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Soil-water and vegetation dynamics through 20 years after big sagebrush control

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Abstract

Soil water withdrawal and vegetation characteristics of mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana* Rydb. Beetle) areas sprayed with 2,4-D (2,4-Dichlorophenoxyacetic acid) were measured for 20 years after treatment. Herbaceous productivity more than doubled in the first 3 years after spraying and was still twice as great as untreated vegetation 10 to 17 years after treatment. Sagebrush removal reduced seasonal water depletion 9% to a 1.8-m soil depth, equal to 2.4 cm of water. The entire difference was realized from soil 0.9–1.8 m deep. Depletion from the surface 0.9 m of soil under grass-dominated vegetation slightly exceeded depletion under sagebrush-dominated vegetation. Mathematical relationships were developed that predict the percent reduction in seasonal water depletion in relation to time since sagebrush control for soil depths of 0.0–1.8 m, 0.0–0.9 m, and 0.9–1.8 m.

Mountain big sagebrush was a minor vegetation constituent on treated areas 20 years after spraying. Sagebrush density increased from 2,100 to 4,400 plant/ha between 10 and 20 years after spraying while herbaceous production ranged between 28 and 52 kg/ha. Both density and canopy cover of sagebrush on untreated areas declined significantly over the study because of the actions of a snowmold fungus.

Key Words: big sagebrush, sagebrush control, herbicides, soil moisture, herbaceous productivity

Control of big sagebrush (*Artemisia tridentata* Nutt.) using the herbicide 2,4-D (2,4-Dichlorophenoxyacetic acid) was a common range improvement practice for about 25 years after World War II[1]. Vegetation responses to spraying are well documented in years following treatment. However, hydrologic responses in years immediately after spraying have received much less attention than vegetation responses and little information exists concerning the long-term hydrologic consequences of sagebrush control. Replacement of big sagebrush by shallower rooted herbaceous species affects the soil water regime, and increased spring flow has been observed following treatment.

This paper focuses on changes in the soil water regime, and changes in vegetation composition and production for a 20-year period following control of mountain big sagebrush (*A.t.* ssp. *vaseyana* Rydb. Beetle) by spraying with 2,4-D. Treatment responses for these characteristics the first 11 years after spraying were discussed by Sturges in 1977a and 1983. The study also offers insights into the long-term hydrologic consequences of big sagebrush control through burning, or through the use of herbicides that are more environmentally acceptable than 2,4-D.

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[1]This article reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that uses discussed here have been registered. All uses of pesticides must be registered by appropriate state and/or federal agencies before they can be recommended. Use all pesticides selectively and carefully; read and follow the directions on the label.

Literature Review

Herbaceous Production

Because of a differential selectivity of 2,4-D towards monocotyledon and dicotyledon plant classes, sagebrush was killed by spraying and forb production was suppressed (Blaisdell and Mueggler 1956, Tabler 1968), while grass production commonly increased 2 to 3 times above pretreatment levels in years immediately after spraying (Hull et al. 1952, Hyder and Sneva 1956, Tabler 1968, Orpet 1978, Miller et al. 1980, Sturges 1986). Unlike spraying, burning sagebrush rangeland usually did not greatly alter forb/-grass composition (Harniss and Murray 1973, Nimir and Payne 1978, Johnson and Strang 1983) although exceptions to this generalization were reported (West and Hassan 1985). Some grass species, such as Idaho fescue (*Festuca idahoensis* Elmer) and needle-andthread (*Stipa comata* Trin & Rupr.), were particularly vulnerable to fire damage (Blaisdell 1953, Conrad and Poulton 1966, Wright 1971).

The longevity of increased herbaceous production after sagebrush control is variable and often linked to grazing management. Grass and forb production returned to pre-treatment levels sometime between 12 and 30 years after burning (Harniss and Murray 1973). Sneva (1972) reported a treatment effect persisting for 17 years after spaying with 2,4-D in Oregon. In another Oregon study, reestablishment of sagebrush occurred primarily in years immediately following treatment (Bartolome and Heady 1978). A positive response in grass production was present between 12 and 18 years after spraying with 2,4-D at 4 or 5 project sites in Wyoming if lands were protected from livestock grazing, but not if lands were open to livestock grazing (Orpet 1978). At other Wyoming locations, the increase in forage production had dissipated within 6 years of spraying (Johnson 1969), or between 3 and 10 years after spraying (Thilenius and Brown 1974).

Soil Water

A slight decrease in water withdrawal from the surface meter of soil was reported by a number of investigators the first 2 years after spraying sagebrush stands with 2,4-D (Sonder and Alley 1961, Cook and Lewis 1963, Tabler 1968, Shown et al. 1972, Sturges (1977a), Tabler (1968), and Sturges (1977a) found a 15% reduction in water withdrawal from the surface 1.8 m of soil the second year after spraying in locations possessing deep soils that are fully recharged each spring by melting snow. The only soil water study extending more than 5 years beyond treatment was conducted by Sturges (1983). Measurements were taken to a 1.8 m depth and the reduction in seasonal water use by treated vegetation averaged 7%

