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12 Fertilization of Annual Grasslands of California and Oregon

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I. INTRODUCTION

The annual grasslands of the Pacific Coast extend from the coast of southern California near San Diego northward to central Oregon in the area west of the Sierra Nevada-Cascade Mountains below about 900 m. The rainfall occurs during the cool season of the year, and total rainfall and length of the rainy season increase generally from south to north. Rainfall varies from less than 25 cm to greater than 250 cm and the length of the rainy season varies from less than 6 to about 9 months (Jackson, 1960; Love, 1967). In this region of Mediterranean-type climate, the nonirrigated annual grassland species germinate in the fall, grow slowly through the winter, and complete their life cycle after a period of rapid growth in the spring. Although annual grasses and forbs are dominant, perennials do occur, particularly in areas of higher rainfall. Love (1955) grouped some common annual species into two classes:

Undesirable	*Desirable*
Nit grass	Broad-leaved filaree
Native fescue	Soft chess
Introduced fescue	Slender wild oats
Wild barleys	Native annual clovers
Red brome	Red stem filaree
Ripgut	Bur clover

All of these species and many more grow without being seeded. Those considered most undesirable are first on the list. Ripgut, a borderline grass, is palatable and nutritious when young, but the ripe panicles are obnoxious because of the barbed awns on the seeds which do not readily shatter. Broad-leaved filaree produces early feed, but is not much value late in the season.

Annual grasslands produce feed for livestock in a "feast or famine" cycle each year. In many years the first germinating fall rain does not come until temperatures are too low for rapid plant growth. Therefore, during November, December, and January, livestock generally lose weight, or the pasturage must be supplemented. In late February the forage supply is usually sufficient, and in March and April pasture growth is so rapid that reserve supplies are built up. Then in April, May, or June, the plants dry and the animals must survive on dry feed until the first rains come in the fall. During the winter period the young grass is high in protein, but low in energy. In the dry season there is ample dry matter to provide energy for ruminant animals, but the protein level is usually below minimum amounts required for maintenance of livestock. Rossiter (1966) provides useful background on the ecology of the annual-type pastures of the Mediterranean climatic regions.

The annual grassland soils are nearly always N deficient. If early winter feed is desired and total production is to be increased, N must be added either by a legume or through N fertilization. Phosphorus and S deficiencies are widespread (Martin, 1958). In some areas Mo deficiencies are quite common (Dawson and Bhella, 1972; Jones and Ruckman, 1972). Deficiencies of K, B, and lime on acid soils occur, but are not widespread. Usually these latter deficiencies become evident only after adequate amounts of P and S have been applied on legume pastures.

The annual grasslands, or potential grasslands, include about 4 million hectares of open treeless grassland, 4 million hectares of oak-grass-woodland, and 4 million hectares of brush lands in California. Love (1967) estimated that 60 to 70% of these three categories of land would be 3 to 12 times more productive if improved plant species were planted and properly fertilized. Wagner and Jones (1968) estimated that only 1 to 2% of California annual grasslands have been fertilized. In Oregon, Jackson (T. L. Jackson, personal communication) estimates that there are presently 80,000–160,000 hectares of improved subclover pastures out of 1.2 million hectares that could be highly productive if planted to this species.

II. NITROGEN

A. Sources of N

Many observations have indicated that ammoniacal forms of N should be used for fertilization of annual grasslands (W. E. Martin, personal communication). Nitrate nitrogen tends to leach too rapidly, and is often lost in the first year before it can be utilized by the forage plants. McKell et al. (1965) showed that chicken manure is a satisfactory source of N where transportation and spreading costs do not make its use prohibitive. Other types of manure also increase production.

B. Effects of N

1. FORAGE PRODUCTION

a. Many factors influence time of nitrogen application. The amount and distribution of rainfall, as well as temperature, govern the timing of N fertilization. Nitrogen is not profitable in central and southern California where rainfall is less than 30 cm annually because drought restricts growth (Figs. 1 and 2). In the 30-to 75-cm rainfall zone, N is generally applied in the fall to lengthen the green-feed period by increasing winter growth (Hoglund, Miller, and Hafenrichter, 1952; Martin and Berry, 1960; Greenwood, Davies, and Watson, 1967).

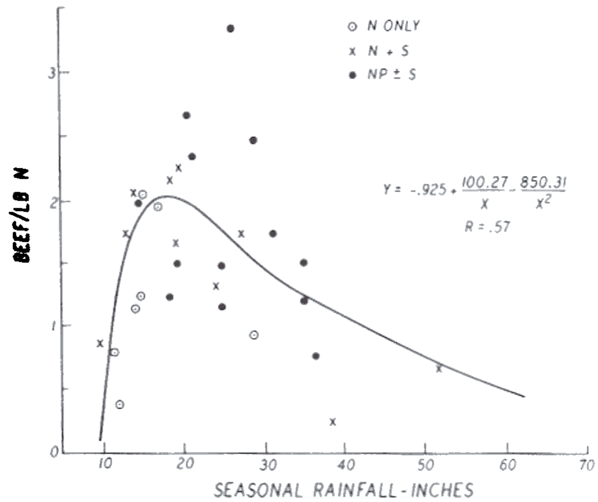

Fig. 1—Pounds beef produced per pound of N (Y) as related to rainfall (X) and source of N (Martin and Berry, 1970).

Jones (1960) applied N at different times of the year in a 100-cm rainfall zone. He found that the earlier N was applied the greater the winter forage growth. Total forage as measured at the end of the growing season was not affected by time of application unless the application was made after February. Later studies in the 100-cm rainfall zone (Jones, 1967) indicated that where pastures are closely grazed during the winter months, they may become extremely N-deficient in the spring, even though N was applied the previous fall.

