



Effect of nitrogen and sulfur fertilization on forages in the Gallatin Valley of Montana
by Raymond George Gavlak

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in AGRONOMY

Montana State University

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Abstract:

Sulfur (S) deficiency of forage crops is being reported in southwestern and western Montana with increasing frequency. Several factors may contribute to this problem. The utilization of relatively high analysis fertilizer materials has reduced the by-product S application formerly derived from lower analysis fertilizers. Crop removal with high yields has also contributed to increased incidence of S deficiency on some soils.

Nitrogen (N) fertilizer application to irrigated orchardgrass in 1978 inhibited growth and development while predisposing plants to secondary infection from disease organisms. This suggests other nutrition problems, including perhaps S. It was determined from a field plot experiment that S was deficient and warranted further investigation. Subsequent field experiments were undertaken in 1979 to determine optimal S level for initial and residual response and to compare soluble and insoluble S sources. Additional studies were conducted in 1980 to clarify the interaction of applied N and S fertilizers on forage yield and chemical composition.

Significant forage yield response to S was found in 1978. Plant tissue levels of total nitrogen and total sulfur in ratio form (N/S)+ successfully predicted S deficiency in orchardgrass. Maximum yields were obtained with at least 34 kg S/ha (kilograms sulfur per hectare) as gypsum with residual S apparent at rates in excess of 67 kg S/ha. Sulfur source comparisons provided data on soluble and insoluble sources. Soil tests for S cannot predict deficient situations, however, the S soil test can identify incremental applications of spring applied S. Nitrogen-sulfur interaction was apparent in forage yield and chemical composition with maximum yield occurring only when both N and S were adequately supplied.

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EFFECT OF NITROGEN AND SULFUR FERTILIZATION ON FORAGES
IN THE GALLATIN VALLEY OF MONTANA

by

RAYMOND GEORGE GAVLAK

A thesis submitted in partial fulfillment
of the requirements for the degree

of

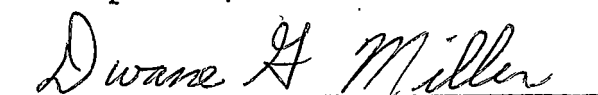
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ABSTRACT

Sulfur (S) deficiency of forage crops is being reported in southwestern and western Montana with increasing frequency. Several factors may contribute to this problem. The utilization of relatively high analysis fertilizer materials has reduced the by-product S application formerly derived from lower analysis fertilizers. Crop removal with high yields has also contributed to increased incidence of S deficiency on some soils.

Nitrogen (N) fertilizer application to irrigated orchardgrass in 1978 inhibited growth and development while predisposing plants to secondary infection from disease organisms. This suggests other nutrition problems, including perhaps S. It was determined from a field plot experiment that S was deficient and warranted further investigation. Subsequent field experiments were undertaken in 1979 to determine optimal S level for initial and residual response and to compare soluble and insoluble S sources. Additional studies were conducted in 1980 to clarify the interaction of applied N and S fertilizers on forage yield and chemical composition.

Significant forage yield response to S was found in 1978. Plant tissue levels of total nitrogen and total sulfur in ratio form (N/S)_t successfully predicted S deficiency in orchardgrass. Maximum yields were obtained with at least 34 kg S/ha (kilograms sulfur per hectare) as gypsum with residual S apparent at rates in excess of 67 kg S/ha. Sulfur source comparisons provided data on soluble and insoluble sources. Soil tests for S cannot predict deficient situations, however, the S soil test can identify incremental applications of spring applied S. Nitrogen-sulfur interaction was apparent in forage yield and chemical composition with maximum yield occurring only when both N and S were adequately supplied.

CHAPTER 1

GENERAL INTRODUCTION

Sulfur (S) deficiency of irrigated orchardgrass was identified in the Gallatin Valley, Montana by Christensen and Kresge (1978). Highly significant yield responses were obtained with the application of S as ammonium nitrate-sulfate (ANS). This thesis is the culmination of a three year study designed to investigate methods of identification and correction of S deficiencies of forage crops in the mountain valleys of southwestern Montana.

The objectives of the study were 1) to define the magnitude of the S deficiency in forages and attempt to determine the level of S required by the crop to provide optimum yield; 2) to determine what commercially available S sources would correct the deficiency the year of application and what residual effect these sources had on yield and chemical composition; 3) to assemble a data base of plant tissue chemical analyses to assist in the development of a diagnostic tool for the identification of S deficient forage; 4) to assess the effects of spring applied S fertilizer on post-harvest soil sulfate-S levels.

A multi-phase approach was utilized to address the problems. Chapter 1 summarizes the initial work on irrigated orchardgrass (1978) and includes data designed to

check the residual effect of S fertilization with a single source. Chapter 2 describes experiments conducted on high elevation nonirrigated hayland designed to compare the initial and residual effects of several S sources on total forage yield and chemical composition. Chapter 3 deals with the interaction effects of nitrogen (N) and S fertilization on yield and plant tissue N and S concentrations through the growing season. Summarized data from this chapter describe the integration of a combination of plant tissue tests that successfully predict the need for S fertilization when optimum N requirements are met. Chapter 4 describes methods used to quantify the post-harvest soluble S fraction in the soil as a result of S applied in the spring.

Data generated in this study are presented in Appendix I. Forage yield, total N, total S, and N to S ratios $(N/S)_t$ are calculated for all sites. Results of further tissue chemical analyses conducted on selected treatments are presented.