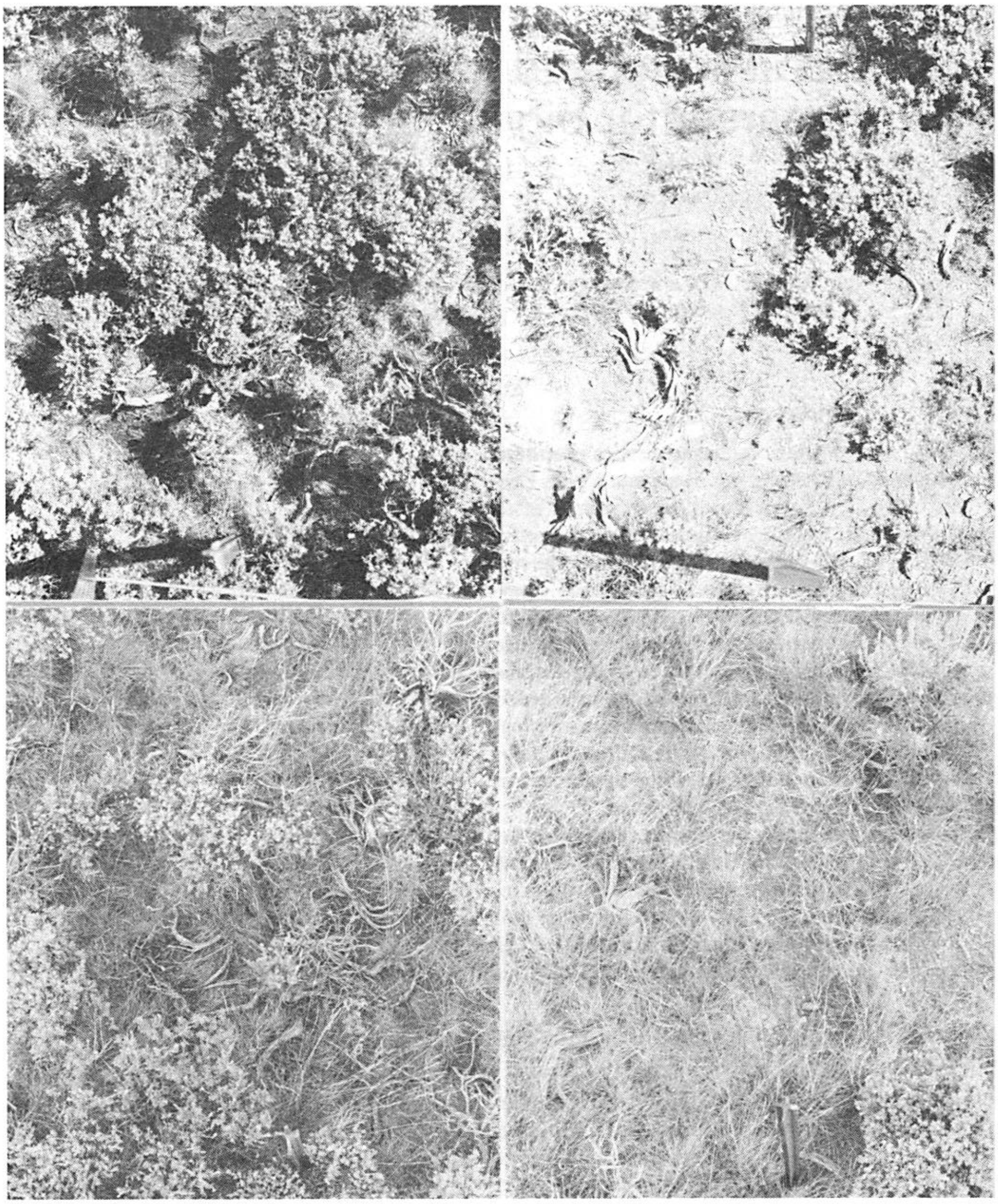

Fig. 1. Photographs of vegetation taken at permanent photo points in 1969, the year preceding 2,4-D application (top) and in 1990, 20 years after spraying (bottom). A snowmold fungus had reduced sagebrush cover on unsprayed experimental units by the end of the study (left). A vigorous grass stand was still present on sprayed experimental units at the end of the study even though some sagebrush invasion had occurred (right).

between 5 and 11 years after spraying. This difference accrued from soil 0.9 to 1.8 m deep.

Study Area and Methods

The study was conducted between 1969 and 1990 at the Stratton Sagebrush Hydrology Study Area located 29 km west of Saratoga, Wyo. Elevation at the site is 2,225 m. Annual precipitation in the 21-year period from 1969 to 1989 averaged 516 mm and more than two-thirds of the total fell as snow. Effective precipitation at the study site exceeded annual precipitation because of deposition of wind-transported snow. Summer precipitation (June–September) was 117 mm. Overland flow generated by rainfall was extremely rare at the study site.

The study was conducted on a 6% north-facing hillside possessing a uniform cover of vegetation dominated by mature mountain big sagebrush plants (Fig. 1). Understory species were comprised primarily of Idaho fescue, bluegrasses (*Poa* spp.), and needlegrasses (*Stipa* spp.). Forbs were a minor vegetation constituent. Soil in the A horizon had a loam texture and belonged to the Youga series, an Argic Cryoborall. The site was grazed by sheep prior to study initiation, but livestock grazing was excluded during the study.

The study utilized a randomized block design; each of the 7 blocks were comprised of two, 0.4-ha experimental units. Spray and nonspray treatments within a block were assigned at random. Study measurements began in 1969 when all experimental units were in an undisturbed state and continued until 1990, 20 years after sagebrush control. In 1970, experimental units selected for treatment were sprayed with 2,4-D at the rate of 3.1 kg ai/ha using a truck-mounted sprayer.

Table 1. The number of herbaceous production plots clipped and read with the capacitance meter in each experimental unit and percentage composition of vegetation for unsprayed and sprayed experimental units.

Year	Spray		Unspray		Sagebrush		Grass		Forb	
	Clipped	Meter	Clipped	Meter	Spray	Unspray	Spray	Unspray	Spray	Unspray
	(No. plots/exp. unit)				(Percent Composition)					
1969	10	0	10	0	74	71	22	25	4	4
1970	2	15	2	15	0	63*	92	29	8	8
1971	5	10	5	10	0	61*	99	35*	1	4*
1972	5	10	5	10	0	67*	98	29*	2	4
1973	10	0	5	10	0	66*	98	29*	2	5*
1980	2	10	2	10	0	48*	96	45*	4	7
1981	6	0	2	10	3	54*	95	45*	2	1
1986	6	0	2	10	4	70*	90	28*	6	2
1987	6	0	2	10	5	56*	92	40*	3	4

*Significant difference between treatments at the 0.05 level of probability.