Nitrogen is generally not recommended where rainfall is greater than 75 cm since leaching losses are high. Denitrification contributes to N losses, especially on poorly drained soils. However, some early spring applications are made in Oregon (Jackson, 1960)and North Coastal sections of California. The effects of split applications or spring applications of N on annual grasslands has not been critically evaluated.

Data reported by Jones, McKell, and Winans (1963) indicates that winter temperatures averaging much below 10 C severely limit responses to N fertilization. Daily mean temperatures below this limit are common in northern California and Oregon during the months of December, January, and

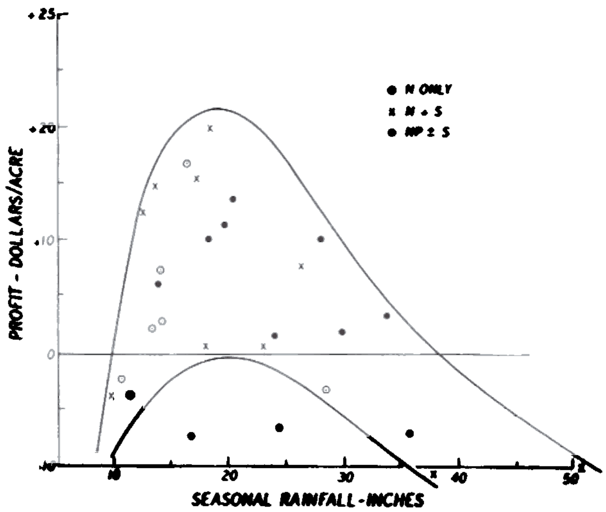

Fig. 2—First-year profit from fertilization as related to seasonal rainfall and nutrient response. Area inside curved lines represents 95% confidence limits. (Martin and Berry, 1970).

February. It is important to apply N before the first autumn rains when mean temperatures are at or above 10 C. Lack of response in cold weather is mainly a simple restriction of plant growth, but N fertilized grass often is less damaged by frost and appears to recover faster than N-deficient grass.

b. Rate of application influences crop yields. Hoglund et al. (1952) applied increasing rates of N up to 94 kg/ha in a 51-cm rainfall zone. They reported that yields increased with each increment of N applied. Jones (1963) applied N at rates up to 179 kg/ha and found that top yields were produced by the 90 kg/ha rate when first germinating rains came in late October and total rainfall ranged between 66 and 74 cm. In a 152-cm rainfall year when germinating rains fell in September with favorable distribution and temperature for forage production, yields increased up to the 179 kg/ha rate.

2. BEEF PRODUCTION

In 54 field experiments, Martin and Berry (1970) evaluated the effects of N fertilization of California grasslands, as measured by weight gains of grazing cattle. Extending over a 15-year period, the tests involved 7,650 animals grazing on 6,791 hectares on 28 ranches in 20 counties. Results the first year after application on fertilized and unfertilized fields are summarized in Table 1. The data are grouped according to treatment so that "N" includes 7 trials where only N or no N was used, "NS" includes 10 trials where only N plus S or no fertilizer was used, and "NPS" includes 13 trials

Table 1—First-year effects of different nutrients on cattle gains and profits (Martin and Berry, 1970)

Fertilizer	No. of tests	Avg treatment N	Avg treatment P	Avg treatment S	Avg liveweight gain Check	Avg liveweight gain Fert.	Avg liveweight gain Increase	kg beef/ kg N	Avg grazing income Check	Avg grazing income Fert.	Fertilizer profit
		kg/ha							$/ha		
N	7	64	--	--	83	159	76	1.19	28.81	37.11	8.30
NS	10	80	--	72	59	176	117	1.48	20.36	32.04	11.69
NSP	13	77	29	40	65	219	154	2.00	23.52	41.19	17.67
Avg		75	--	--	67	191	124	1.63	23.70	37.19	13.49

where NPS or no fertilizer was used. Mean average daily gain per head was slightly greater on the fertilized fields than on the control fields, indicating that fertilized fields were not over-stocked in relation to the control fields. One kilogram of N alone produced 1.19 kg of beef with a profit of $8.30 per ha. Where NPS was applied profit increased to $17.67 per ha. This was to be expected, as a dual or multiple deficiency was corrected. A portion of the benefits must be attributed to the S and P applied with the nitrogenous fertilizers.

Residual effects were measured in 13 tests, the first and second year effects indicated in Table 2. In every instance but one there was an appreciable residual effect from nitrogenous fertilization, the residual gain being approximately equivalent to 50% of the first year effects. Part of the gains should be credited to PS, but the amount of credit to be given can not be determined with the data at hand. Without applied N or a good stand of legumes there is usually no response to P or S on annual grasslands of California.

Table 2—First-year and residual effects of nitrogen fertilizer on cattle gains (Martin and Berry, 1970)

Year	Avg treatment N	Avg treatment Cost	Avg liveweight gains Check	Avg liveweight gains Fert.	Avg liveweight gains Increase	Beef/ kg N	Avg grazing income Check	Avg grazing income Fert.	Fertilizer profit
	kg/ha	$/ha	kg/ha				$/ha		
Treatment year	75	29.92	72	197	125	1.67	26.22	44.35	18.13
Residual year	--	--	63	115	52	0.69	22.46	37.14	14.68
2-year total	75	29.92	135	312	177	2.36	48.68	81.49	32.81

3. FORAGE QUALITY

The quality of annual grassland pasture is influenced by N fertilization in at least two ways: changes in botanical composition and chemical composition. Some of the annual pasture species and their relative acceptability and usefulness to animals were listed above. Plant species also differ in chemical composition; thus a change from clover to grass may make a difference in protein level as illustrated below.

a. *N fertilization changes botanical composition.* Application of N generally increases the percentage of grasses and nonleguminous forbs and decreases the percentage of legumes in the pasture (Jones et al., 1961). The particular grasses or forbs which increase will depend upon the grazing or

clipping management of the pasture in question. For example, slender wild oats or ripgut may become dominant where N fertilizer is applied to ungrazed plots. In similarly treated plots that are heavily grazed, soft chess may become dominant. This is due to the greater tillering ability of soft chess when grazed as compared to wild oats or ripgut which are poor tillerers. Moderate to heavy grazing pressure tends to reduce the impact of the fertilizer on botanical composition (Table 3 and 4). The data of Greenwood et al. (1967) in Table 4 also shows the wide year-to-year fluctuation in botanical composition that may be expected on annual grassland.

