Effects of Sulfur Fertilization on Productivity and Botanical Composition of California Annual Grassland

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Abstract

Changes in botanical composition and productivity of total herbage and 14 categories of annual range plants caused by elemental sulfur fertilization, range site, and precipitation were studied. Total herbage production on the wetter and more fertile swale sites was not affected by sulfur fertilization, but production on adjacent open upland and rocky, brushy upland sites usually increased with added S. Herbage production increased 28% or 1,400 kg/ha on fertilized open upland sites and 51% or 1,800 kg/ha on fertilized rocky, brushy upland sites during the wettest year sampled. Over the 3 years sampled, the most desirable grass, soft chess, averaged 68, 22, and 66% higher production (438, 287, and 388 kg/ha increases, respectively) on fertilized versus control range units for swale, open upland, and rocky, brushy upland range sites, respectively. Likewise, the less desirable but important early-forage species, ripgut brome, increased 164% or 544 kg/ha on swales and 205% or 437 kg/ha on rocky, brushy uplands with fertilization; only a 16% increase or 98 kg/ha occurred on open upland sites. Grass responses were offset by decreased forb production, while the proportion of legumes remained nearly the same. Upland sites benefited from sulfur fertilization by exhibiting both increased clover and other legume production in the wettest year. Filaree was unaffected by sulfur fertilization.

Sulfur is recognized as an important macro-nutrient on California's unimproved and improved annual-type rangeland. Martin (1958) noted a sulfur deficiency on sites in 34 of the 58 California counties representing 60 soil series. Conrad (1950) found that elemental sulfur significantly increased hay production on 4 widely separated sites in California. Yield of dryland pasture species increased significantly when sulfur was applied as gypsum at the Hopland Field Station (Jones 1964), and substantial increases in herbage productivity occurred during the first year on plots sulfur-fertilized with gypsum or elemental sulfur (Jones and Ruckman 1966). In the second year elemental S was more effective than gypsum. Winter forage was optimized with 67 kg S/ha yearly with elemental S or 25 kg S/ha as gypsum yearly on subterranean clover (*Trifolium subterraneum* L.) seeded rangeland at Hopland (Center and Jones 1983).

Studies of sulfur fertilization with gypsum showed that herbage yield and grazing capacity on upland range sites increased (Bentley et al. 1958). Conrad et al. (1966) reported only slight increases in herbage production on pastures fertilized with gypsum but found an increase in grazing capacity on the fertilized pastures, although individual cattle gains were unaffected. Wagnon et al. (1958) observed that steers exhibited increased weight gain during the summer dry-forage season on pastures fertilized with gypsum and Green et al. (1958) showed that summer forage had higher crude protein, phosphorous, and calcium levels when fertilized with gypsum. McKell et al. (1960) also reported higher protein levels in forage on range fertilized with gypsum. Increased production and improved quality of forage due to legume enhancement may extend the amount of time cattle graze without supplementation.

Plants take up sulfur as sulfate, while elemental sulfur must be oxidized by soil bacteria before plants can use it. Plants respond more quickly to sulfate forms of sulfur during low-rainfall years (McKell and Williams 1960, Williams et al. 1964). With higher rainfall sulfate fertilizers are susceptible to leaching and runoff during the application year (Williams et al. 1964) and sulfate fertilizers have lower residual value than elemental sulfur (Jones et al. 1968, Jones et al. 1970, Jones and Ruckman 1966). In high rainfall areas elemental sulfur elicits longer lasting results.

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Table 1. Average total herbage production on control and sulfur fertilized range sites.

Year	Fertilizer effect	Swale		Open-upland		Rocky, brushy upland	
		Control kg/ha	Fertilized kg/ha	Control kg/ha	Fertilized kg/ha	Control kg/ha	Fertilized kg/ha
1	1st year	2200	1600	2000	1250*	1400	1500
2	Carry-over	3500	3700	2400	2200	1200	1200
4	1st year	3600	4200	3300	3800	2200	2800
7	1st year	6800	6500	5500	6900	3500	5300
8	Carry-over	3800	3700	3200	4800	2400	3800*
Orthogonal components[1]		L 0.01 Q 5.2	L 0.01 Q 0.12	L 0.03 Q 10.6	L 0.00 Q 3.7	L 0.44	L 0.00

*Control vs. fertilized significance level $\alpha = 0.05$.
[1]Linear (L) and quadratic (Q) orthogonal component significance level (%).