Vegetation

Herbaceous productivity, including the leaves and current year's stem growth of sagebrush, was measured annually beginning the year before spraying and continuing for 3 years after spraying; measurements were also conducted 10, 11, 16, and 17 years after spraying. A capacitance meter was utilized for production measurements on unsprayed experimental units beginning in 1970 and on sprayed experimental units between 1970 and 1980. Vegetation on sprayed experimental units was sampled directly by clipping after 1980. Procedures described by Morris et al. (1976) for using the capacitance meter in sagebrush-dominated vegetation were followed. Both metered and clipped plots were 30 cm by 61 cm, and were randomly located each year. The number of plots that were clipped and read with the capacitance meter is tabulated in Table 1 for years when productivity was sampled. Measurements were taken in mid-July as grass species matured. Clipped material was separated into sagebrush, grass, and forb components to provide information about vegetation composition. Herbaceous matter was weighed after being oven-dried at 105° C for 24 hours.

The canopy cover of big sagebrush was determined by the line intercept method in the first and last year of the study (1969 and 1990, respectively). Measurements were taken on 5 randomly located transects on each experimental unit; transects were 15.2 m long. That portion of the sagebrush plant containing live trunk, stem, or leaf tissue, was defined as intercept. In addition, canopy cover measurements were taken on unsprayed experimental units in 1980 and 1987.

The density of big sagebrush was determined on all experimental units in 1969 and on unsprayed experimental units in 1990 by counting the number of plants rooted in a belt 1.3 m wide and 7.6 m long centered over a line intercept transect. Density counts were made on 2 of the 5 line intercept transects in 1969 and on all 5 transects in 1990.

The density of big sagebrush inhabiting sprayed experimental units was measured in 1980, 1987, and 1990 (10, 17, and 20 years after spraying, respectively) by counting the number of plants rooted within 5 circular plots on each experimental unit. These plots were 20 m^2 in size and were randomly located each year.

Snow Accumulation

Soil water content was fully recharged by melting snow in most years. Maximum snow deposition on an index transect located about 37 m from the eastern boundary of the study site was determined annually in conjunction with other hydrologic investigations conducted at the Stratton site. The transect was 122 m long and snow depths were measured at 15.2-m intervals along the transect. The water content of snow was estimated from the relationship Tabler (1985) developed between the depth of wind-transported snow and its density. Actual snow deposition on experimental units was determined in 1970 and 1, 3, and 4 years after treatment as part of a study that evaluated the effect of sagebrush control upon snow accumulation and melt (Sturges 1977b). The water content of snow on experimental units was recalculated for this paper utilizing the same depth-density relationships as for data from the index transect.

Soil Water

The water content of soil was measured with a neutron moisture meter at 4 randomly located access tubes on each experimental unit. Several different radium-beryllium neutron probes were used for measurements from 1968 to 1975 while the same americium-beryllium neutron probe was used through the remainder of the study. The manufacturer-supplied calibration relationship was employed to convert field counts to volume water content. Soil water measurement procedures were described in detail by Sturges (1977a).

Soil water measurements began at the 15-cm depth and extended downward by 30.5-cm increments to provide information about water content at 6 levels within the surface 1.83 m of soil. The evaluation of treatment effect was based upon the change in water content between 2 measurement dates, rather than on the absolute water content of soil. Data collected at the conclusion of snowmelt (usually in May) and in the fall when vegetation was dormant (about October 1) provided information about seasonal water depletion. Information was available from 1969 to 1990 except for 1974 and 1976. Soil water measurements were also made at 2 to 3 week intervals throughout the season beginning the year before spraying and extending through the third year after spraying. Similar measurements were repeated 5, 10, 11, and 19 years after spraying to determine if differences between treatment in seasonal water-use patterns changed in years subsequent to spraying.

Data Analysis

A randomized block design was employed to minimize the effects of any differences in soil or vegetation characteristics within the study site on treatment evaluation. Snow accumulation, vegetation, and soil water data, were collected in 1969 when all experimental units were in an undisturbed state to test the assumption that experimental units assigned to the spray and nonspray treatments were similar at study initiation.

Soil water data were statistically analyzed utilizing a split-plot analysis imposed on the randomized block design. The 0.4-ha experimental units served as whole units and the 6 measurement depths served as subunits. Differences between sprayed and unsprayed experimental units in seasonal water depletion were tested for statistical significance. Additionally, differences in depletion at the 6 measurement depths, and a treatment × depth interaction were tested for significance within the split-plot analysis. Differences in water depletion between treatments at each of the 6 soil depths were tested for significance utilizing a modified "t" value calculated for the split-plot design (Steel and Torrie 1980). Similar analyses, based on soil water depletion between consecutive measurement dates, were performed in years when soil water data were collected through the growing season. Statistical significance in this paper is based on a 0.05 probability level.

Seasonal soil water depletion data from the 2 treatments were also tested for significance by regression analysis (Steel and Torrie 1980). This analysis was based on average soil water depletion for sprayed and unsprayed experimental units in the first to twentieth year after spraying.

Treatment differences in vegetation composition, herbaceous production, sagebrush density, and sagebrush canopy cover, were tested for statistical significance utilizing a randomized block experimental design. Analyses were based on the average value of a parameter on an experimental unit as determined from replicate measurements on the unit. The yearly analysis of variance for yields of sagebrush, grasses, and forbs was based on data from production plots that were clipped. Data from the capacitance meter were used in variance analyses of total herbaceous yield. Herbage percentage composition data were transformed to arcsin values before performing the analysis of variance. The least significant difference method (Steel and Torrie 1980) was utilized to identify significant changes in canopy cover of sagebrush on undisturbed experimental units over time.

Results

Big Sagebrush Characteristics

In 1969, density of mountain big sagebrush was 50,000 and 43,000 plants/ha on experimental units assigned to the spray and nonspray treatments, respectively, while sagebrush canopy cover was 29% and 28% for the 2 treatments. Differences were not significant. Herbicide application in 1970 and follow-up hand control measures in 1971 virtually eliminated big sagebrush on treated experimental units (Fig. 1).