Table 3—Effect of N applied and of moderate grazing on botanical composition of annual pasture seeded to three clovers (Jones and Evans, 1960)

N applied annually,* kg/ha		Species					
		Subclover	Rose clover	Crimson clover	Soft chess	Ripgut	Other species
		% of stand (May, 1959)					
0	Ungrazed	15	7	13	33	10	32
0	Grazed	26	20	2	22	3	27
56	Ungrazed	2	0	2	45	31	20
56	Grazed	18	10	4	29	8	31

* The N was applied as urea in October of 1957 and 1958.

Table 4—Effects of ammonium sulfate and stocking rate on the percent subclover and soft chess at the end of the growing season (Greenwood et al., 1967)

	Ammonium sulphate, kg/ha						Ammonium sulphate, kg/ha					
	280				840		280				840	
	Stocking rate, sheep/ha						Stocking rate, sheep/ha					
	8.6	12.3	8.6	12.3	8.6	12.3	8.6	12.3	8.6	12.3	8.6	12.3
	Subclover, % dry wt						Soft chess, % dry wt					
Year 2 (1962)	65*	58*	9*	12*	3*		34	39	87	76	94	
Year 3 (1963)	84	84	25*	51*	0		8	5	56*	30*	93	
Year 4 (1964)	40*	70*	1*	25*	0		25*	4*	60**	21**	72	
Year 5 (1965)	40	38	17	18	0		8	1	42*	21*	57	

* Significant difference between means (P = 0.05). ** [illegible]

b. N fertilization causes an initial rise in protein levels. Fall nitrogen fertilization generally increases the percentage of protein in annual grasses and broadleaf forbs early in the growing season. However, an early season increase in protein percentage is not particularly beneficial since there is adequate protein for animals in unfertilized pasture at that time of year. The primary benefit from N in the early part of the season is an increase in total dry matter production. As the season advances, the protein levels often decrease more rapidly in plants fertilized at moderate N rates (45 to 90 kg/ha) than in those not fertilized. As a result, at the end of the growing season fer-

Table 5—Percent protein in annual grassland species in late spring as affected by increasing rates of N applied the preceeding autumn (Jones, 1963)

N applied, kg/ha	Soft chess	Slender wild oats	Ripgut	Fescue	Filaree	Native clovers	Other forbs
	% protein, dry wt basis						
0	7.5	6.3	6.3	6.3	6.3	15.6	16.9
45	6.3	5.6	4.4	5.6	5.6	16.2	15.6
90	6.3	6.3	5.6	6.3	5.6	15.5	11.9
-	7.5	10.6	7.5	8.1	8.1		9.4

tilized plants often are lower in protein than are unfertilized plants (Table 5). Exceptions may occur in very dry spring seasons when moisture becomes limiting and plants are unable to grow to their full extent, and thus dry up before growth dilutes the N to a low level (McKell, Graham, and Wilson, 1960).

C. Annual Clover-grass Mixtures Versus N Fertilized Grass

Where annual legumes such as subclover, rose clover, or bur clover can be established, they provide an almost ideal solution to the problem of poor winter forage growth and low quality summer feed. The winter growth of grass growing in association with clover is increased, and the level of protein at the end of the growing season remains high enough to meet animal needs, if the pasture is managed to maintain a good stand of clover. This high protein level is due mainly to the clover itself, but the grass may also be higher at the end of the season (Table 6).

Table 6—Effect of P on a rose clover-grass pasture the first and second years after application (Martin et al., 1957)

Date applied	P applied, kg/ha	Rose clover Yield, lb/acre	Rose clover Protein, %	Grass Yield lb/acre	Grass Protein, %	Total forage Yield, lb/acre	Total forage Protein, %
Oct. 1955	0	135		738	7.0	872	
	28	1,614		848	7.6	2,470	
	56	2,706		807	7.5	3,512	
	112	2,875		830	6.2	3,705	
LSD (0.05)		733		ns	1.2	719	
Oct. 1955	0	408		1,064	5.4	1,472	7.6
Oct. 1955	28	1,154		1,385	5.6	2,539	9.0
Oct. 1955 & 1956	28	3,582		1,343	7.3	4,925	12.1
Oct. 1955	56	2,595		1,306	6.0	3,901	10.7
Oct. 1955 & 1956	56	3,261		1,908	7.3	5,169	11.0
Oct. 1955	112	2,873		1,534	5.8	4,407	10.6
Oct. 1955 & 1956	112	3,337		1,799		5,136	11.7
LSD (0.05)		711		502		666	

Jackson (1960) indicated that subclover pastures in Oregon can carry 2 ewes per acre, and market two 40- to 45-kg lambs by the middle of June. In contrast, 1.2 to 1.6 ha were required to carry one ewe on unimproved grassland. Similar improvements have been made in the North Coastal mountains of California (Unpublished data—University of California Hopland Field Station). Love (1952) reported a fourfold increase in animal production over unimproved pasture on the eastern edge of the Sacramento Valley from seeding annual clovers and applying 224 kg/ha single superphosphate.

