ENVIRONMENTAL FATE AND THE EFFECTS OF HERBICIDES IN FOREST, CHAPARRAL, AND RANGE ECOSYSTEMS OF THE SOUTHWEST

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Biological methods, fire, herbicides, and mechanical methods have all been studied in an effort to determine appropriate ways of manipulating arid land vegetation for improvement of wildlife habitat, streamflow and water yield, increasing forage for livestock, and enhancing recreational benefits and scenic diversity. Because water is ultimately essential for all of these uses, and because of an increasing concern over the availability of water for human consumption, augmentation of water yield has been a significant part of many of these studies. Many of the studies conducted between the mid-1950s and mid-1970s have been reviewed (Hibbert et al. 1974; Hibbert 1979). Other research on water yield augmentation in the West has been reviewed by Anderson et al. (1976), Harr (1983), and Kattelmann et al. (1983). Water yield can be increased by managing snow and by managing vegetation. Managing snow requires reducing the evaporative loss from snow, and/or redistributing snow pack (by fencing, etc.) to increase the snow melt and runoff to streams. Deep-rooted woody perennial species, notably shrub live oak (*Quercus turbinella* Greene), birchleaf mountain mahogany (*Cercocarpus betuloides* Nutt.), sumac (*Rhus ovata* S. Wats.), hollyleaf buckthorn (*Rhamnus crocea* Nutt.), Emory oak (*Q. emoryi* Torr.), yellowleaf silktassel (*Garrya flavescens* S. Wats.), New Mexico locust (*Robinia neomexicana*) and similar species tap soil water and through evapotranspiration greatly reduce potential water yield. The impact of vegetation on evapotranspiration losses can be reduced in the most drastic terms by conversion of the cover type to one that demands less water, or by reducing the vegetation density. However, even type conversion does not always give significant or economically useful increases in water yield. The areas with the greatest potential for water yield increases due to vegetation manipulation are those with greater than 450 mm (>18 in) of annual precipitation and where potential evapotranspiration exceeds 380 mm (15 in) per year (Hibbert 1979). Thus, in general, the warmer and moister locations provide the greatest opportunities for increased water yield.

Herbicides have been used in the Southwest for more than 50 years to manipulate forest, range, and chaparral vegetation. The purpose of this paper is to review that use, identify compounds that have been used historically, and discuss the impacts of those still in use on water quality.*

Herbicides for Vegetation Management in the Southwest

Buthidazole, fenuron, karbutilate, and 2,4,5-trichlorophenoxy acetic acid were tested and in some cases put into use for controlling chaparral species. However, they are no longer available for use. They are covered here to give an historical perspective on the use rates for the more commonly used chemicals. Buthidazole was tested for efficacy against fire sprouts of shrub live oak. It was found to be effective at rates of 4.5 and 9.0 kg/ha active ingredient (ai) (4 and 8 lb ai/ac; Davis et al. 1980). This compound was generally not tested against more mature forms of live oak.

Fenuron, a substituted phenylurea herbicide, was found to be somewhat effective against shrub live oak, and mountain mahogany when applied in the winter at 17.9 kg/ha ai (16 lb ai/ac; Davis and Pase 1969). Spot treatment

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* Although this report discusses research involving pesticides, such research does not imply that the pesticide has been registered or recommended for the use studied. Registration is necessary before any pesticide can be recommended. If not handled or applied properly, pesticides can be injurious to humans, domestic animals, desirable plants, fish, and wildlife. Always read and follow the directions on the pesticide container.

enabled selective control of undesirable species, but eradication of the target species was not possible, even at this high rate. Hibbert et al. (1982) reported excellent control of shrub live oak and mountain mahogany with 25.8 kg/ha ai (23 lb ai/ac) in the conversion of chaparral to grass cover. Application was by hand using 25 percent ai pelleted fenuron distributed beneath the shrubs. Follow-up treatment was not necessary.

Karbutilate, a carbamate herbicide, was used in the control of woody species at rates up to 22.4 kg/ha ai (20 lb ai/ac). Davis (1982) reported that control of shrub live oak and mountain mahogany was excellent 3 years after treatment. Davis et al. (1980) documented that control of mature shrub live oak was also accomplished with 4.5–9.0 kg/ha ai (4–8 lb ai/ac) when applied in the summer, but control of shrub live oak fire sprouts was best when application was made in mid-winter.