Soil profile descriptions for the experimental sites are shown in Appendix II. Procedures used in the analysis of plant tissue and selected soil analysis procedures are presented in Appendix III. Appendix IV provides data on

growing season precipitation for 1979 and 1980.

CHAPTER 2

LITERATURE REVIEW

The increased utilization of high analysis, by-product-free fertilizer materials and sub-optimal S mineralization characteristics of many soils have helped cause S deficient soil-plant systems on many continents of the world.

Sulfur fertilization of alfalfa (Medicago sativa L.) has become necessary in many areas to maximize yields. Long term field experiments were conducted with alfalfa in Queensland, Australia. Dickson and Asher (1974) found that various S carriers equally maintained stand vigor, reduced weed populations and increased both the N and S content of the forage.

The yield response of alfalfa to S fertilizer was checked in a pot experiment (Martel and Zizka, 1977) with two types of soil, a sandy-loam and silty-clay. Dry matter yields were significantly increased in both soils by the application of S with the greatest response in the silty-clay soil.

Cairns and Carson (1961) found that S treatments effectively increased alfalfa yields on S deficient soils. Gypsum was more available than elemental S in the year of application. Similar responses were observed in

Merced County, California (Rendig, 1956) where gypsum treatments yielded more than double the unfertilized check plots at all five cuttings. Seim et al. (1968) showed that alfalfa in Minnesota, when fertilized with gypsum, outyielded unfertilized alfalfa every year of the study. Yields in the gypsum fertilized plots were three times that of the check plots in the third year of the experiment.

Workers in various geographic locations have attempted to establish methods to detect S deficiency in alfalfa. Simple soil analysis results are not consistent, therefore, a trend toward tissue analysis resulted.

Plant tissue contains nutrients at a consistent level in a given plant part, at a particular stage of maturity. Plant growth should not be inhibited when the concentration of an essential element exceeds a critical range (Westermann, 1975). The critical nutrient level of alfalfa was investigated by many scientists. Bear and Wallace (1950), McNaught et al. (1961), Andrew (1977) and Graham (1973) suggest that the critical level of S in mature alfalfa should be 0.20%. A greenhouse experiment conducted by Harward et al. (1962) proposed a 0.22% critical level for alfalfa in the early bloom stage of growth. Later field work in Oregon by Pumphrey and Moore (1965b)

confirmed the findings of Harward et al. Significant yield increases were measured only in field experiments where the alfalfa plant tissue S content was initially less than 0.22%.

The critical nutrient level may be utilized as a diagnostic tool for deficiency identification when the stage of growth and plant part sampled are well defined. The $(N/S)_t$ ratio, or the ratio of total N to total S in the herbage, was proposed by Dijkshoorn et al. (1960) as a method for diagnosing S deficiency. The stage of maturity of alfalfa seems to have more influence on the total S content than on the $(N/S)_t$ ratio of alfalfa (Pumphrey and Moore, 1965a). Ratios of N to S reflect the S status of the plant. Sulfur is adequately supplied to alfalfa when the $(N/S)_t$ ratio is 11:1 (Pumphrey and Moore, 1965b; Aulakh et al., 1976).

Sulfur deficiency of grasses and the grass-legume mixture has received considerable attention in recent years. As with alfalfa, response to S fertilization is a global occurrence. Workers have investigated not only responsive locations but also rates and sources of S fertilizer applied. Baker et al. (1973) observed drastic $(N/S)_t$ ratio reduction in irrigated orchardgrass (Dactylis glomerata L.)

with increasing levels of S fertilizer. Gypsum, potassium sulfate, and ammonium sulfate provided more rapid response than did elemental S. The relatively reduced solubility of elemental S however, resulted in greater residual effect. Experiments conducted on dryland pasture in California (Jones, 1964) showed significant yield response to applications of 22, 45 and 90 kg S/ha as gypsum when harvested in May. Residual S response was only apparent in the 45 and 90 kg S/ha rates. Jones et al. (1970) compared 45 Kg S/ha levels of an elemental S-bentonite mixture with elemental S and gypsum treatments on grassland pasture. Elemental S with bentonite was less effective the year of application than gypsum or elemental S alone. Residual yield response showed that the soluble gypsum produced significantly less forage than elemental S or the elemental S-bentonite complex.

Workers in New Zealand compared yield response of a grass-clover mixture to various levels of S provided by elemental S, potassium sulfate, and gypsum (Adams, 1973). The clover portion of the stand responded to gypsum the year of application with clover yields significantly higher than yields with potassium sulfate or elemental S at the 22 kg S/ha rate. The response of clover to gypsum was only

detectable in the year of application at the 22 kg S/ha with no additional response above 22 kg S/ha. No significant differences were noted between sources at the 88 kg/ha level. This suggests that elemental S at the higher rate provided a sufficient quantity of available S to the stand as did the lower level of gypsum.

McLachlan and DeMarco (1971) applied gypsum to a grass-clover pasture at four levels: 8, 17, 34, and 50 kg S/ha in each of four years. The pasture responded to S in all years of application if at least 34 kg of S was applied. The residual value of the first year application in the second year was greater than the response from similar levels of S applied the second year, excluding the 8 Kg S/ha rate. By the fourth year of the study the residual response from applications the first year had decreased to similar levels which were not significantly different from the control.