Berry (unpublished data) indicates that establishment of annual clover pasture costs $56.80/ha on foothill or old grain land. This includes disking, seed, inoculant, planting, rolling, and fertilization with 560 kg singlesuperphosphate/ha. This treatment increased carrying capacity on foothill pastures from 1.2 to 7.4 animal unit months/ha. The same treatment of nonirrigated grain land gave a carrying capacity of 14.6 animal unit months/ha. These treatments were paid for in about 1 year when pastures were rented at $5.00/AUM, and will last many years if properly grazed and 112 kg single-superphosphate/ha is applied every other year. In southern Oregon, Mosher (1968) obtained good results on subclover pastures from an annual application of 112 kg/ha concentrated superphosphate fortified with elemental S, at a cost of $13.59/ha. Mosher's (1968) recommendations apply to many areas of northern California.

In comparing subclover-grass with N fertilized grass Jones and Winans (1967) noted that increasing rates of fall-applied N increased the level of protein in the plant early in the season (Fig. 3). The subclover-grass mixture gave protein values equivalent to plots fertilized with 90 kg N/ha. As the season advanced, protein values dropped more in plots fertilized with N than in unfertilized plots of subclover and grass. In another part of the same study (Fig. 4), Jones (1967) found that during a dry, cool year, poor for clover growth, yields from subclover-grass plots were equivalent to about 75 kg N/ha. In a wet year when conditions were more nearly ideal for clover growth, the subclover-grass swards produced more forage than plots fertilized with 179 kg N/ha (Fig. 5). Watson (1963) reported that N accumulated in the soil at the rate of 47 kg/ha per year over a 5-year period in a subclover-grass pasture.

Davies, Greenwood, and Watson (1966) studied the effect of N fertilization of a subclover-grass pasture on sheep production in the southern part of Western Australia, where climatic conditions are similar to those in North Central California. Three levels of $(NH_4)_2SO_4$ [(0, 56, and 168 kg N/ha)] were applied as a split dressing each year at emergence and in late winter for 4 years. There were two stocking rates–8.65 and 12.36 sheep/ha. In the

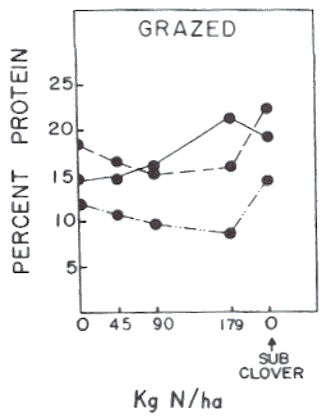

Fig. 3–The percentage of protein in subclover-grass compared with that of native grassland fertilized with various rates of N. A solid line represents winter conditions, dashes indicate early spring, and a dash and two dots represents late spring. (Jones and Winans, 1967).

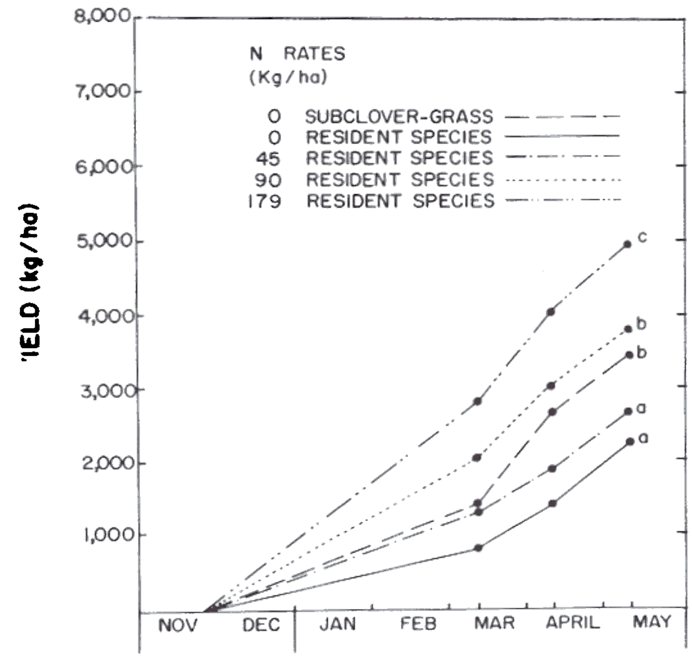

Fig. 4—Cummulative forage production by subclover-grass compared with fall applied N on annual grasslands in a dry year. Cummulative yield values followed by the same letter are not significantly different at the 5% level (Jones, 1967).

first year, $(NH_4)_2SO_4$ increased liveweight of the sheep as well as wool production, in autumn and winter. In the last 2 years of the experiment, the sheep grazing the plots topdressed with $(NH_4)_2SO_4$ lost more weight in autumn and winter and produced less wool per head than did sheep on pastures receiving no N (Fig. 6). Wool per acre was less from the heaviest N-fertilized pasture in the last year of the study then from the check. This loss of animal production was due to low quality feed produced by the high nitrogen treatment. Greenwood et al. (1967) reported the agronomic aspects of this study. The percentage of subclover and soft chess is given in Table 4. Ammonium sulfate increased the soft chess and other grasses and reduced subclover and other broadleaf weeds. At the highest level of applied N clover did not persist even at the highest stocking rate. High N increased winter growth during the early years of the experiment. In later years, large quantities of straw accumulated on the $(NH_4)_2SO_4$ plots, regeneration was poor and the N fertilized ineffective.

Davies et al. (1966) reported the chemical composition of the subclover and soft chess in the fourth summer of the experiment. Protein appeared to be the critical factor with subclover at 11.8% and soft chess at 2.6%, indicating that sheep on pasture with no clover had diets deficient in protein.