The phenoxy herbicide, 2,4,5-T, was the most-used herbicide in the history of brushy species control in the U.S. Because of environmental concerns it is no longer registered by the United States Environmental Protection Agency for use in the U.S. Applied at rates of up to 13.4 kg acid equivalent (ae)/ha (12 lb ae/ac) for general weed control, it was frequently used in multiple applications of 2.2 kg ae/ha (2 lb ae/ac) for control of many brushy species (Elwell 1964). DeBano et al. (1984) report that four annual applications of 1.7 kg ae/ha (1.5 lb ae/ac) for the control of shrub live oak fire sprouts and birch-leaf mountain mahogany (*Cercocarpus betuloides*) resulted in only 42 percent and 72 percent control, respectively. Ingebo and Hibbert (1974) report the use of a 6.6 percent solution of 2,4,5-T as a basal spray on desert ceanothus and shrub live oak. Spot treatment was required in the second year following initial treatment for good control. While it is difficult to relate a solution composition to an area rate, use of 187 L/ha (20 gallons/ac) of such a solution would equal approximately 11.8 kg ae/ha (10.5 lb ae/ac). Control of chamise (*Adenostoma fasiculatum*) was accomplished with 4.5 kg ae/ha (4 lb ae/ac) (Plumb et al. 1977)

Picloram and 2,4-D are two phenoxy acetic acid herbicides that were commonly used for brush control. Picloram is a chlorinated picolinic acid, most frequently used in chaparral vegetation control as the 10 percent ai pelleted formulation of the potassium salt. Picloram pellets applied at the rate of 10.4 kg ai/ha (9.3 lb ai/ac) gave marginal control of shrub live oak, but were more than was needed for other chaparral species (Davis et al. 1968). Picloram was also frequently used in combination with 2,4-D. Picloram (2.8 kg ai/ha or 2.5 lb ai/ac) and 2,4-D (5.6 kg ae/ha or 5 lb ae/ac) were applied to pinyon–juniper woodland by backpack mist blower. This treatment gave good control of juniper, but shrub live oak and pinyon recovered after 2–3 years (Baker 1984).

Tebuthiuron, a substituted urea herbicide, is still used at rates up to 4.5 kg ai/ha (4 lb ai/ac) for control of most woody species, and at rates up to 17.9 kg ai/ha (16 lb ai/ac) for control of hard-to-kill perennial weeds. In general, higher rates are required for weed control on deep fine-textured soils than on shallow coarse soils (Herbel et al. 1985). Many species of the Southwest can be controlled with 0.6–1.1 kg ai/ha (0.5–1.0 lb ai/ac), including creosote bush (*Larrea tridentata*), whitethorn acacia (*Acacia constricta*), tarbush (*Flourensia cernua*), skunkbush (*Rhus trilobata*), and ocotillo (Herbel et al. 1985). In a comparison study on juniper and pinyon, Johnsen and Dalen (1990) found that tebuthiuron treatment gave better control than picloram at the same rates, but tebuthiuron was also more damaging to understory plants. When compared with picloram for control of sand shinnery oak (*Q. havardii*), tebuthiuron gave acceptable control at rates of 0.3–1.1 kg ai/ha (0.3–1.0 lb ai/ac), while rates of 2.2 kg ai/ha (2 lb ai/ac) of picloram were required to give similar control (Jacoby and Meadors 1982). Similarly, Jones and Petit (1984) found that 0.5 kg ai/ha (0.4 lb ai/ac) gave 98 percent control of sand shinnery oak, and resulted in increased grass production in the second year after treatment. Davis et al. (1980) determined that shrub live oak requires up to 9 kg ai/ha (8 lb ai/ac) depending on the level of control required and whether the target vegetation is mature brush (higher rates) or fire sprouts (lower rates). In a brush-to-grass conversion study, Davis (1982) used 4.6 kg ai/ha (4.1 lb ai/ac) tebuthiuron to control shrubs left over from an earlier (10 years) treatment with fenuron. Sagebrush (*Artemisia tridentata* and *A. cana*) was controlled with 1.1 kg ai/ha (1 lb ai/ac) of tebuthiuron while most associated grasses were not damaged (Whitson and Alley 1984).