McLachlan and Demarco (1973) continued to study the effects of S on similar pastures in New South Wales by applying four initial levels of S and four maintenance levels each of the succeeding years. They found that maximum dry matter production and optimum fertilizer efficiency was accomplished at the 34 kg S/ha initial rate with

subsequent 8 kg S/ha levels as annual dressings. The residual value of the initial S application was enhanced by relatively low maintenance levels applied the following years. McLachlan (1975) suggested the utilization of soluble S sources to provide for early crop growth with applications of less soluble sources for residual availability.

Several experiments in New Zealand were designed to assess the effect of S fertilization on the yield and chemical composition of mixed-species grazed and ungrazed swards. Walker et al. (1956) found that the grass portion of an ungrazed mixed-species sward received supplemental N from underground transference from the S fertilized clover. The yield response to S of the entire plant population was three times that of the control. Metson (1978) reported a higher total S content in grasses than in clovers in a mixed-species pasture. This occurrence was attributed to the increased tendency of grasses to absorb non-protein S.

The interaction of plant N and S resulting from N and S fertilization has been addressed by several workers. Goh and Kee (1978) noted that increasing rates of applied N increased the total N content of perennial ryegrass (Lolium perenne L.) dry matter in all S treatments. Similarly, the

total S concentration of the dry matter was significantly increased with additional S at all N levels. The maximum total S content was found in the N_0S_3 treatment due to the accumulated S in the N deficient grass. Nitrogen to S ratios were consistently higher in treatments with N but lacking S. With applied S, the $(N/S)_t$ ratios were significantly reduced. Tahtinen (1977) found that timothy (Phleum pratense L.) in S deficient soils of Finland exhibited S contents under 0.13%. In S deficient soils, S application reduced the $(N/S)_t$ ratio. With sufficient S the $(N/S)_t$ ratio remained under 14, which is consistent with critical $(N/S)_t$ ratio values of other plants in the Graminaceae family (Metson, 1973).

A followup study was conducted (Tahtinen, 1978) to determine the effect of S deficiency and S fertilization on the compounds in timothy. Nitrogen fertilization had little effect on the protein-N content of plants deficient in S. Sulfur fertilization increased protein-N content by 26%. Fertilizer S applications decreased the concentrations of amino-, ammonium-, and nitrate-N in the plant suggesting that these soluble forms were incorporated into protein-N. Significant increases in hay yields were attained with S fertilizer in a study conducted in Iceland

(Helgadottir, 1977). The critical S level of the grasses was 0.095% with an $(N/S)_t$ ratio of 16 estimated as the upper limit of optimum yield.

Sulfur requirements of various crops have been reviewed by Saalbach (1970), Metson (1973), and Martin and Walker (1965). Saalbach (1970) showed that grasses were adequately supplied with S when the $(N/S)_t$ ratio was 14.5. A controlled environment pot experiment conducted by Bolton et al. (1976) at the Rothamsted Experiment Station indicated that increased yields of perennial ryegrass due to S fertilization occurred when the grass S content was less than 0.20%. Maximum yields were associated with $(N/S)_t$ ratios of approximately 10. Lancaster et al. (1971) significantly increased total S in five forage species grown in pots with incremental increases in S. Dramatic reductions of $(N/S)_t$ ratios were apparent with all species. Ratios of total N to total S, $(N/S)_t$, were reduced from 32 with no S applied to 10 with an 11 ppm S treatment. O'Connor and Vartha (1968) completed studies which indicated that orchardgrass response to S fertilizer was partially dependent on the level of N uptake. Therefore, in S deficient situations, applications of N fertilizer without additional S would widen the $(N/S)_t$ ratio (McLaren,

1976). Similarly, with the potential of the soil organic matter to mineralize a constant amount of S, heavy additions of N fertilizer would cause an imbalance of N and S in the plant, impeding protein formation (Stewart, 1966).

CHAPTER 3

EFFECTS OF SULFUR FERTILIZER LEVELS ON THE INITIAL AND RESIDUAL RESPONSE OF FORAGE: YIELD AND CHEMICAL COMPOSITION.

INTRODUCTION

The increased utilization of high analysis fertilizer materials low in S or lacking S combined with the limited S mineralization potential of many soil-organic matter complexes has created areas deficient in adequate S for optimal crop production. Locations found to be S deficient are not limited to specific soil types or geographic regions, as S responses have been reported on several continents (Martin and Walker, 1966; Helgadottir, 1977; McLachlan and Demarco, 1973).

The identification of potential S deficient soils is difficult due to poor correlations of soil $\text{SO}_4\text{-S}$ concentrations with crop response, therefore, a trend toward plant tissue analysis resulted. Several analytical criteria have been presented to assess the S status of plants (Metson, 1973): total S (S_t), sulfate-S ($\text{SO}_4\text{-S}$), and the total N to total S ratio $(\text{N/S})_t$ which is the result of earlier work (Dijkshoorn et al. 1960) based on the proportional S and N content of vegetable protein.

Researchers have utilized the $(\text{N/S})_t$ ratio as an indicator of crop S status. Generally, data have been

generated to provide a range in which crops can be identified as S sufficient or S deficient. Pumphrey and Moore, (1965b) in Oregon and Aulakh and Dev, (1976) in India found that alfalfa was adequately supplied with S when the $(N/S)_t$ ratio was 11. Critical $(N/S)_t$ ratios have been established for legumes and grasses and are summarized by Metson (1973) and Saalback (1970).