Some invasion of big sagebrush into sprayed experimental units did occur in the 20 years after treatment. Sagebrush canopy cover on treated experimental units was 1.5% at the end of the study. Average sagebrush density increased from 2,100 plants/ha to 4,400 plants/ha between the 10th and 20th year after spraying, but this change was not statistically significant. A single plot containing 119 sagebrush plants accounted for most of the change in density. Data from plots used to evaluate sagebrush invasion indicated that plants were unevenly distributed (Fig. 2). One-sixth of individual plots remained free of sagebrush 20 years after spraying and about half of the plots contained from 1 to 4 plants. The number of plots free of sagebrush declined between the 10th and the 20th year after treatment while the number of plots inhabited by 1–4 plants increased.

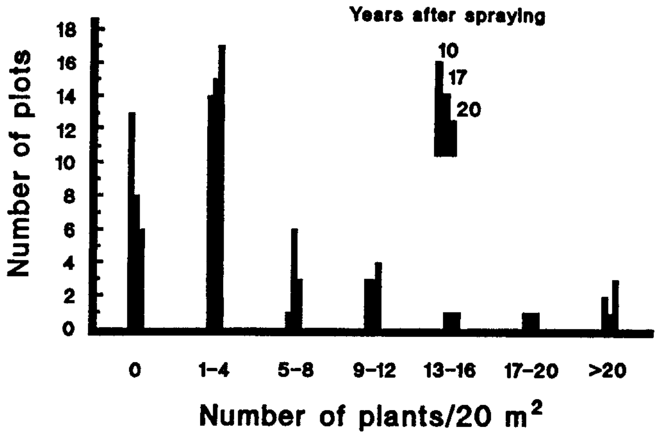

Fig. 2. The number of big sagebrush plants on plots 20 m² in size 10, 17, and 20 years after treated experimental units were sprayed with 2,4-D.

Characteristics of the mountain big sagebrush stand on nonspray experimental units changed significantly during the study even though sagebrush is a long-lived shrub. Sagebrush density declined from 43,000 plants/ha in 1969 to 22,000 plants/ha in 1990. Canopy cover decreased from 27.5% to 18.1%, between 1969 and 1980, but remained about 20% over the succeeding 10 years. A snowmold fungus was the primary causal agent thinning the sagebrush stand.

Vegetation Composition and Yield

When vegetation was in an undisturbed state in 1969, herbaceous composition (Table 1) and production (Table 2) were similar for the 2 treatments. Spraying eliminated big sagebrush the year of treatment, significantly increased grass productivity, and significantly decreased forb productivity. The typical response of big sagebrush-dominated vegetation to application of 2,4-D became evident the first year after spraying and persisted through the study. Grass yields more than doubled in the first 3 years after spraying and were still about twice as great as grass yields of untreated experimental units between 10 and 17 years after spraying. Forb production was significantly reduced 0, 1, and 3 years after spraying, but returned to production levels existing on untreated experimental units between the 4th and 10th year after spraying. Big sagebrush was first detected on sprayed experimental

Table 2. Herbaceous production on unsprayed and sprayed experimental units through 17 years after treatment.

Year	Years after spraying	Sagebrush		Grass		Forb		Total	
		Unspray	Spray	Unspray	Spray	Unspray	Spray	Unspray	Spray
		(kg/ha)							
1969	-1	946	1,124	334	328	54	59	1,334	1,511
1970	0	828*	0	377*	450	102*	39	1,307*	489
1971	1	818*	0	472*	939	60*	13	1,350*	952
1972	2	1081*	0	468*	1,102	59[a]	21	1,608*	1,123
1973	3	859*	0	383*	993	71*	17	1,313*	1,010
1980	10	401*	0	376*	712	58	30	835	742
1981	11	656*	31	545*	928	15	16	1,216[a]	975
1986	16	840*	28	337*	657	26	42	1,203*	727
1987	17	617*	53	447*	891	48	29	1,112	973

*Treatment differences significant at 0.05 probability level.
[a]Treatment differences significant at 0.10 probability level.

units in production data the 11th year after spraying, but remained a minor vegetation constituent. Sagebrush production ranged from 28 to 53 kg/ha between 11 and 17 years after spraying. Differences in sagebrush and grass production and in their composition on spray and nonspray experimental units were significant in all post-spray years. The net effect of treatment was to significantly reduce total herbaceous production from 0 to 3 years after spraying as well as in the 16th year.

Snow Accumulation

The water content of snow on the index transect ranged from 0.1 cm to 103 cm during study years (Table 3). The 4 years of information available when snow accumulation was also measured on experimental units indicates that water storage on the index transect exceeded water storage on experimental units by 25 cm. Water contained in snow was usually sufficient to replenish evapotranspirational losses from the previous growing season. Sagebrush control retarded snow accumulation before snow completely covered vegetation at the study site, but had no effect upon the depth of maximum snow accumulation or upon the rate of snowmelt (Sturges 1977b). Snow water storage exceeded winter precipitation in all but drought years which emphasizes the importance of snow relocation as a hydrologic process in windswept regions of the sagebrush ecosystem. Burke (1989) and Burke et al. (1989) quantified the relationship between topographic position and soil moisture, soil temperature, and nitrogen mineralization that arises

Table 3. Hydrologic information about maximum snow water accumulation on the snow course and on the experimental units, soil water content, and seasonal depletion to a 1.8-m depth, for experimental units sprayed with 2,4-D in 1970, and for experimental units remaining in an undisturbed condition.