Important shifts in botanical composition may occur as an initial response to sulfur fertilization. Stimulation of legume growth, notably resident annual clovers (Bentley et al. 1958, Bentley and Green 1954) and seeded subterranean clover (Jones 1964) occurs during the first growing season after application. Carry-over year responses are, typically, increased production of grasses and legumes. Production of legumes has been correlated with the amount of residual sulfur remaining in the soil (Jones 1964). Overriding the sulfur response, changes in productivity are most dependent on the amount and timing of rainfall during the winter and spring months (Duncan and Woodmansee 1975, Murphy 1970, Pitt and Heady 1978) and inherent characteristics of the site such as soil fertility, soil depth, and aspect.

This study was conducted at the U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, San Joaquin Experimental Range (SJER), from 1961 to 1968 to evaluate production and botanical composition changes due to elemental sulfur fertilization on 3 range sites. Total and 14 plant-category herbage productions were evaluated to determine benefits of sulfur fertilization. Cattle responses in this study were highlighted in Duncan and Reed (1973).

Study Area and Methods

The experimental range covers 1,820 ha at 213-518 m elevation in the central Sierra Nevada foothills 40 km northeast of Fresno, Calif. Annual precipitation averaged 48.6 cm between 1934 and 1979 and fell primarily as rain from September through May (Fig. 1). Of the 5 years sampled over 8 years, only years 2 and 7 were near or above this 45-year average. Winters at SJER are generally moist and have mild temperatures, whereas summers are hot and dry.

The major range sites on the experimental range were classified by Bentley and Talbot (1951) into swales, open uplands and rocky, brushy uplands and their relative area proportions are 6, 11, and 83%, respectively. Swale sites occupy drainage bottoms and typically have highest herbage yields because they are wet for longer periods. Soils on these sites are alluvial, coarse, sandy loams (Visalia Series, coarse-loamy, mixed thermic Pachic Haploxeroll). Open uplands are intermediate in productivity with few exposed rocks or shrubs and slopes of 5–15%. Rocky, brushy uplands are generally low in productivity, contain exposed granitic rock, and support varying amounts of brush. Soils on both upland types are residual, coarse and rocky, sandy loams (Ahwahnee Series, coarse-loamy, mixed thermic Ultic Haploxeralf). Soil depth generally decreases from swales (over 75 cm) to rocky, brushy uplands (less than 10 cm).

Clipped herbage was separated into 14 categories. Nine graminoid categories were soft chess (*Bromus mollis* L.), fescues (*Vulpia* spp.), ripgut brome (*B. diandrus* Roth), Mediterranean barley (*Hordeum geniculatum* All.), Australian chess (*B. arenarius* Labill.), slender oat (*Avena barbata* Pott. ex Link), red brome (*B. rubens* L.), a miscellaneous category named other grasses, e.g., mouse barley (*Hordeum leporinum* Link), silver hairgrass (*Aira caryophyllea* L.), and little quakinggrass (*Briza minor* L.), and grasslike plants (mainly *Juncus* spp.). Forbs were separated into 3 legume categories: (1) clovers (*Trifolium* spp.); (2) other legumes, e.g., fine-leaved deer vetch (*Lotus strigosus* [Nutt. in T. & G.] Greene), bicolor lupine (*Lupinus bicolor* Lind.), and Bentham's lupine (*L. benthamii* Heller); and (3) Spanish clover (*Lotus purshianus* [Benth.] Clem. and Clem.), along with filarees (*Erodium* spp.) and other broadleaved plants, e.g., common forbs such as popcorn flower (*Plagiobothrys nothofulvus* Gray), fiddleneck (*Amsinckia* spp.) and bluedicks brodiaea (*Brodiaea capitata* Benth.).