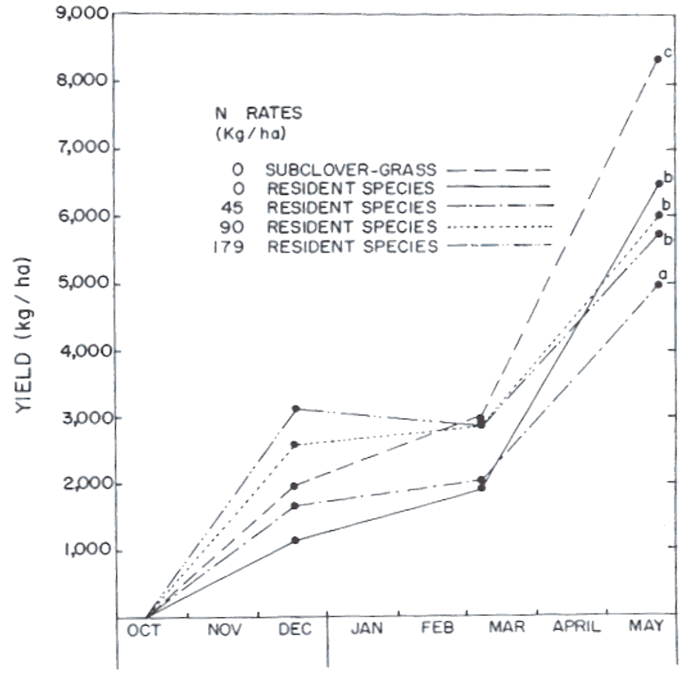

Fig. 5—Cummulative forage production by subclover-grass compared with fall applied N on annual grasslands in a wet year. Cummulative yield values followed by the same letter are not significantly different at the 5% level (Jones, 1967).

In California we do not recommend N on subclover pastures. The recommended practice has been to fertilize native grass pastures with N no more often than once every other year. Thus, the undesirable effects on pasture quality and animal production have not been quite so drastic as those reported by Davies et al. (1966). If similar treatments were applied, our experiments indicate that similar results would be expected in California. Our native grass pastures may contain from 2 to 15% native clover.

III. PHOSPHORUS

A. Diagnosing P Deficiencies

1. PLANT ANALYSIS

Tyson (1955) reported that when subclover yields approached maximum, 17 weeks after seeding under greenhouse conditions, the concentration of P was 0.13% in clover tops. Ozanne, Keay, and Biddiscombe (1969) reported that 0.1 to 0.2% P in subclover tops was required for maximum yields

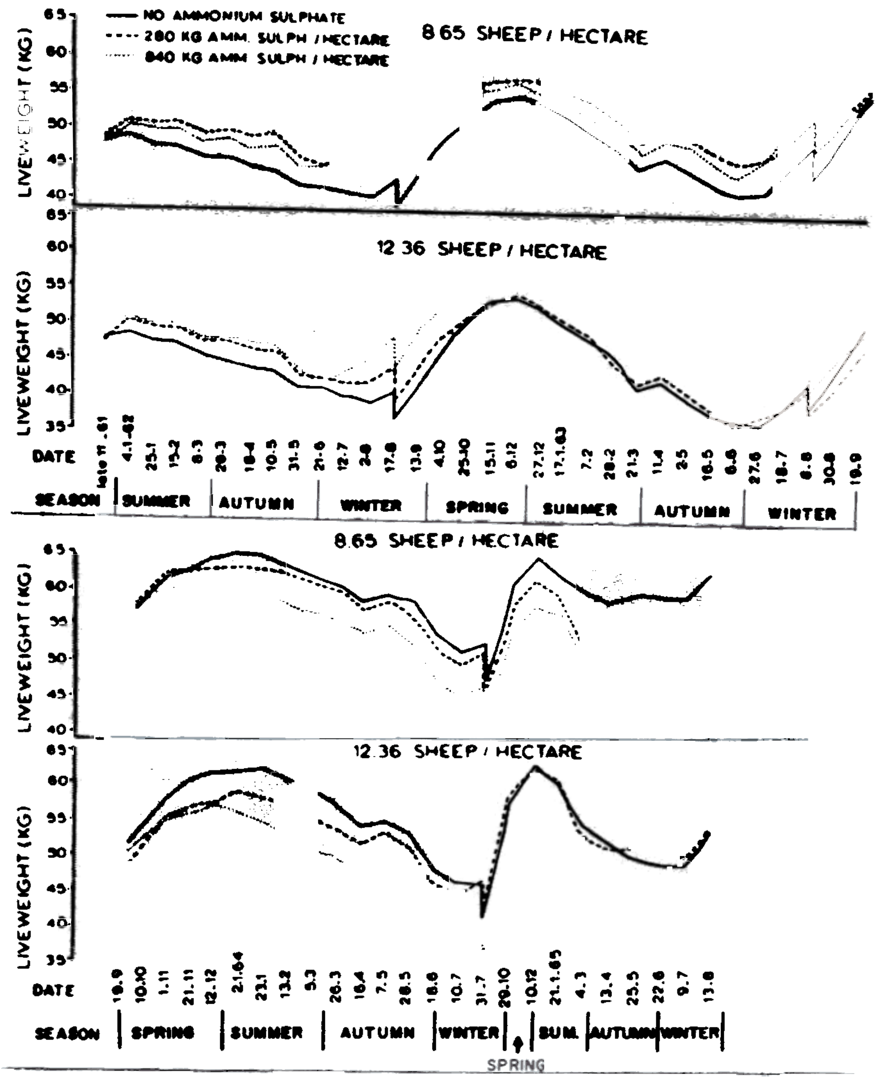

Fig. 6—Effect of N applied to subclover-grass pasture on the live-weight of Merino sheep in Western Australia. Fertilizer N applied as a split dressing each year at subclover emergence and in late winter. (Davies et al., 1966).

when the plants were 92 days old. At 29 days the value was 0.7 to 0.8% P. Jones, Ruckman, and Lawler (1972b) found that critical P values in subclover varied according to stage of growth, plant part, and frequency of presampling defoliation. With these variables influencing P concentrations, their use in assessing the P status of subclover under field conditions is very limited, especially in pastures where animals defoliate the plants.