			Snow water			Soil water measurement		Soil water			
		Years after						Water content		Seasonal	Decrease in
Year	Treatment	treatment	Date	Snow course	Exp. units	Interval	Precip. cm	Spring	Fall	depletion	withdrawal
				----- (cm) -----			(cm)	-------- (cm) --------			(%)
1969	Spray	-1				05/13–09/29	11.7	70.1	44.6	25.5	+4
	Unspray		4/09	39.0				70.5	45.9	24.6	
1970	Spray	0			31.3	05/27–09/30	16.5	68.3	54.3	14.0	33*
	Unspray		4/30	51.4	30.0			68.5	47.4	20.8	
1971	Spray	1			34.1	05/23–09/14	8.7	70.6	52.4	18.2	17*
	Unspray		3/30	61.7	32.5			67.1	45.1	22.0	
1972	Spray	2				05/18–10/04	11.2	69.2	51.9	17.3	15[a]
	Unspray		3/10	57.2				66.8	46.4	20.4	
1973	Spray	3			50.8	05/13–10/04	12.4	80.3	54.4	25.9	11*
	Unspray		4/05	70.8	46.9			79.7	50.6	29.1	
1974	Spray	4			39.2						
	Unspray		3/20	68.8	38.0						
1975	Spray	5				06/02–09/30	5.7	78.3	54.4	23.9	8
	Unspray		4/24	64.8				77.7	51.7	26.0	
1976	Spray	6									
	Unspray		4/13	64.3							
1977	Spray	7				04/28–10/06	19.2	79.0	56.0	23.0	9
	Unspray		4/07	14.5				78.5	53.2	25.3	
1978	Spray	8				05/15–10/02	14.8	93.8	64.4	29.4	3
	Unspray		4/04	35.4				92.7	62.3	30.4	
1979	Spray	9				06/04–10/02	7.1	89.8	59.9	29.9	10*
	Unspray		4/11	103.0				91.2	58.0	33.2	
1980	Spray	10				05/27–10/02	9.0	91.0	63.9	27.1	7[a]
	Unspray		4/08	73.0				90.3	61.1	29.2	
1981	Spray	11				06/01–10/01	8.6	83.9	59.2	24.7	6[a]
	Unspray		4/02	0.1				82.4	56.2	26.2	
1982	Spray	12				05/26–10/04	15.0	89.5	71.5	18.0	1
	Unspray		3/25	61.7				88.2	70.1	18.1	
1983	Spray	13				05/24–10/08	17.8	95.6	67.2	28.4	7
	Unspray		3/09	46.4				95.7	65.3	30.4	
1984	Spray	14				05/31–10/02	23.9	93.8	71.3	22.5	7
	Unspray		4/11	83.3				94.8	70.6	24.2	
1985	Spray	15				05/09–10/01	12.8	91.3	62.2	29.1	5
	Unspray		4/03	56.3				92.3	61.6	30.7	
1986	Spray	16				05/12–10/01	21.7	90.1	72.4	17.7	10
	Unspray		3/04	45.7				91.0	71.4	19.6	
1987	Spray	17				04/28–10/09	12.5	80.6	56.3	24.3	14*
	Unspray		3/10	16.4				83.3	55.1	28.2	
1988	Spray	18				05/11–10/05	9.2	90.5	62.8	27.7	14*
	Unspray		3/30	49.8				93.4	61.1	32.3	
1989	Spray	19				05/03–10/02	14.4	88.8	65.2	23.6	9*
	Unspray		3/13	53.3				90.3	64.5	25.8	
1990	Spray	20				05/15–09/24	12.8	88.5	62.2	26.3	13*
	Unspray							89.2	59.0	30.2	
Avg.	Spray				38.9	(1–20)	13.2	85.8	61.5	24.3	9
	Unspray			53.2	36.9			85.8	59.1	26.7	
Number of years				21	4		18	18	18	18	18

*Significantly different at 0.05 level of probability.
[a]Significantly different at 0.10 level of probability.

because of snow redistribution. Their study site included the north-facing slope where the study was conducted.

Soil Water Regime

Soil water data collected the year before spraying indicated that the soil water regime was similar for plots assigned to the 2 treatments. In the spring of 1969, water content averaged 70.1 cm and 70.5 cm for experimental units assigned to the spray and nonspray treatments, respectively, and 44.6 and 45.9 cm in the fall (Table 3). The change in water content between consecutive measurement dates was similar for the 2 treatments in 1969 and in 1970 until June 23 when sagebrush was sprayed (Sturges 1973). The lack of a significant treatment difference for vegetation, snow accumulation, and water depletion characteristics, prior to treatment indicates that changes in these characteristics after spraying can be reasonably ascribed to control of big sagebrush.

The water content of soil in spring, when averaged over the 1st to 20th year after spraying, was identical for the 2 treatments (Table 3). Initial profile water content was reasonably similar considering the wide range in yearly snow deposition and the effect this had on the spring soil water measurement date. Following the drought winters of 1976–77, 1980–81, and 1986–87, sufficient precipitation fell between the date of maximum snow accumulation and the spring measurement to wet soil nearly to the level present in years of normal winter precipitation. The discontinuity in profile water content evident in data collected before and after 1975 is attributable to the 2 types of neutron probes used during the study. Instrument differences were minimized by basing the analysis of treatment effect upon the change in water content between measurement dates.

In the 20 years after sagebrush control, seasonal water withdrawal from the surface 1.8 m of soil averaged 24.3 and 26.7 cm on sprayed and unsprayed experimental units, respectively (Table 3), a reduction of 9% in water use. The relationship between seasonal depletion for treatments was significant (Fig. 3). Precipitation received between the spring and fall measurements averaged 13.2 cm; thus evapotranspirational water usage by untreated sagebrush

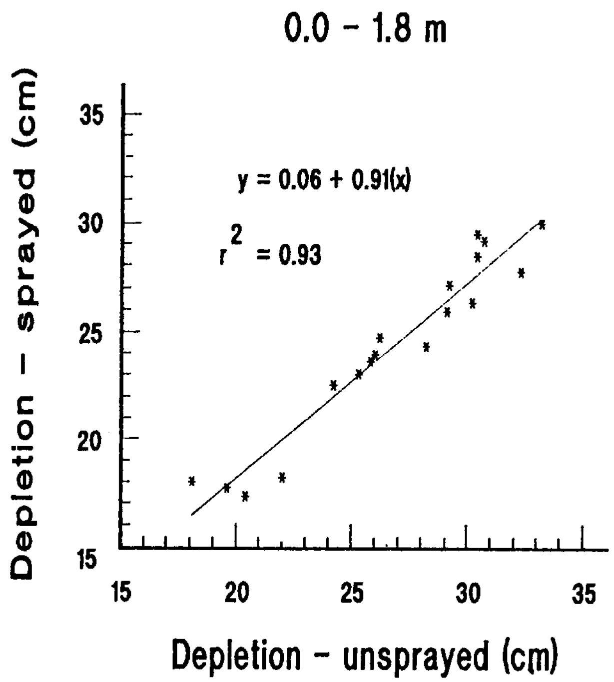

Fig. 3. The relationship between seasonal water depletion for sprayed and unsprayed experimental units based on a soil depth of 0.0–1.8 m. Data includes information from the 1st to 20th year after spraying.