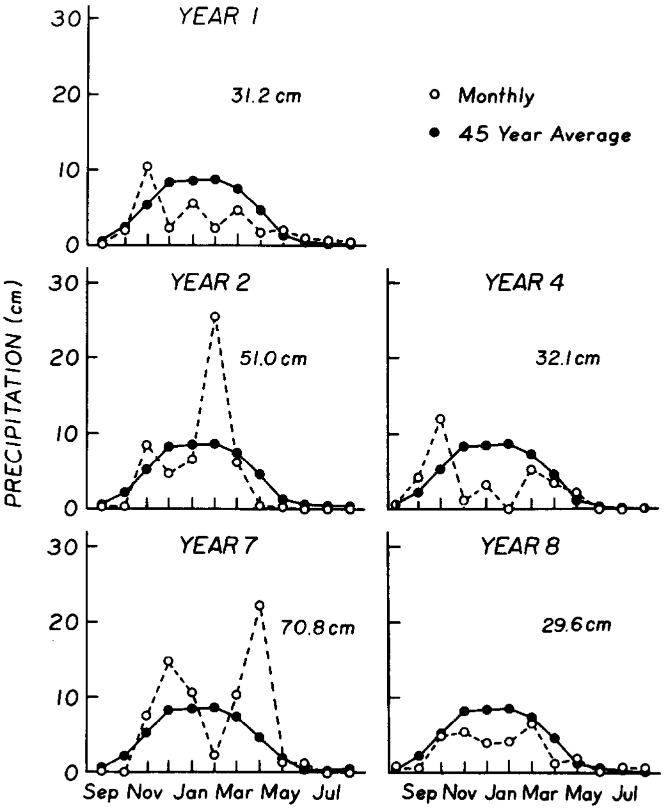

Fig. 1. *Monthly and annual precipitation at the San Joaquin Experimental Range during 5 study years over a period of 8 years compared to a 45-year average.*

Two replications of control and sulfur fertilized pastures were fenced in early spring and grazed during a calibration phase for 2 years to allow for adjustments in carrying capacity. During the study each pasture was grazed yearlong under moderate utilization to nominally leave 350 kg/ha of dry plant residue on 1 September. Elemental sulfur was applied at the rate of 67 kg/ha by helicopter during late fall prior to rapid growth of sampling years 1, 4 and 7.

Table 2. Herbage production (kg/ha) in sulfur fertilization studies in California (C is control, F is fertilized).

	Present study		Bentley & Green (1954)		Bentley et al. (1958)		Conrad et al. (1948)		Conrad et al. (1966)		Green et al. (1958)		Jones (1964)	
Location	SJER		SJER		SJER		[1]		SJER		SJER		Hopland	
Sulfur source	Elemental		[2]		Gypsum		Elemental		Gypsum		Gypsum		[3]	
Sulfur rate (kg/ha)	67		67		67		112		67		—		45	
Number of years	3,5[4]		4		8		2		3		2		2	
Treatment	C	F	C	F	C	F	C	F	C	F	C	F	C	F
Total production	2390	3100	3970	4760	2260	3280	3850	5230	2000	2380	2850	3810	3590	7000
Total grasses	1740	2500	2620	2970	1310	2010	—	—	1190	1420	1380	1910	1710	2270
Clover	170	400	360	1020	—	—	—	—	170	320	230	740	1880	4970
Other legumes	60	140	140	80	—	—	—	—	—	—	110	190	—	—
Total legumes	230	540	500	1100	—	—	808	3090	—	—	340	930	1880	4970
Filarees	750	830	700	500	250	650	—	—	—	—	1050	840	—	—
Other broadleaved plants	280	200	150	180	—	—	—	—	—	—	80	130	—	—
Total broadleaved plants	1030	1030	850	680	700	620	—	—	—	—	1130	970	—	—

[1]Upper Ojai Valley, California; legume principally bur clover *(Medicago polymorpha)*
[2]Averaged over replications of soil sulfur, gypsum, superphosphate, gypsum-sulfur mix, and superphosphate-sulfur mix.
[3]Treble superphosphate and soil sulfur.
[4]Three years for species groups, five years for total production.

Each pasture was divided into 3 sectors of equal width, and 2 transects were randomly chosen within each sector. Transects were then plotted on a map of the pasture, and the distance each transect passed through each site was measured. Plots (0.1 m^2) protected by 1.0-m^2 cages were systematically laid out along each transect to obtain a sample size of 25 plots for swales, 18 for open uplands, and 70 for rocky, brushy uplands. Pilot-study sampling showed that for the total herbage production on swale and open uplands, there was a 90% chance that the sample mean would be within 20% of the true population mean and that for rocky, brushy uplands, there was a 90% chance of being within 15% of the true population mean (Reppert et al. 1962).