Yield responses of forage crops have been demonstrated by many workers (Jones, 1964; McLachlan and Demarco, 1971; Helgadottir, 1977) with a variety of S sources and S levels. In general, applications of S result in increased yields and reductions of $(N/S)_t$ ratios. The residual effect of first year S applications generally appear at the maximum levels of applied S.

This study was conducted to evaluate the effect of different S levels on the initial and residual forage yield response and chemical composition.

MATERIALS AND METHODS

Three experimental areas were selected to evaluate the effects of S fertilizer levels on $(N/S)_t$ ratios and total forage yield. These sites were maintained one additional growing season to identify any residual fertility response. The study areas included an irrigated orchardgrass (Dactylis glomerata L.), hay stand 6 km southwest of Bozeman, Montana (Dr. Jim Boyd) and two dryland fields, predominately orchardgrass, timothy (Phleum pratense L.) and brome grasses (Bromus sp.) located approximately 1 km southeast of Bozeman (Myers 1W and 2E). Soils of the Bridger series (fine, mixed Argic Cryoborolls) dominate these locations.

Fertilizer treatments were topdressed to a 335 m² area (Boyd) in a randomized, complete block design with three replications on 9 June 1978 (Table 1). Plant tissue samples (leaves only) were collected from each test plot on 26 June, 25 July, and 1 August, 1978. A 0.915 m by 5.33 m area of each plot was harvested using Jari mowers 1 August, 1978. Fertilizer sources included ammonium nitrate (34-0-0), urea (46-0-0), and ammonium nitrate-sulfate (30-0-0-6.5) at the Boyd location.

The experiment (Boyd site) was reestablished in the spring of 1979. Test plots went untreated in 1979 to

Table 1. Treatments applied to irrigated orchardgrass
(Boyd site) June, 1978

Treatment No.	Fertilizer Rate kg/ha				Source
	N	P ₂ O ₅	K ₂ O	S	
1	0	0	0	0	--
2	168	0	0	0	Urea
3	168	0	0	0	AN
4	168	112	0	0	AN
5	168	112	56	0	AN
6	168	112	56	37	ANS

clarify residual effects of fertilizer treatments applied in 1978. Soil samples were collected from each plot in June, 1979. Plant tissue sampling (leaves only) occurred 14 June, 17 July, and 26 July, 1979. Plots were harvested 26 July, 1979, with a Rem forage plot harvester.

Two 128 m by 100 m experiments were established on nonirrigated mixed species hayland (Myers 1W and 2E) in a randomized complete block design having three replications on 22 May, 1979, (Table 2). Soils in the rolling upland area are fine, mixed Argic Cryoborolls. All fertilizer treatments were topdressed 22 May except the S portion of

treatment 11 which was applied 5 June. Soil samples were collected before fertilizer application. In the analyses reported in Table 3, pH was determined with a glass electrode (soil/water ratio of 1:2); organic matter colorimetrically (Sims and Haby, 1970); K from ammonium acetate extraction (Bower et al., 1952); P by the acid fluoride method of Smith et al. (1957); acetate-soluble S by Bardsley and Lancaster (1965). Plant tissue samples (leaves only) were taken through the growing season; 13 June, 29 June, 17 July, and 25 July, 1979. A 0.609 m by 6.75 m area of each plot was harvested 25 July, 1979, with a Rem forage plot harvester.

To quantify residual effects of both N and S fertilizers on forage yield and $(N/S)_t$ ratios, background fertilizer rates of 67 kg N/ha as urea and 45 kg P_2O_5 /ha (diammonium phosphate) were applied 2 May, 1980, to both experiments at the Myers locations (1W and 2E). Soil sampling of all plots occurred 29 April, 1980. Plant tissue samples (leaves only) were collected on 6 June and 8 July at the 1W site and 13 June and 8 July, 1980, at the 2E site. Test plots were harvested using a Rem forage plot harvester 8 July for the 1W site and 11 July, 1980, at the 2E site.

Table 2. Treatments applied to nonirrigated hayland
(Myers 1W and 2E sites) May, 1979.

Treatment ^{1/} No.	Fertilizer Rate kg/ha				Sulfur Source
	N	P ₂ O ₅	K ₂ O	S	
1	0	0	0	0	--
2	168	0	0	0	--
3	168	112	0	0	--
4	168	112	56	0	--
5	168	112	56	34	Gypsum
6	168	112	56	67	Gypsum
7	168	112	56	101	Gypsum
8	168	112	56	34	ANS
9	168	112	56	34	APS
10	168	112	56	34	Amm.Thio.
11	168	112	97	0	--
12	168	112	97	34	Pot.Sulf.
13	168	0	0	0	--
14	168	112	56	0	--
15	168	112	56	100	Gypsum
16	168	112	56	100	SCU

^{1/} Treatments 1-12, N as Ammonium Nitrate (34-0-0);
treatments 13-16, N as Urea (46-0-0).

Table 3. Soil analysis at Myers 1W and 2E sites, May, 1979.

Site Sampled	Depth cm	Texture	pH	OM %	P -----	K ppm	SO ₄ -S -----
1W	15	Cl	6.2	5.8	44	303	9.4
2E	15	Sil	6.0	6.0	51	265	10.3

Plant material harvested from each plot for the three experiments was weighed in the field. A subsample was weighed, dried at 65 degrees C for 72 hours, and reweighed for moisture content determination. Plant tissue samples were ground in a Wiley mill to pass a 40 mesh screen and stored in manila coin envelopes pending chemical analyses.