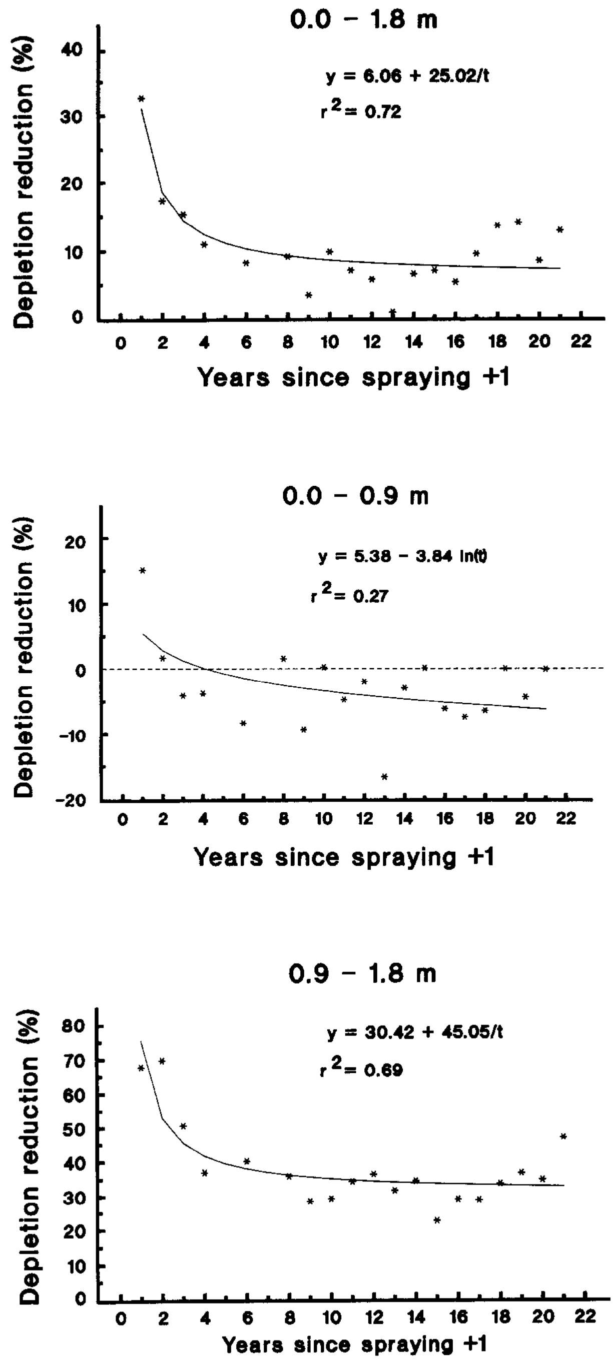

Fig. 4. The relationship between the number of years since spraying and percentage reduction in seasonal water depletion based on soil depths of 0.0–1.8m, 0.0–0.9 m, and 0.9–1.8 m. The variable t represents the number of years since spraying + 1.

vegetation was 39.9 cm at the study site.

Study data were also used to develop a relationship to predict the percentage reduction in seasonal water withdrawal for the surface 1.8 m of soil in relation to time since sagebrush control. The relationship applies in the treatment year and was strongly curvilinear during the first 5 years after treatment (Fig. 4). This contrasts with the linear relationship of Figure 3 that was based on the quantity of seasonal depletion and excluded data from the treatment year. The relative reduction in seasonal depletion to a 1.8 m depth was predicted by:

$$y = 6.6 + \frac{25.02}{t} \quad (1)$$

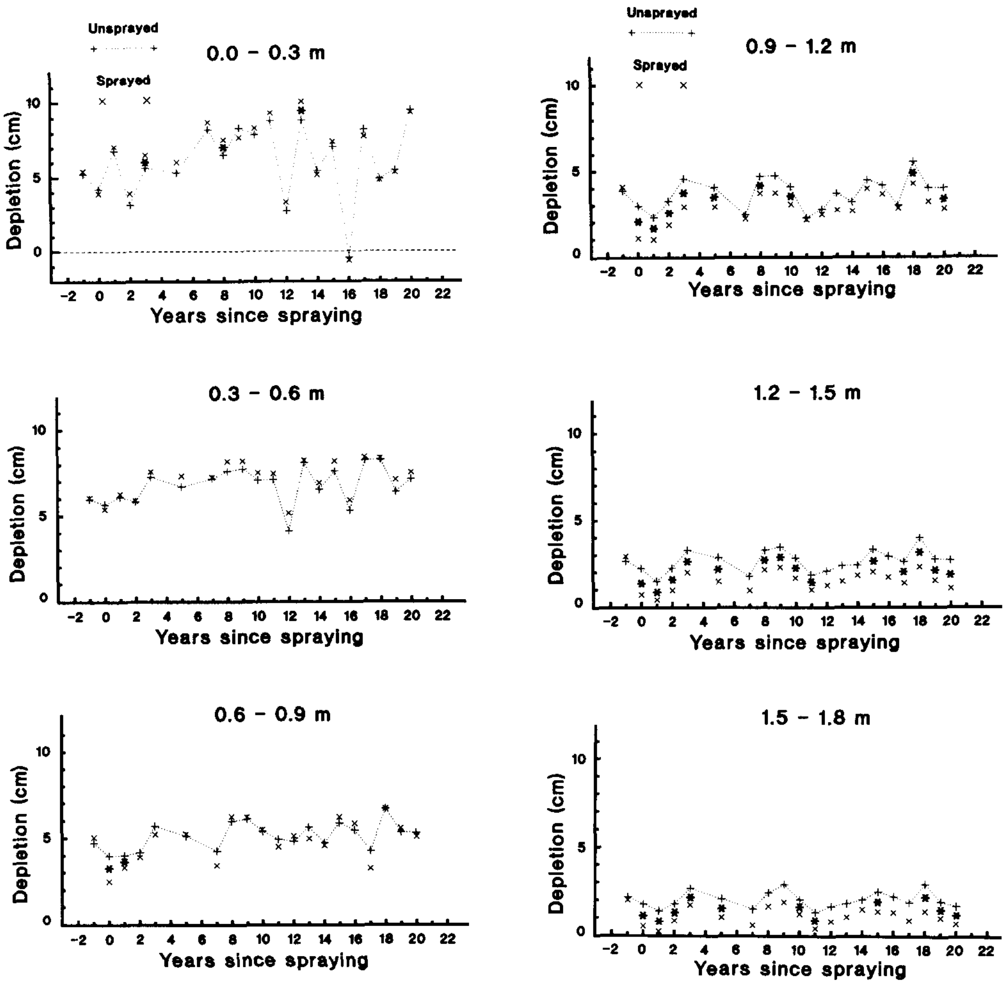

Fig. 5. Seasonal water depletion at the 6 measurement depths for all years of study. A star indicates that yearly treatment differences are significant at the 0.05 level of probability.

where y = percentage reduction in the fall soil water recharge requirement t = number of years + 1 since control of big sagebrush.

The reduction in water use on treated experimental units did not accrue uniformly through the soil profile. Sprayed vegetation withdrew less water at all soil depths in the treatment year; differences were statistically significant below a depth of 0.6 m, but this effect was short-lived. By the second year after spraying, a marked treatment difference was present in soil above and below 0.9 m (Fig. 5). Vegetation on treated experimental units usually withdrew more water in the surface 0.9 m of soil than did sagebrush-dominated vegetation, but differences were seldom significant. Relative differences in seasonal depletion for the surface 0.9 m of soil (Fig. 4) were predicted by:

$$y = 5.38 - 3.84 \ln(t) \tag{2}$$

where y = percentage reduction in the fall soil water recharge requirement t = number of years + 1 since control of big sagebrush.

Beginning the second year after spraying, almost the entire reduction in water use was realized from soil 0.9 to 1.8 m deep. Seasonal reductions in depletion within the 3 measurement depths of this zone were usually significant especially in the first 10 years after treatment (Fig. 5). The relative reduction in seasonal depletion within soil 0.9 to 1.8 m deep (Fig. 4) was predicted by:

$$y = 30.42 + \frac{45.05}{t} \tag{3}$$

where y = percentage reduction in the fall soil water recharge requirement t = number of years + 1 since control of big sagebrush.

The duration of a treatment effect predicted by equations 1 and 3 exceed values indicated by earlier prediction relationships (Sturges 1977a, 1983). The asymptotic form of equations indicates that a 6% reduction in water use will persist indefinitely over a 1.8 m soil depth while the reduction from soil 0.9–1.8 m deep will be 30%. Sagebrush, however, was increasing in density on treated experimental units as the study progressed. The form of the prediction relationships will continue to change with additional information in order to mirror the influence of sagebrush establishment.

The soil water measurements conducted at biweekly intervals through the growing season provided information about timing of water use. The year after spraying, treatment differences in water withdrawal through a 1.8 m soil depth were significant over the 40-day period from 10 June to 20 July. This effect dissipated in years after spraying. A significant difference existed only from 17 July to 31 July in the 10th post-treatment year. Differences in water depletion between consecutive measurement dates were not significant in the 19th post-treatment year.

Water-use zones shifted seasonally as shown by data collected the 1st and 19th year after spraying at depths of 0.3–0.6 m and 1.2–1.5 m (Fig. 6). These depths represent zones without and with a significant treatment difference, respectively. Both grass and sagebrush-dominated vegetation utilized water primarily from surface soil through June. Thereafter, additional depletion from this zone was largely in response to summer precipitation. Total seasonal depletion was similar for both treatments at the 0.3–0.6 m