Herbage in caged plots was clipped near peak standing crop during years 1, 2, 4, 7, and 8, air-dried, and weighed to estimate total dry matter production. A sub-sample from each was sorted into the 14 categories in years 4, 7, and 8.

A complete factorial design (Steel and Torrie 1960) was used to study fertilizer, year and range site effects on herbage production and botanical composition. Linear and quadratic trends over years 4, 7, and 8 were analyzed within range sites and fertilization treatments for the 14 plant categories; trends in total herbage production were analyzed over years 1, 2, 4, 7, and 8. Responses with significance levels less than 15% are discussed.

Results and Discussion

Total herbage production varied among years ($p<0.001$), among the 3 range sites ($p<0.001$), and between the control and sulfur-fertilized pastures ($p<0.025$, Table 1). Productivity was highest on all sites in year 7 when rainfall was highest and 46% above the 45-year average (Fig. 1). Production in the control swales averaged 6,800 kg/ha in year 7, whereas fertilized swales averaged 6,500 kg/ha. Total herbage production on the fertilized swales was nearly equal to that of the control pastures in each of the 5 years sampled. Fertilized open upland sites in year 7 averaged 6,900 kg/ha, which was 1,400 kg/ha higher than that produced on the controls. During this year, the less productive rocky, brushy uplands averaged 5,300 and 3,500 kg/ha, respectively, on the fertilized and control pastures. This 1,800 kg/ha difference was a greater increase (51%) than that on the open uplands (28%). Similar responses were noted in the following carry-over year.

Fertilizer versus control responses on the swale sites were not significantly different in any of the 5 years sampled (Table 1). Swale sites are not as sulfur deficient as the upland sites and this might be attributed to sulfate transport in run-on from upland sites as Williams et al. (1964) showed sulfate leaching under wet conditions with fertilization.

In years 1 and 2 the fertilized upland sites showed no increase in total herbage production and open upland sites actually showed a significant depression in production the first year. After the second sulfur application, however, both fertilized open uplands and rocky, brushy uplands produced approximately 600 kg/ha more herbage than did the control sites in year 4. In year 8, production on rocky, brushy uplands was 1,400 kg/ha and significantly higher on fertilized than on control pastures. Fertilized open uplands produced over 1,500 kg/ha more herbage than did the controls in the same year. Although these large increases in production were observed on the upland sites, only 2 replications were insufficient to detect significance in most cases.

Lack of rainfall during year 1 was responsible for the poor response of the upland sites during the first growing season following the initial fertilizer. Little precipitation fell during late winter and spring when rainfall is critical to rapid growth. There was no carry-over response in year 2, although fertilized range production increased nearly 1,000 kg/ha compared to a 400 kg/ha increase for the control.

Control and fertilized range units on all sites showed a highly significant upward linear trend in production (Table 1). This was largely due to the characteristics of the years sampled. Quadratic trends were most significant in swales where both control and fertilized range units responded similarly to weather and first-year or carry-over year fertilization. Large increases in the fertilizer response on upland sites in the later years of the study were responsible for a stronger linear trend. In both years 7 and 8 sulfur fertilization resulted in upland sites comparing favorably to swale sites in productivity.

Table 2 gives a comparison of results among several sulfur fertilization experiments in California. Average total herbage production over the 5 years in this study (combining all sites on the fertilized pastures) closely agrees with that on pastures studied by Bentley and Green (1954) and Conrad et al. (1948).

Graminoids

Soft chess production was significantly different among the 3 sites ($p<0.005$) and between fertilized pastures ($p<0.025$, Table 3). Open uplands had the highest average production over the 3 years sampled, followed by swales and rocky, brushy uplands. Fertilized swales averaged 68% higher production of soft chess than the controls. Average fertilized range unit production of soft chess was 66% higher on the rocky, brushy uplands and 22% higher on open uplands than on corresponding sites in control pastures. Quadratic trends on the fertilized pastures (Table 3) resulted from high soft

Table 3. Average graminoid plant production (kg/ha) on control and sulfur fertilized range sites during years 4, 7 and 8.