Plant tissue analyses were conducted on all treatments at each sampling date. Dried, ground tissue was analyzed for total N and total S (Appendix III). The total S procedure for plant material was developed by Dr. D. T. Westermann, USDA, ARS, Snake River Conservation Research Center, Kimberly, Idaho, and is described in its entirety in Appendix III.

A nitric-perchloric acid digest (Appendix III) was used to prepare selected plant tissue samples for further analyses. Calcium, Mg, K, Zn, and Mn levels were

determined using flame atomic absorption spectrophotometry. Phosphorus analysis (Appendix III) was accomplished colorimetrically from aliquots of the nitric-perchloric acid digest.

Two-factor analysis of variance and least significant difference (LSD) values were calculated for all experiments for comparison of treatments.

RESULTS AND DISCUSSION

The experiment at the Boyd site was established on irrigated orchardgrass which received 110 kg N/ha earlier in the spring (Christensen and Kresge, 1978). Significant yield response was apparent only in the treatment receiving 37 kg S/ha (Table 4). Treatments 2 and 3 received 168 kg N/ha as ammonium nitrate and urea resulting in a substantial yield reduction.

Table 4. Response of irrigated orchardgrass to N and S fertilization, August, 1978.

Treatment No.	Yield ^{1/} kg/ha	(N/S) _t Ratio
1	2345	34
2	1744	53
3	1360	53
4	3489	47
5	3252	53
6	5499	11
LSD _{0.01}	1300	12.96

^{1/} Forage at 0.0% moisture.

With the application of N alone, the ratio of non-S-containing amino acids to S-containing amino acids becomes extremely wide. The ratio of these amino acids in protein of adequately fertilized grass is approximately 14:1. When excess N is applied in the absence of adequate S the plant accumulates amide N, nitrate and other nitrogenous compounds. Protein synthesis (plant growth) is inhibited by the lack of S containing amino acids, thereby reducing yield and widening the $(N/S)_t$ ratio. The addition of N alone reduced yield in treatments 2 and 3 and forced the $(N/S)_t$ ratios to 53. Phosphorus and K application did not change the $(N/S)_t$ ratio but did result in greater yields than the control and N treatments. Sulfur applied at 37 kg S/ha significantly increased yield and reduced the $(N/S)_t$ ratio to 11 which is within the normal range of 11 - 14 proposed by others (Metson, 1973, Tahtinen, 1977).

The Boyd site was maintained through 1979, without further fertilizer addition, to determine what residual effect the 37 kg S/ha treatment would have on second year yield and chemical composition. Results displayed in Table 5 indicate that there was residual S available the second year of the study. Orchardgrass yields were

drastically lower than in 1978 (no additional fertilizer), however, significant yield response to residual S was apparent in 1979. The $(N/S)_t$ ratio of the S treatment was not significantly different from treatments 1 and 3.

Table 5. Residual response of irrigated orchardgrass to N and S fertilization, July, 1979.

Treatment No.	Yield ^{1/}	$(N/S)_t$ Ratio
1	977	20
2	633	25
3	916	21
4	685	31
5	700	25
6	2080	15
LSD _{0.05}	666	7.78

^{1/} Forage at 0.0% moisture.

Nitrogen to S ratios of treatments 2, 4, and 5 were significantly greater than treatment 6 which indicates that the crop did benefit from residual S. The effect of residual S on forage yield in 1979 was significant.

However, the forage yield produced was less than half of that produced in the year of S application.

Having demonstrated the need for S fertility and the effect of S on crop yield and composition, two studies were established in 1979 to assess the potential residual effectiveness of gypsum at three S levels. A portion of the treatment set (Table 6) shows yield response to N at both Myers 1W and 2E locations. Significant response to S as gypsum was detected only with the S₂ (67 kg S/ha) level at the 2E site.

Table 6. Response of nonirrigated grass hay to N and S fertilization, July, 1979.

Treatment ^{1/} (and no.)	Yield ^{2/} kg/ha		(N/S) _t Ratio	
	1W	2E	1W	2E
(1) Check	213	315	16	16
(4) NPK	2671	2369	30	25
(5) S ₁	3026	2630	12	13
(6) S ₂	3131	3202	13	10
(7) S ₃	3000	2760	10	10
LSD _{0.05}	601	637	6.86	13.58

^{1/} Refer to Table 2 for complete fertilizer rates.

^{2/} Forage at 0.0% moisture.

The tendency for yield to increase with S application was apparent. Ratios of total N to total S in the plant were widened from 16 in the check to 30 and 25 with the addition of N, P and K fertilizer. The addition of S at all levels reduced the $(N/S)_t$ ratio to the normal range for grasses (11-14).

The residual effect of the treatment set applied at Myers 1W and 2E sites in 1979 can be seen in the selected results of the 1980 harvest data (Table 7). The S_2 and S_3 levels of gypsum at the 1W site significantly increased hay yields the year following application, while the S_1 rate (34 kg S/ha) did not provide enough carryover S for similar yields. The 2E location also showed significant yield response to residual S fertilizer but did so at the S_1 and S_3 levels. The residual response at the 2E site to the S_1 level in 1980 could be a function of the amount of S mineralized in 1980. Less of the available S may have been utilized in 1979 because of low rainfall condition (Appendix IV) thereby leaving it for crop use in 1980. The $(N/S)_t$ ratios reflected the yield response to S by falling into the 11-14 range with the maximum S levels at both locations.