Martin, Williams, and Johnson (1957) found the critical range of rose clover tops sampled in an ungrazed field during May to be 0.19 to 0.24% P.

2. SOIL TESTING

In California, the bicarbonate method of extracting soil P is used to determine the P status of grassland soils, and 10 ppm is considered to be the critical value (University of California Extension Service handout sheet). The amount of P applied may vary with soil type, as the experience of the local farm advisor indicates. Recommendations may vary from 560 kg single-superphosphate/ha on previously unfertilized hill soils with test values less than 10 ppm P down to 112 kg/ha as a maintenance dose on good clover pasture with high P test values. In Oregon, if the bicarbonate soil test values are between 0 and 10 ppm, 336 to 504 kg singlesuperphosphate/ha is recommended; if the soil test reads between 10 and 20 ppm, 224 to 336 kg/ha is recommended. If values are 20 to 40 ppm, 168 to 224 kg/ha singlesuperphosphate is recommended and over 40 ppm extractable P, no fertilizer is recommended (Oregon State University handout sheet FG 4, 1970).

B. Effects of P

1. FORAGE PRODUCTION

Many of the soils that are deficient in P require heavy applications to increase forage production to desired levels. Jones (M. B. Jones, unpublished data) found that heavy applications of P broadcast on the soil surface have resulted in large increases in production of clover up to 10 years after application. Additional maintenance doses of P have given further increases above the residual effect, even when soil test values were above the critical level.

Research on P-deficient soils in Australia (Anonymous, 1968; Anderson and McLachlan, 1951; McLachlan and Norman, 1962; McLachlan, 1963) has indicated that, if obtaining a good sward of clover in the shortest possible time is the object, it is better to apply a large dressing in the first year rather than the same amount spread over several years. Once the reserves in the soil have been brought to a reasonable level, annual applications are usually better than larger but less frequent ones.

On some grassland soils which are extremely deficient in P, application of P to clover pastures can produce spectacular increases as illustrated in Table 6 (Martin et al., 1957). In the first year after P was applied total yield increased from about 900 kg/ha to about 3,500 kg/ha with application of 56 kg P/ha. Additional P did not increase yields significantly. This increase was primarily the result of the increased growth of rose clover, which yielded 135 kg/ha in the check and 2,700 kg/ha in the 56 kg P/ha treatment. Residual effects of the 56 and 112-kg P/ha rates were greater than with the 28-kg rate. The 28-kg rate applied 2 years in a row resulted in second-year yields greater than with 56 kg P/ha applied the first year only, and about equivalent to two applications of 56 or 112 kg P/ha.

2. BOTANICAL COMPOSITION

The marked change in botanical composition that can be produced by P fertilization is illustrated in Table 6. In the first year after P application all of the yield increase was due to growth of rose clover. In the second year grass also increased but not so much as rose clover.

Rossiter (1964) studied the relationship between available soil P and botanical composition, and concluded that as yields increased to 50% of maximum, the percentage of subclover increased. Further yield increases due to applied P reduced the percentage of subclover over the long term (Fig. 7). Rossiter attributed the changing pattern of dominants and subdominants to differences in species demand for P, capacity to absorb labile soil P, and root competition for P.

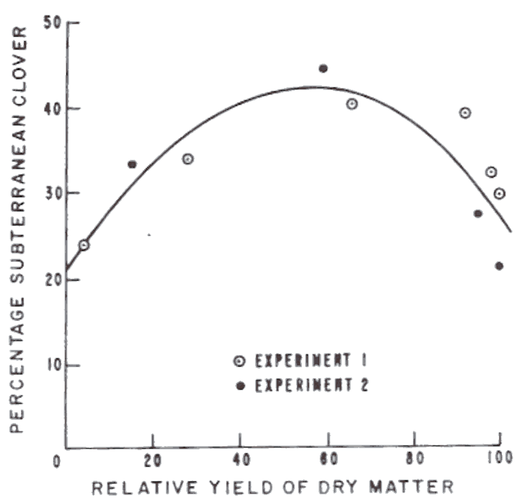

Fig. 7—Relation between percentage subclover in pasture and relative dry matter yield. Dry matter increased with increasing rates of applied P (Rossiter, 1964).

3. CHEMICAL COMPOSITION AND FORAGE QUALITY

Changes in botanical composition have an important influence on the level of protein in the forage. In Table 6, the first year application of 56 kg P/ha increased clover protein about 3%, which resulted in a 5% protein increase in the total forage even though grass protein made no significant change. In the second year, repeat P applications increased protein in both clover and grass about 2%. Total forage increased 5%.

Jones, Oh, and Ruchman (1970) studied the *in vitro* digestibility of subclover grown on extremely P-deficient soils, and found that when the concentration of P went below 0.10%, digestibility was reduced. Extremely low levels of P in the plant had the effect of reducing the level of soluble carbohydrates, which were directly correlated with digestibility.

C. Effect of Grazing on P Requirements

The applied P requirement of a pasture sown to subterranean clover was measured with and without grazing by Ozanne and Howes (1971) in Australia. Under moderate grazing pressure the year of establishment, the pasture required about 50% more P than when ungrazed. In the following season, which had a higher stocking rate, the grazed areas needed twice as much P as the ungrazed to make 90% their maximum growth. In both years this difference in requirement between stocked and unstocked treatments was present throughout the growing season. Increased P requirements under grazing were associated with the need for greater uptake of P under conditions where redistribution of absorbed P within the plant was prevented by defoliation. Increased need for P did not appear to be due to effects of defoliation on root size, nor did it depend on differential light interception or changes in botanical composition.