	Swale		Open-upland		Rocky, brushy upland	
Year	Control	Fertilized	Control	Fertilized	Control	Fertilized
Soft chess						
4	780	1490	1460	1510	460	900
7	530	610	960	1060	550	570
8	610	1140	1450	2160	760	1460**
O.C.[1]		Q 15.0		Q 3.5		Q 8.2
Fescues						
4	720	750	280	170	90	110
7	1740	1400	780	520	210	500
8	1050	1120	660	600	400	590
O.C.	L 4.2	L 8.0	L 10.7	L 11.0		L 7.6
	Q 0.6	Q 14.6				
Ripgut brome						
4	610	1330	880	790	250	670
7	120	340	330	490	200	600*
8	260	960*	620	840	200	690
O.C.		L 7.5				
		Q 2.7				
Mediterranean barley						
4	590	50	1	4	0	0
7	290	260	0	7	0	13
8	430	130	0	45**	0	0
O.C.	L 8.2					
	Q 12.6					
Australian chess						
4	27	49	150	140	310	160
7	0	0	100	150	60	80
8	39	7	90	230	90	90
O.C.					L 1.4	
Slender oat						
4	0	6	23	190	110	190
7	0	0	44	320	90	130
8	6	0	32	20	15	10
O.C.				Q 4.4		
Red brome						
4	0	33	55	68	80	90
7	37	37	25	93**	50	70
8	14	26	21	16	70	90
O.C.				Q 6.2		
Other grasses						
4	14	1	2	1	1	9
7	95	5	11	0	0	30
8	150	120	3	0	5	5
O.C.	L 2.8	L 11.2				
		Q 11.9				
Grasslike plants						
4	190	20	2	20	1	61
7	1370	1120	3	6	0	2
8	340	20	8	0	1	0
O.C.	Q 0.5	Q 0.4				

*Control vs. fertilized significance level $\alpha = 0.10$.
** $\alpha = 0.05$.
[1]Linear (L) and quadratic (Q) orthogonal component (O.C.) significance level (%).

chess production in the drier years 4 and 8.

Fescue species showed little response to sulfur fertilizer (Table 3), but significant differences ($p<0.001$) in production were evident among the 3 sites and among years ($p<0.001$). Fertilized swale sites had a combined average production of about 1,100 kg/ha during the 3 years sampled, whereas the 2 fertilized upland sites averaged only about 400 kg/ha. Production on swales was significantly higher than production on the upland sites. Fertilization of the rocky, brushy uplands brought fescue production up to nearly that of open upland sites.

Ripgut brome showed the most significant fertilizer response ($p<0.004$) and no differences due to site. Fertilized swales and rocky, brushy uplands increased 164 and 205%, respectively, over controls. Swales showed dramatically less ripgut production in the wet year (7) with below-average February rainfall.

Mediterranean barley was largely restricted to swale sites except on fertilized open uplands in year 8 (Table 3). Sulfur fertilization appeared to reduce Mediterranean barley on swale sites probably due to competition from soft chess and ripgut.

Australian chess was highly variable in productivity among sites (Table 3). Swale productivity was lowest with no Australian chess production in control and fertilized pastures in year 7. No Australian chess fertilizer response was apparent on any site. Likewise, slender oat showed little production on swale sites during all 3 years. It appeared to respond positively to first-year fertilizer applications (years 4 and 7) on upland sites but showed no carry-over effect.

Rocky, brushy upland sites produced significantly more ($p\leq 0.01$) red brome than swales, while open upland site productivity was not different from that for either of the other two sites (Table 3). There was a slight response to sulfur fertilizer on all sites ($p\leq 0.14$) with the largest response ($p\leq 0.015$) on open uplands in year 7 when production increased nearly 70 kg/ha.

Other grasses were restricted ($p\leq 0.031$) primarily to the swale sites and were not significantly affected by fertilizer (Table 3). Production of these grasses on the upland sites was never greater than 35 kg/ha. Highest productivity on the swale sites occurred in year 8, when the control and fertilized pastures produced about 150 and 120 kg/ha, respectively.