Table 7. Residual response of nonirrigated grass hay to N and S fertilization, July, 1980.

Treatment ^{1/} (and no.)	Yield ^{2/} kg/ha		(N/S) _t Ratio	
	1W	2E	1W	2E
(1) Check	110	333	10	19
(4) NPK	1590	1916	30	31
(5) S ₁	2092	3131	16	16
(6) S ₂	2346	2794	15	15
(7) S ₃	3018	3194	13	13
LSD _{0.05}	747	889	5.33	5.51

^{1/} Refer to Table 2 for complete fertilizer rates.

^{2/} Forage at 0.0% moisture.

CHAPTER 4

INTERACTION EFFECTS OF NITROGEN AND SULFUR FERTILITY ON YIELD AND CHEMICAL COMPOSITION OF DRYLAND FORAGE.

INTRODUCTION

Diagnosis of S deficiency is difficult due to poor correlation of soil sulfate-S ($\text{SO}_4\text{-S}$) concentration with crop response. The lack of a soil test capable of identifying S deficient soils has led to the use of plant tissue analysis as an indicator of the system's S status. Due to the dynamic nature of nutrient concentrations in plant tissue as a function of anatomical position or stage of maturity, the use of tissue analysis must be standardized to a specific plant part at a specific growth stage (Westermann, 1975). By measuring the level of total N and total S in tissue, workers have been able to identify plant S status with the ratio of the two elements (Metson, 1973). With the absence of a soil test to accurately predict S deficiency, western Montana forage producers are not able to identify potential S deficient production areas.

Yield responses of forage crops to S fertilizers has been documented over the years in many geographical locations (Jones, 1964; Walker et al., 1956; Rendig, 1956; Seim et al., 1968). In general, the application of S fertilizer

to forages resulted in yield increases and reduced (N/S)_t ratios.

Recent investigations have identified S deficient soil/plant systems in southwestern Montana. Results of work by Christensen and Kresge (1978) showed that additions of N increased S deficiency on irrigated orchardgrass. Orchardgrass plants appeared stunted and pale yellow which is indicative of S deficiency. The application of 37 kg S/ha as ammonium nitrate-sulfate corrected the crop's S deficiency. Visual symptoms of S deficiency were apparent only in the treatments not receiving S. The S treated plots maintained a healthy, green orchardgrass stand which eventually produced yields in excess of 5,000 kg/ha. A later study (Kresge and Gavlak, 1980) found that S deficiency on nonirrigated hayland could be corrected with the application of S. Approximately 34 kg S/ha as gypsum was necessary to alleviate the deficiency when the N fertility level was optimized.

This study was initiated to establish a method or procedure to assist southwestern Montana forage producers with the identification and correction of potential S deficient crop production acreage. A further objective was to define the agronomic effectiveness of varying N and S

levels on forage yield and chemical composition.

MATERIALS AND METHODS

Three nonirrigated locations approximately 1 km apart, 15 km southeast of Bozeman, Montana were selected for experiments designed to investigate the agronomic effectiveness of varying levels of N and S fertilizer on (N/S)_t ratios and total forage yield. The predominant species were orchardgrass (Dactylis glomerata L.), timothy (Phleum pratense L.) and brome-grasses (Bromus sp.) at the 3W and 4E locations. The 5E site maintained an established mixed species stand of sainfoin (Onobrychis viciifolia Scop.) and orchardgrass. Soils at these locations are fine, mixed Argic Cryoborolls lying approximately 1525 meters above sea level (Appendix II).

Similar randomized, complete block designs were established at each site. Treatments, shown in Table 8, were applied to 2.5 m by 7 m plots. Experiments 3W and 5E contained four replications and the 4E site had three replications. The treatment set consisted of three levels of N (20, 80 and 140 kg/ha) as urea phosphate (TVA 17-44-0) and four levels of S (0, 20, 40 and 60 kg/ha) as gypsum in all combinations. A constant background rate of 52 kg P₂O₅/ha from urea phosphate and 30 kg K₂O/ha as KCl.

Table 8. Treatments applied to nonirrigated hayland
(Myers 3W, 4E, and 5E sites) May, 1980.

Treatment ^{1/} No.	Fertilizer Rate kg/ha	
	N	S
1	20	0
2	20	20
3	20	40
4	20	60
5	80	0
6	80	20
7	80	40
8	80	60
9	140	0
10	140	20
11	140	40
12	140	60

^{1/} N source 17-44-0, S source Gypsum.

Prefertilizer soil samples were collected by replication from each site followed by fertilizer topdressing between 2 May and 6 May 1980. Soil sample analyses included pH by glass electrode (soil/water ratio

of 1:2); organic matter colorimetrically (Sims and Haby, 1970); K from ammonium acetate extraction (Bower et al., 1952) P by the acid fluoride method of Smith et al., (1957); and acetate-soluble S by the procedure of Bardsley and Lancaster (1965).

Plant tissue samples (leaves only) were collected from all plots at the three sites during the growing season. A 0.609 m by 6.75 m area of each plot was harvested between 11 July and 15 July with a Rem forage plot harvester.