Water Yield

The main objective of herbicide use on forest lands in most parts of the country is control of competing vegetation during postharvest regeneration. When herbicides were used more extensively in the Southwest, the principal goal of herbicide use was water yield augmentation. Most of the studies of herbicide effects on water yield were done in chaparral ecosystems (Hibbert et al. 1974; Hibbert et al. 1975; Hibbert 1983; Davis 1984; Hibbert and Davis 1986; Ingebo 1972; Ingebo and Hibbert 1974). Clary et al. (1974) and Baker (1984) reported on water yield responses to herbicide application in pinyon–juniper ecosystems.

The results of water yield research in chaparral using fire and herbicides were summarized by Hibbert et al. (1974, 1975) and Brown and Fogel (1987). Davis (1984) reported that application of 22 kg ai/ha of karbutilate to chaparral on the Three Bar watersheds increased runoff efficiency (percent of precipitation yielded to stormflow). The ratio doubled from 0.56 (pre-treatment) to 1.3 (post-treatment). Over a 3-year period the mean annual water yield increase amounted to 703 percent. Hibbert and Davis (1986) documented a streamflow increase of 68 mm/yr (+72%) in the chaparral-covered Whitespar watersheds after application of 3.4 kg ai/ha tebuthiuron to 55 percent of one watershed. Application of a 6.6 percent solution of 2,4-D and 2,4,5-T on two chaparral watersheds at Sierra Ancha resulted in a 22–35 percent increase in streamflow (Ingebo and Hibbert 1974). For chaparral ecosystems in Arizona, water yield increases from herbicide treatments (up to 703% increase) were equivalent to those from fires (up to 700% increase), and were dependent on watershed aspect, annual precipitation, vegetative cover reduction, and season. Most streamflow increases came during the winter months, and some ephemeral watersheds produced perennial flow.

Clary et al. (1974) and Baker (1984) reported on streamflow changes to a Beaver Creek pinyon–juniper watershed after application of 2.8 kg ae/ha of picloram and 5.6 kg ae/ha 2,4-D. Compared to an untreated control, the herbicide-treated watershed produced 130 percent more storm runoff, 25 percent higher peakflow, and greater basin recharge during a 20 to 50-year storm (Baker 1984). The herbicide effect was a combination of greatly reduced evapotranspiration losses due to foliage leaf area reduction and shading by standing dead stems.

Water Quality: Herbicide Residues

Concentrations of fenuron (Davis and Ingebo 1970), karbutylate (Davis 1975), picloram (Davis and Ingebo 1973), and tebuthiuron (Emmerich et al. 1984) in streamflow and storm runoff in the Southwest have been studied at a number of locations (Table 1). Measured peak concentrations fall in the same low range (0–820 mg/m^3) as those reported for forestry herbicides elsewhere in North America. These peaks were low enough and of such short duration that they did not pose a water pollution problem. Persistence in runoff documented in the studies reported here ranged from 14 months (picloram) to 72+ months (tebuthiuron). The latter herbicide is particularly persistent—hence its utility as a brush control herbicide. Total losses of herbicide residues in streamflow ranged from less than 0.5 percent to as high as 4.5 percent. The losses at the upper end of the range exceed those measured in the South or Pacific Northwest (Neary and Michael 1993).

Sediment

The use of herbicides for weed control or species type conversions usually does not result in significant sediment yield increases (Neary and Hornbeck 1994). However, in the arid Southwest widely separated variations can occur. Natural sediment yield rates can range from 0.002 to 2.5 Mg/ha/yr. Ingebo and Hibbert (1974) reported an eight-fold reduction in sediment loss from a herbicide-treated chaparral area due to grass growth along channel margins. But, Hibbert at al. (1974) noted a ten-fold increase in sediment yield due to channel adjustments to higher flows and slope instability on steep upper slopes. By contrast, wildfires in the Southwest can increase sediment loss rates by factors of 1,000–369,000 times normal (Table 2).

Nitrates

The side effects of killing vegetation include interruption of major nutrient cycling pathways, increased organic matter decomposition, and increased microbial activity. These effects can

Table 1. Maximum herbicide concentrations in streamflow from operational applications to forests and woodlands.