IV. SULFUR

A. Diagnosing S Deficiency

PLANT ANALYSIS

Critical S and SO_4-S concentrations have been determined for different plant parts of subclover and bur clover under greenhouse conditions (Jones, 1962; Jones, Ruckman, and Lawler, 1972a) (Table 7). Other work (Jones and Martin, 1964; Jones, 1964) in the field with subclover as well as rose

Table 7—Critical S concentrations for annual grassland legumes

Species	Type of culture	Tissue sampled	Days from planting or growth stage	Critical level	
Subclover	Soil (pots)	Leaf blades	135–145 days	170 ppm SO_4-S	0.22% S†
		Petioles	135–145 days	170 ppm SO_4-S	0.12% S†
		Stems	135–145 days	170 ppm SO_4-S	0.11% S†
		Tops:	91	200* ppm SO_4-S‡	
			128	250 ppm SO_4-S‡	
			155	200 ppm SO_4-S‡	
		Tops:	Flowering in May	200 ppm SO_4-S§	
			Wilting in June	300 ppm SO_4-S§	
Rose clover			Flowering in May	240 ppm SO_4-S¶	
			Flowering in May	150 ppm SO_4-S¶	
Native clover			Flowering in May	380 ppm SO_4-S¶	
Bur clover	Solution	Immature leaves	Flowering	160 ppm SO_4-S	0.23% S**
		Mature leaves	Flowering	140 ppm SO_4-S	0.23% S**
		Midstems	Flowering	100 ppm SO_4-S	0.08% S**
		Lower stems	Flowering	160 ppm SO_4-S	0.08% S**
Spanish clover		Midstems	Flowering	100 ppm SO_4-S	0.05% S††

* Not deficient at 91 days, but became deficient by 155 days. † Jones (1962). ‡ Jones (1963). § Jones and Martin (1964). ¶ Jones (1964). ** Jones (1972). †† Hylton, Cornelius, and Ulrich (1968).

clover and some annual native *Trifolium* sp., has indicated that plant analysis for S or SO_4-S is a very useful tool for determining the S status of annual pasture. Age of the plant is important, and plant part must be considered, particularly if total S is being determined. If SO_4-S is determined, differences between plant parts are not so great or not so important at or below the critical level.

2. SOIL TESTS

In a pot study, Arkely (S Compounds of Soil Systems, 1961 Ph.D. thesis, University of California) correlated S-uptake by plants with S extracted from the soil. Comparing several solutions he found the 1/10 normal LiCl or Morgan's solution extracted amounts of S which gave the highest correlation. However, when these two extractants and $NaHCO_3$ were tried under field conditions, very poor correlations resulted (M. B. Jones, unpublished data). Dawson (1969) reported that when 7 ppm SO_4-S were extracted from the surface soil by a KH_2PO_4 solution, application of S gave a highly significant subclover yield response.

B. Sources of S

Elemental S has been compared with SO_4-S as a source of S under different environmental conditions in California and Oregon. Conrad (1950) concluded that elemental S gave yield increases about equal to those from gypsum S except when the former was applied in areas or seasons of limited rainfall which came only in the colder months. Under these conditions, gypsum plots outyielded the elemental S plots the first season.

In the wetter areas, elemental S appears to have a definite advantage, since it produced yields equivalent to those produced by SO_4-S sources (Jones and Ruckman, 1966, 1969) in the first growing season and did not leach so rapidly as SO_4-S. In a lysimeter study, Jones, Martin, and Williams (1968) found that nearly all gypsum S applied in October 1965 was leached from the soil by December, 1965 when the first rains came Nov. 7, 1965, and continued in heavy amounts. Temperatures were cool, so plants did not grow and were unable to absorb SO_4-S from the soil. Losses of gypsum applied 3 years earlier was not as rapid or as heavy when there was better distribution of the mineral and first autumn rains came early. When temperatures remained warm after the first rains, plants grew rapidly and were able to absorb sufficient S for their needs. McKell and Williams (1960) reported that SO_4-S leached rapidly from a sandy loam soil on the San Joaquin Experimental Range in a wet year, but hardly at all in a series of dry years (Williams, McKell, and Reppert, 1964). These examples illustrate the importance of using elemental S where rainfall is heavy.

Elemental S is not available to plants, but must be oxidized to SO_4-S by soil bacteria (Starkey, 1966). The S oxidation rate in a given soil is dependent on favorable temperature, adequate moisture for metabolic activity of the bacteria, and particle size of the S (Jones and Ruckman, 1969). The larger the S particles, the slower is the transformation to SO_4-S. When environmental conditions are satisfactory, S particles less than 0.1 mm applied at the rate of 45 kg/ha supply ample SO_4-S for yields to be comparable to the same quantities of S supplied as gypsum. A mixture of S particle sizes is sometimes desirable, with the fine particles becoming available soon, and the larger particles giving the product a long-lasting effect. Elemental S mixed with triple superphosphate or with bentonite to form a prill which breaks down when wetted, has been found satisfactory from the agronomic point of view in a 100-cm rainfall region (Jones, Martin, and Ruckman, 1970).

C. Effects of S

1. FORAGE PRODUCTION

a. General crop response to S fertilization. Conrad, Hall, and Chaugule (1948) reported that applications of S to Altamont loam in the upper Ojai Valley, California, resulted in first year three-to fourfold yield increases, principally due to increases in bur clover yield. In the second year after application, yields of nonlegumes, including threshed barley and wild oat hay and other annual grassland species, were double those on unfertilized areas.

In a series of S studies at the San Joaquin Experimental Range, Bentley, Green, and Wagnon (1958) found that 45 kg S/ha applied as gypsum every third year gave nearly 60% annual increase in forage production, in the first year legumes responded. Grasses responded in the second and third year when N levels from legumes had increased. Animal numbers and steer gains also increased during the spring and summer, but not during the winter (Wagnon, Bentley, and Green, 1958).