Plant material harvested from each plot for the three experiments was weighed in the field. A subsample was weighed, dried at 65 degrees C for 72 hours, and reweighed for moisture content determination. Plant tissue samples were ground in a Wiley mill to pass a 40 mesh screen and stored in manila envelopes pending chemical analyses.

Plant tissue analyses were accomplished on all treatments at each sampling date. Dried, ground plant tissue was analyzed for total N and total S (Appendix III). The total S procedure for plant material was provided by Dr. D. T. Westermann, USDA, ARS, Snake River Conservation Research Center, Kimberly, Idaho, and is described in its entirety in Appendix III.

A nitric-perchloric acid digest (Appendix III) was

used to prepare selected plant tissue samples for further analyses. Calcium, Mg, K, Zn, and Mn levels were determined using flame atomic absorption spectrophotometry. Phosphorus analysis (Appendix III) was accomplished colorimetrically from aliquots of the nitric-perchloric acid digest.

Two-factor analysis of variance, and least significant difference (LSD) values were calculated for all experiments for comparison of treatments.

RESULTS AND DISCUSSION

Forage yield responses to applied N and S are illustrated for the three sites in Figures 1-3. The figures represent data listed in Appendix I. Analysis of variance indicates significant yield response to both N and S when applied in the proper proportion (Table 12).

Yield of forage was significantly increased at the Myers 3W site (Figure 1) by application of 140 kg N/ha. Little change in yield was detected with S application when only 20 kg N/ha was applied. Greater yield differences between S levels were seen at the 80 kg N/ha level suggesting that N was limiting the potential yield response of applied S. It appears that the crop was N deficient at the 80 kg N/ha level when S was increased to 60 kg/ha at both the Myers 3W and 4E locations (Figures 1 and 2) by the distinct depression seen in the response surfaces. This yield depression was eliminated with adequate N at the 140 kg/ha level. Yield response to incremental application of S at the maximum N rate was significant at locations 3W and 4E (Figures 1 and 2).

The N to S ratios consistently reflected the S status of the forage at harvest. Additions of N without S nearly doubled the $(N/S)_t$ ratio from 14 with 20 kg N/ha to 27 with the 140 kg N/ha level at the Myers 3W location (Figure 4).

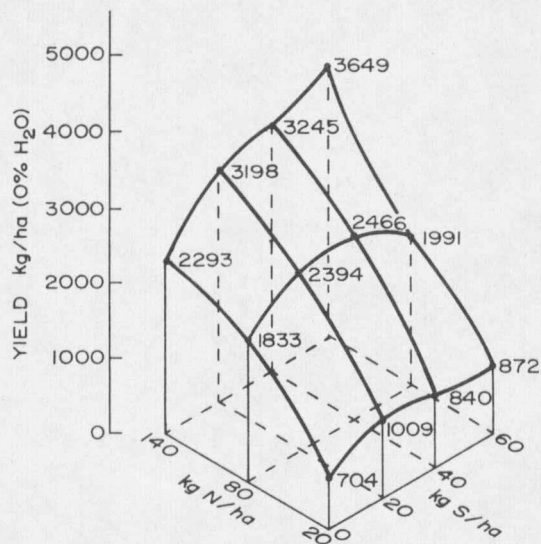


Figure 1. Crop response to applied N and S fertilization at the Myers 3W location, 1980.

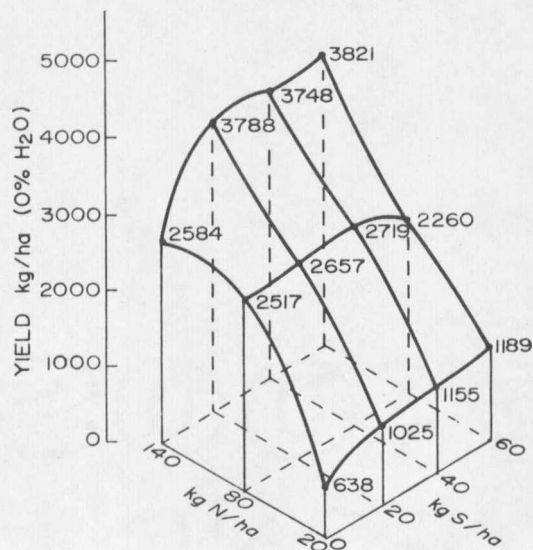


Figure 2. Crop response to applied N and S fertilization at the Myers 4E location, 1980.

There is little doubt that the plant tissue was severely S deficient. The exaggerated $(N/S)_t$ ratios accurately depicted the accumulation of nitrogenous compounds in the tissue. A similar but less severe situation was apparent at the Myers 4E and 5E sites (Figures 5 and 6). The addition of 20 kg S/ha sharply reduced the $(N/S)_t$ ratios at all N levels at the Myers 3W and 4E locations (Figures 4 and 5) bringing the $(N/S)_t$ ratios within the acceptable range of 11-14 for grasses.