Grasslike plants produced significant amounts ($p\leq 0.005$) of herbage only on the swale sites and primarily ($p<0.04$) during the wet, year 7 growing season (Table 3). During this year, production on the control swale sites was about 1,400 kg/ha, compared with 1,100 kg/ha on the fertilized swales. Grasslike plant production on the 2 upland sites was negligible for all years sampled, most likely due to low moisture retention in these shallow soils during the warm spring months. During the 2 dry years (4 and 8) fertilization almost eliminated grasslike plant production in swales.

Forbs

Filaree is the dominant forb on all sites at the San Joaquin Experimental Range. Production with and without sulfur fertilization was remarkably similar (Table 4). Open upland site filaree production was enhanced most by wet conditions in year 7 when 1,100 and 1,200 kg/ha more herbage was produced on control and fertilized pastures, respectively, than in the dry year (4). On both upland sites high production in year 7 resulted in quadratic trend responses for both fertilized and control range units.

Although no fertilizer responses for clover were significant, productivity of fertilized pastures decreased on swales in each of the 3 years sampled while it consistently increased on both upland sites except for rocky, brushy uplands in year 8 (Table 4). Fertilized open uplands averaged over 400 kg/ha more clover production than control pastures and produced over 1,000 kg/ha more clover than controls in the wet year (7). Consistently more ($p\leq 0.001$) clover was produced in year 7 with production in the dry years being relatively low on all sites.

Clover is an important forage species on annual-type ranges and, in addition to its importance as a nitrogen-fixer, may account for 20–30% of the diet of cattle in July (Green et al. 1958). Clover composition of forage increased 80 and 33%, respectively, on fertilized open upland and rocky, brushy uplands in year 7 but decreased by 80% on swale sites in that same year. When accounting for the relative areas of the 3 sites on the experimental range, average clover production nearly doubled from 167 to 315 kg/ha due to fertilization with 67 kg/ha elemental sulfur. This response closely parallels the gypsum (67 kg/ha) fertilizer response found by Conrad et al. (1966) of 170 and 320 kg/ha, respectively, on control

Table 4. Average forb production (kg/ha) on control and sulfur fertilized range sites during years 4, 7 and 8.

Year	Swale		Open-upland		Rocky, brushy upland	
	Control	Fertilized	Control	Fertilized	Control	Fertilized
Filarees						
4	410	540	600	570	880	830
7	610	780	1670	1780	1050	1200
8	430	390	440	390	300	430
O.C.[1]			Q 0.22	Q 0.12	Q 8.7	Q 6.2
Clovers						
4	80	30	15	130	20	160
7	1870	950	820	1830	320	620
8	50	10	30	160	20	10
O.C.	L 10.4			L 9.5		
	Q 0.0	Q 0.46	Q 1.3	Q 0.0		Q 6.2
Other broadleaved plants						
4	70	5	6	0	120	0
7	240	520	220	170	570	290
8	380	70	140	160	210	40
O.C.	L 10.3	Q 1.0			Q 2.7	Q 12.3
Other legumes						
4	0	0	0	0	0	10
7	6	7	145	300	210	460*
8	0	0	2	0	2	0**
O.C.			Q 2.8	Q 0.01	Q 0.30	L 5.8
						Q 0.0
Spanish clover						
4	3	10	2	5	15	25
7	35	170	75	70	60	270
8	35	20	120	5	25	0
O.C.		Q 5.3				Q 0.25

*Control vs. fertilized significance level $\alpha = 0.10$.
**$\alpha = 0.05$.
[1]Linear (L) and quadratic (Q) orthogonal component (O.C) significance level (%).

and fertilized range units (Table 2).

Other broadleaved plants showed no consistent response to sulfur fertilizer and no differences in production among the 3 sites (Table 4). Sulfur fertilization appeared to reduce other broadleaved plant production on rocky, brushy upland sites. Other legume plant production was significantly increased ($p<0.053$) by fertilization on both upland sites. However, production was only significant in year 7 when 105 and 123% increases were observed on fertilized open and rocky, brushy uplands, respectively.

Spanish clover is an important range legume for extending green-season forage, and 2 reports indicate that productivity increases after fertilization with sulfur (Westfall 1966, Green et al. 1958). Production in this study was generally low all 3 years, and no consistent trends due to fertilization were observed. Maximum response occurred in year 7 on fertilized swale and rocky, brushy upland sites with increases of 140 and 210 kg/ha, respectively. Poor spring rainfall during years 4 and 7 may have contributed to low production. High rainfall in year 7 stimulated production of more abundant and taller species, which likely shaded-out this legume.