Summarizing the results from a large number of tests, Martin (1958) and Dawson (1969) both concluded that S deficiencies are widespread in California and Oregon. This is not surprising in view of the low amount of S that comes in the rainfall each year. Dawson (1969) estimated that only 6 to 7 kg/ha were added in rainfall at two locations in Oregon. Williams, McKell, and Reppert (1964) reported an average of 2.1 kg S/ha deposited by rain at the San Joaquin Range in the 3 years from 1959 through 1961. In a 13-year period covering the rainy seasons from 1959 through 1971, there was an average of 3.57 kg S/ha per year in the rainfall at Hopland, Calif. (unpublished data).

b. Rate of S application has residual effects. Maximum forage yields are generally obtained when total S uptake by the plants is about 11 kg/ha

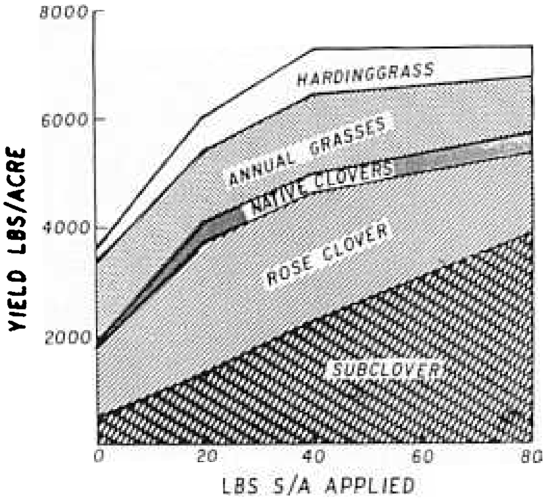

Fig. 8—Production of clover and grass harvested May 5, 1961 as affected by increasing rates of S applied in October 1958 and again in October 1960 (Jones, 1964).

(Martin and Walker, 1966). To accomplish this, about 45 kg S/ha must be applied (Jones, 1964) (Fig. 8). When elemental S is applied, such small amounts are often difficult to spread, and usually about 112 kg/ha are recommended, especially where a mixture of particle sizes can be used. Such a mixture is expected to last about 3 years. Research in Oregon (Dawson, 1969) has indicated that red hill soils retain S against leaching better than do some of the other soils. This observation has been substantiated in California (W. E. Martin, unpublished data).

2. BOTANICAL COMPOSITION, CHEMICAL COMPOSITION, AND QUALITY

The increase in growth of native clovers in the year S is applied to deficient pastures was noted above (Conrad et al., 1948; Bentley et al., 1958). The decrease in legumes and increase in grass percentages may not necessarily follow in subsequent years if adequate S for legume growth is maintained (Jones, 1964).

To be competitive, subclover apparently requires higher levels of available S than do some of the annual grass species. Figure 8 illustrates the effect of increasing applications of S on yield of several components of an annual-type pasture. Maximum yields were obtained with 45 kg S/ha, but when the rate was increased to 90 kg S/ha, subclover continued to increase where other components either decreased or remained the same. Adequate grazing pressure in the early part of the growing season is needed to maintain a stand of subclover.

3. CHEMICAL COMPOSITION AND FORAGE QUALITY

Green, Wagnon, and Bentley (1958) showed that S fertilization of annual grasslands reduced the proportion of weedy plants, increased the protein, P, and Ca in the forage and also increased steer gains during the dry season. Work by Jones, Oh, and Ruckman (1970) has indicated that protein, soluble carbohydrates, and digestibility increase with increasing levels of S where S is deficient. In a study by Rendig and Weir (1957), lambs made better gains on alfalfa which had adequate levels of S, than on S-deficient alfalfa. Thus, the evidence indicates that S fertilization increases the quality of pastures.

V. POTASSIUM

Potassium deficiencies are not widespread on the annual grasslands of California. No soil test levels for California annual grasslands have been recommended. Rossiter (1955) has suggested that 0.80% K is the critical level for subclover. In Oregon deficiencies are more frequent. Oregon recommended application of 56 to 93 kg K/ha where soil exchangeable K is 0 to 75 ppm, and 37 to 45 kg K/ha where exchangeable K is 76 to 100 ppm.

VI. MOLYBDENUM

Molybdenum deficiencies usually occur in unlimed acid soils in Oregon and California, and sometimes may be detected when application of S depresses the growth of legumes. Molybdenum can replace the need for lime on some acid soils, provided the legume is effectively nodulated. A slight excess of Mo in forage, however, can be toxic to livestock. Application of S has been shown to reduce the concentrations of Mo in subclover plants (Stout et al., 1951). Because of possible Mo toxicity to animals, the Oregon State University Extension Service recommends that Mo not be applied to fields on the west side of the Coast Range which have been limed, or to fields on the east side of the Willamette Valley when: 1. fields have been treated with Mo within 5 years; 2. the soil pH is 6 or higher; 3. the forage content of Mo exceeds 0.5 ppm on a dry matter basis; and 4. liming may bring the pH to 6.0. Work in California (Jones and Ruckman, 1973) indicates that Mo deficiencies occur in soils of about pH 6.0 if adequate levels of P and S are present. In one 6-year field study on subclover pasture, Mo plus P and S increased forage production about 1,000 kg/ha per year more than P and S alone. Even after 6 years, additional Mo was not required.

VII. LIME AND BORON

In California there are only a few soils of the annual grassland-type which are responsive to lime, and thus little lime is used. In Oregon, where higher rainfall results in more acid soils, more lime is used. In both states, however, lime-pelleted seed, on which nitrogen-fixed bacteria can be concentrated, is recommended as an aid in establishing subclover. In Oregon, it is recommended that if the pH is below 5.5, an application of 1 to 2 tons of lime should be made to help establish stands of subterranean clover. Studies (unpublished data) in California indicate that some serpentine soils of pH 6.7 respond to Ca applied as $CaSO_4$.

Boron deficiencies occur in perennial legumes, but are rare in annual clovers.

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