Herbicide	Application Rate (kg/ha)	Concentration (mg/m^3)	Reference
Southwest USA			
1. Fenuron	27.8	430	Davis and Ingebo 1970
2. Karbutilate	2.2	51	Davis 1975
3. Picloram	9.3	370	Davis and Ingebo 1973
4. Tebuthiuron	0.8	91	Emmerich et al. 1984
6. 2,4-D	*	*	
5. 2,4,5-T	*	*	
Other Locations			
7. Glyphosate	1.3	270	Newton et al. 1984
8. Hexazinone	3.6	820	Legris 1988
9. Imazapyr	2.2	680	Michael and Neary 1993
10. Picloram	5.6	442	Michael et al. 1989
11. Sulfometuron Methyl	0.4	44	Michael and Neary 1993
12. Triclopyr	0.9	620	Wan 1987
13. 2,4-D	2.2	132	Norris 1967
14. 2,4,5-T	4.5	200	Norris 1981

* No information available.

Table 2. Sediment loss and herbicides.

Location	Treatment	First Year Sediment Yield	
		Control (Mg/ha)	Treated (Mg/ha)
Florida	Cut, Herbicide	0.022	0.010
North Carolina	Cut, Herbicide	0.044	0.165
Mississippi	Cut, Herbicide	0.134	0.133
Georgia	Herbicide, Cut	0.067	0.170
Arkansas	Cut, Herbicide	0.071	0.251
Arizona	Herbicide	0.019	0.002
Arizona	Herbicide	2.565	2.049
Arizona	Wildfire	2.200	50.500

impinge on water quality by releasing anions and cations into streamflow. This can best be illustrated by examining nitrate nitrogen (NO_3-N) concentrations in streamflow.

On the chaparral watershed at Three Bar treated with fenuron (20.5 kg ai/ha), karbutilate (7.5 kg ai/ha), and tebuthiuron (0.9. kg ai/ha), Davis and Debano (1986) found high soil NO_3-N levels (82.9 mg/L) to depths of 4.6 m. The mean annual streamflow NO_3-N concentration peaked at 11.7 mg/L, with an instantaneous NO_3-N maximum of 18.4 mg/L (Davis 1987). Elevated NO_3-N concentrations persisted for over 14 years. These high NO_3-N levels are among the highest reported for disturbances to forest ecosystems (Neary and Hornbeck 1994). The main environmental consequences of the prolonged release of NO_3-N from chaparral watersheds are downstream eutrophication and drinking water quality standard violations. No real problems developed as a result of these vegetation conversions due to downstream dilution from untreated areas and the limited extent of chaparral conversions.

Summary and Conclusions

Buthiazole, fenuron, and karbutilate were used in the early research on arid land vegetation control, but the rates required were quite high (up to 22. kg ai/ha–20 lb ai/ac). While they are no longer available for use, they serve to demonstrate the advances made over the last 20 years in herbicide technology. Extremely high rates like those reported for these compounds have been replaced with the much lower rates of newer chemistry. The phenoxy herbicides (2,4,5-T and 2,4-D) were used at intermediate rates (2.2–11.4 kg ae/ha or 2–10 lb ae/ac), but adequate vegetation control frequently required multiple applications. Picloram provided another advance in treatment rate reduction requiring rates of 2.2–5.6 kg ai/ha or 2–5 lb ae/ac, but also required some follow-up treatments. Tebuthiuron is active against many arid land species at rates as low as 0.28 kg ai/ha (0.25 lb ai/ac), and is useful at rates approximately half that required by picloram. Because of the long soil residue time of tebuthiuron, follow-up treatments are usually not needed.

Water yields in the Southwest were increased by 22 to 703 percent by the application of herbicides to mainly chaparral watersheds. The amounts were a function of watershed aspect and elevation, annual precipitation, the percent and amount of vegetation cover removed, and soil depth. Peak flows and flow duration (especially during winter) were increased by herbicide use. Residues of fenuron, karbutilate, and tebuthiuron were measured in streamflow for durations of 14 to 72+ months. The maximum concentrations ranged from 41 to 430 mg/m^3, depending on the application rate. Sediment yields from herbicide use in the Southwest have been increased and decreased, but are nowhere near the magnitude of increased yields produced by wildfires. Concentrations of NO_3-N in streamflow were considerably elevated and persisted for 14+ years.

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