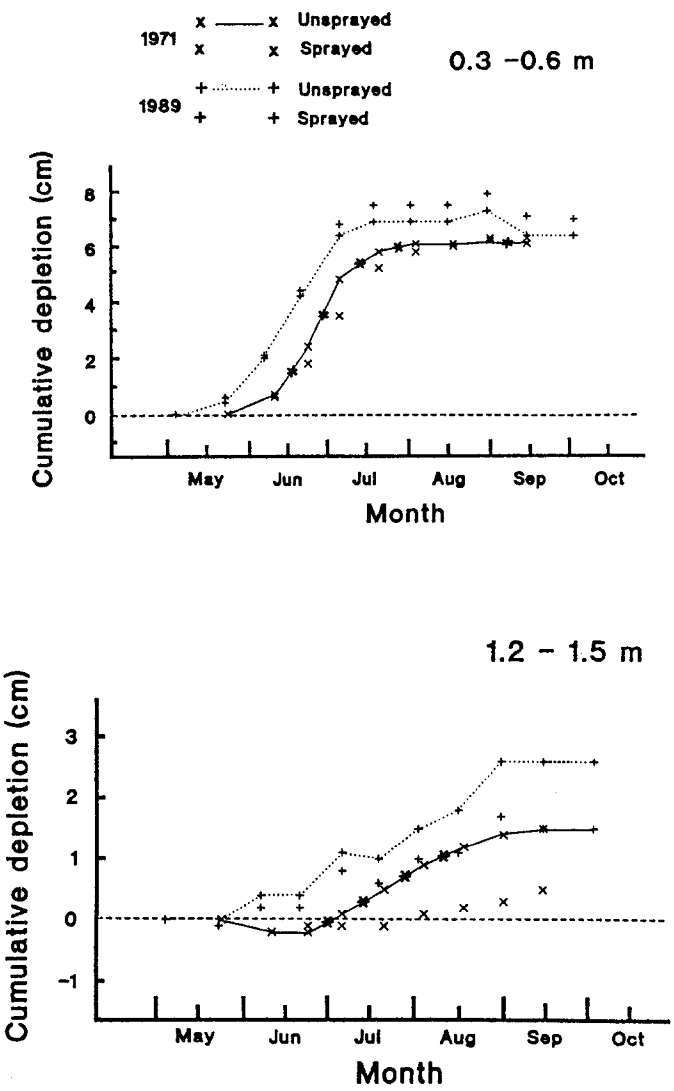

Fig. 6. Soil water depletion on sprayed and unsprayed experimental units in soil 0.3 m to 0.6 m deep, and 1.2 m to 1.5 m deep in the 1st and 19th year after spraying. A star indicates that differences in depletion between successive measurement dates are significant at the 0.05 level of probability.

depths in both the 1st and 19th year after spraying.

The rate of water extraction from soil 1.2 to 1.5 m deep increased sharply in July once available water in surface soil was depleted (Fig. 6). However, extraction under grass-dominated vegetation was less than under sagebrush-dominated vegetation. There were significant treatment differences in the magnitude of depletion between consecutive measurement dates at the 1.2–1.5 m depth in the 1st and 19th year after spraying but only in the first year at the 0.3–0.6 m depth. A marked reduction in the rate of water use by sagebrush-dominated vegetation occurred in late August from soil 1.2–1.5 m deep. At that time, ephemeral sagebrush leaves produced in the spring were being shed and sagebrush floral buds were about ready to open.

Discussion

Biological factors were responsible for the decline in importance of mountain big sagebrush on unsprayed experimental units between 1969 and 1990. Voles (*Microtus* spp.) damaged sagebrush by girdling the trunk during several winters. Mueggler (1967), Tabler (1968), and Frischknecht and Baker (1972) noted that voles can produce significant sagebrush mortality in winters when population levels are high. However, the main agent responsible for thinning the sagebrush stand was a snowmold fungus that also reduced mountain big sagebrush cover on the 663-ha watershed containing the study site (Sturges 1986). Hess et al. (1985) described morphological characteristics of the fungus while Nelson and Sturges (1986) provided information about its growth characteristics in relation to temperature. A minimum snow depth of 40 cm at maximum accumulation was required before the fungus caused appreciable sagebrush mortality (Sturges and Nelson 1986).

Sagebrush control increased production of grass species and induced major changes in soil water dynamics. Both effects persisted through the 20-year interval following treatment. These responses will continue until sagebrush invasion shifts vegetation and water depletion characteristics to those of a sagebrush-dominated system. Because of the absence of livestock grazing and the location of the study site in a mesic portion of the sagebrush zone, study results are probably indicative of the maximum treatment longevity that can be expected when big sagebrush is controlled.

The change in soil water dynamics was closely related to the response of vegetation to herbicide application. The grass-dominated vegetation that resulted from sagebrush control was rooted primarily in the surface meter of soil and utilized all the water made available by the absence of sagebrush roots. However, substantially less water was withdrawn from soil occupied primarily by sagebrush roots. It was this difference located at a 0.9–1.8 m depth which accounted for essentially all differences in water depletion. Total above-ground plant biomass production on treated experimental units was less than production on undisturbed experimental units, which also contributed to reduced water depletion. The increase in production by grasses and recovery of forb production did not fully compensate for the loss of sagebrush production. Similar decreases in above-ground biomass production following sagebrush control have been detected at other locations (Johnson and Strang 1983, West and Hassan 1985).

Previous soil water studies noted a reduction in depletion from the surface meter of soil which persisted only 1 or 2 years after treatment (Hyder and Sneva 1956, Sonder and Alley 1961, Cook and Lewis 1963). These results lead to the conclusion that sagebrush control had only minor short-term effects on soil water use. Current study results and those of Tabler (1968) clearly demonstrate that the effects of sagebrush control upon soil water dynamics must be assessed over sagebrush's full rooting depth.

Management Implications

The control of big sagebrush is a proven method of increasing the quantity of forage available to livestock. This potential could be utilized to alleviate grazing usage within riparian areas, which has become such a contentious issue between ranchers and other users of public lands. Herbaceous production on treated experimental units was still twice as great as on untreated areas at the end of the study. The shift to a grass-dominated vegetation had essentially no effect upon site fertility through the 14th post-treatment year (Burke et al. 1987). The only detectable changes were a redistribution of phosphorus and potassium from depth to the surface 5 cm of soil under grass-dominated vegetation and a reduction in the surface concentration of nitrogen.

Sagebrush control produced desirable hydrologic changes on a 238-ha watershed at the Stratton Sagebrush Hydrology Study Area in addition to causing herbaceous productivity to double (Sturges 1986). Spraying the watershed with 2,4-D resulted in decreased bare ground in the 5 years following treatment accompanied by an increase in litter and grass cover.

Results of this study suggest that sagebrush control can also increase water yield. The 2.4-cm difference in soil water recharge requirement potentially could be translated into increased streamflow in locations such as the study site where winter snow accumulation plus early spring precipitation exceed water required to rewet soil to field capacity. An increase in water yield, however, would not be expected in locations where sagebrush roots were confined to the same volume as replacement grass roots, or where recharge is less than the water holding capacity of soil. Much of the increase in water yield from forested lands after logging is attributable to a reducation in summer water use on areas where trees were removed (Troendle and King 1985). The same hydrologic mechanism is operative on chaparral lands where increased water yields can occur after brush removal (Hill and Rice 1963).

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