Table 5 shows botanical composition based on weight for total grasses, forbs, and legumes on the 3 sites. The most dramatic changes in composition due to fertilization occurred on the rocky, brushy uplands, where grasses increased at the expense of forbs all 3 years, and the proportion of legumes increased in the wet year (7). On the open uplands there was a decrease in grass composition on the fertilized pastures during initial fertilization in years 4 and 7, but there was a 5% increase in the following carry-over year. This increase was again at the expense of forbs. During year 7, legume production increased 12%, mainly because of the large increase in clovers (Table 4).

Table 5. Proportion (%) by weight of grasses, forbs, and legumes on 3 range sites on fertilized and control pastures during years 4, 7 and 8.

Year	Grasses		Forbs		Legumes	
	Control	Fertilized	Control	Fertilized	Control	Fertilized
	Swales					
4	82	86	15	13	3	1
7	51	52	15	26	34	22
8	77	87	21	12	2	1
	Open Uplands					
4	82	80	17	16	1	4
7	43	39	37	29	20	32
8	80	85	16	12	4	3
	Rocky, Brushy Uplands					
4	56	68	43	26	1	6
7	35	41	48	31	17	28
8	74	86	24	14	2	0

Grasses in the swales increased by 10% in carry-over year 8, but otherwise they remained nearly the same on the control and fertilized pastures. In year 7, there was a 12% decrease in legumes and a 11% increase in forbs. In year 8, forbs decreased by 9%, nearly the same amount that grasses increased.

Grass composition reported by Green et al. (1958) on the experimental range for sulfur fertilized ranges was only 28 and 31% in 1950 and 72 and 64% in 1951, respectively, for fertilized and control pastures. Legume composition was 34 and 15% in 1950 and 14 and 9% in 1951 on the respective pastures, whereas total forb composition was 38 and 53% in 1950 and 14 and 26% in 1951. However, weather conditions during these 2 years were quite unlike the conditions in the 3 years sampled during this study. During the 1949-50 growing season, 41 cm of rain fell with an even distribution in the spring. In the 1951 growing season, 54 cm of rain fell, but 34 cm fell prior to January 1.

Conclusions

The 5 years total herbage production response that was measured represented a variety of rainfall patterns and amounts. The results suggest that elemental sulfur fertilization on upland sites is of value if rainfall is adequate during the year of initial application. In years when rainfall during the warm spring months is below normal, as in years 1 and 4, the benefits of fertilizing appear to be small.

Upland sites respond favorably to sulfur fertilization because these sites have shallower soils and nutrients are more limiting than in swales. Rocky, brushy uplands showed the largest positive response in total herbage production. These sites, however, vary in their accessibility for ground application because of shrub cover and rock outcrops, which may make aerial fertilizer application necessary. The open uplands are the most accessible areas to fertilize by ground rig, and they represent a valuable site for sulfur fertilization.

Sulfur deficiency did not appear to be limiting total herbage production on swale sites where no appreciable increases in herbage production were noted, even with above-average rainfall. Swale sites comprise only a small part of foothill rangeland but cost of fertilizing these sites while the uplands are being fertilized would be small. According to observations by Bentley and Green (1954) these sites are likely to benefit more from fertilization with single superphosphate.

Overall, changes in botanical composition on the 3 range sites due to sulfur fertilization were favorable. Increases in soft chess and clover production on fertilized pastures improved both the quality and quantity of desirable forage, thus increasing the grazing value of the upland sites. Ripgut brome is widely viewed as an undesirable forage species; however, its importance early in the growing season makes it an important forage for many foothill ranches. Increases in ripgut production on the fertilized pasture on the experimental range were substantial. No changes in filaree production were noted on the fertilized pastures.

Response of California's annual-type range to sulfur fertilization is complicated by variable range site responses and variable growing seasons, including minimum temperature restrictions and limitations due to timing and amount of precipitation. The wide range of responses of the 14 plant categories demonstrates this complexity. Therefore, conclusions as to the benefits of fertilizing these ranges with elemental sulfur must be considered with caution.

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