control with tebuthiuron. Weed Sci. 29:535-539.

103. Smith, A.E. 1973. Transformation of dicamba in Regina heavy clay. J. Agric. Food Chem. 21:708-710.

104. Smith, A.E. 1974. Transformation of the herbicide dicamba and its degradative product 3,6-dichlorosalicylic acid in prairie soils. J. Agric. Food Chem. 22:601-605.

105. Smith, A.E., A.J. Aubin, and V.O. Biederbeck. 1989. Effects of long-term 2,4-D and MCPA field applications on soil residues and their rates of breakdown. J. Environ. Qual. 18:299-302.

106. Smith, D.T., and A.F. Wiese. 1972. Cotton response to low rates of 2,4-D and other herbicides. Texas Agri. Exp. Sta. B-1120. 8 p.

107. Solomon, K.R., C.S. Bowhey, K. Liber, and G.R. Stephenson. 1988. Persistence of hexazinone (Velpar), triclopyr (Garlon), and 2,4-D in a northern Ontario aquatic environment. J. Agric. Food Chem. 36:1314-1318.

108. Torstensson, L. 1985. Behavior of glyphosate in soils and its degradation. *In* E. Grossbard and D. Atkinson (eds.), The herbicide glyphosate. Butterworth and Co., Ltd. U.K. pp. 137-150.

109. Trichell, D.W., H.L. Morton, and M.G. Merkle. 1968. Loss of herbicides in runoff water. Weed Sci. 16:447-449.

110. VanPelt, N.S., and N.E. West. 1989. Above-ground dissolution of tebuthiuron particles placed beneath the crowns and small pinyon trees. J. Environ. Qual. 18:281-284.

111. Welch, T.G. 1989. Acres of Texas rangeland treated for brush and weed control. Texas Agri. Ext. Serv. College Station. Unpublished data.

112. Welch, T.G. 1990. Chemical weed and brush control, suggestions for rangeland. Texas Agri. Ext. Serv. B-1466. 17 p.

113. Whisenant, S.G., and W.P. Clary. 1987. Tebuthiuron distribution in soil following application of pellets. J. Environ. Qual. 16:397-402.

114. Whisenant, S.G., and E.D. McArthur. 1989. Triclopyr persistence in northern Idaho forest vegetation. Bull. Environ. Contam. Toxicol. 43:660-665.

115. Wiedemann, H.T., L.F. Bouse, R.H. Haas, and J.P. Walters. 1973. Spray equipment, herbicide carriers and drift control. *In* C.J. Scifres (ed.), Mesquite Research Monograph 1. Texas Agri. Exp. Sta., College Station. pp. 33-45.

116. Wiese, A.F., and R.G. Davis. 1964. Herbicide movement in soil with various amounts of water. Weeds. 12:101-103.

117. Young, A.L., C.E. Thalken, W.E. Ward, and W.J. Cairney. 1974. The ecological consequences of massive quantities of 2,4-D and 2,4,5-T herbicides. Summary of a five-year field study. Abstr. No. 164. Weed Sci. Soc. Am.

118. Zandvoort, R. 1989. Leaching of fluridone, hexazinone and simazine in sandy soils in the Netherlands. Netherlands J. Agric. Sci. 37:257-262.

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