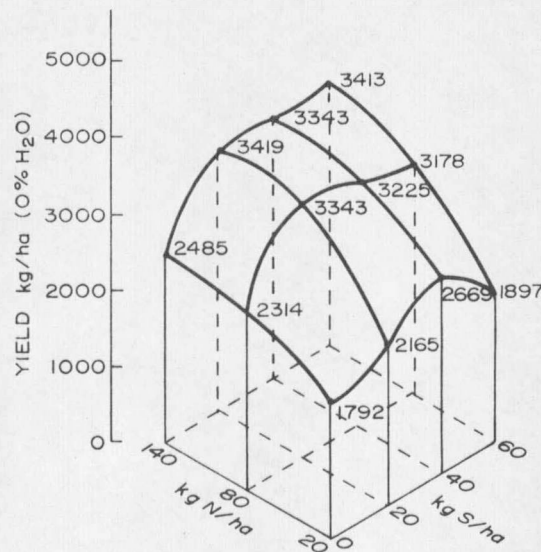


Figure 3. Crop response to applied N and S fertilization at the Myers 5E location, 1980.

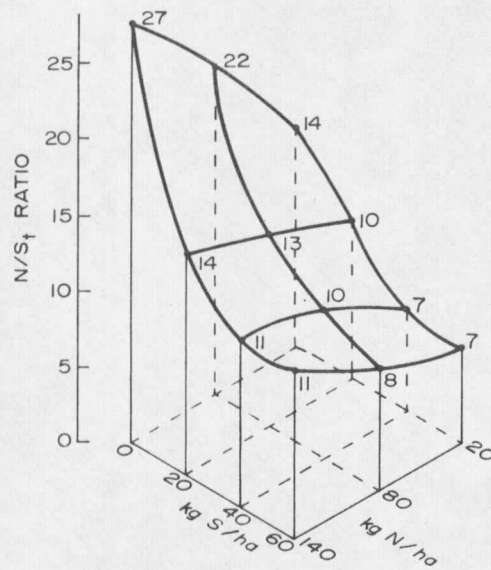


Figure 4. Forage $(N/S)_t$ ratios in response to N and S fertilization at the Myers 3W location, 1980.

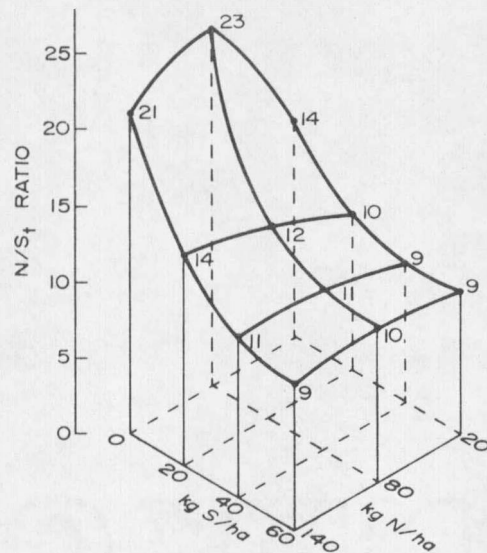


Figure 5. Forage $(N/S)_t$ ratios in response to N and S fertilization at the Myers 4E location, 1980.

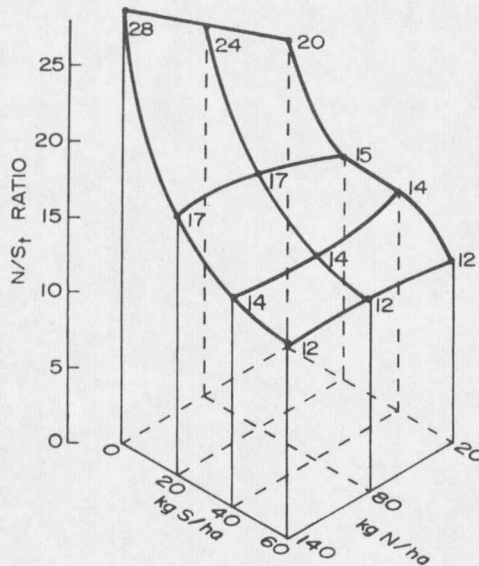


Figure 6. Forage $(N/S)_t$ ratios in response to N and S fertilization at the Myers 5E location, 1980.

Forage yield (Figure 3) and $(N/S)_t$ ratios (Figure 6) of the sainfoin-grass location (Myers 5E) followed the pattern presented by the data from the Myers 3W and 4E sites except that $(N/S)_t$ ratios were reduced less with the first 20 kg S/ha. Nitrogen to sulfur ratios of sainfoin may be balanced at $(N/S)_t$ ratio values in excess of those for grasses (11-14) so that the sainfoin component of the harvest sample mixture kept the $(N/S)_t$ ratios above the level of adequately S supplied grass. Data in Table 9 shows the individual species $(N/S)_t$ ratios at harvest. There is a dramatic difference in $(N/S)_t$ ratios between the grass and sainfoin at all levels of N and S.

Multiple linear regression analysis (Tables 10 and 11) indicates the predictability of yield and $(N/S)_t$ ratio from the components listed. Highly significant values of r suggest that the yield response and relative $(N/S)_t$ ratios are a function of the levels of applied N and S as noted by the contribution of the interaction components.

Table 9. Sainfoin and grass $(N/S)_t$ ratios at harvest from the Myers 5E location, July, 1980.

Treatment	Sainfoin	Grass
1	28	13
2	25	8
3	24	7
4	24	6
5	26	20
6	28	13
7	24	10
8	20	8
9	30	26
10	25	14
11	24	10
12	22	10

Table 10. Multiple linear regression coefficients, value of F and r for yield at varying levels of applied N and S, Myers 3W, 4E, and 5E locations.

b ₀	b ₁ (N) ^{1/}	b ₂ (S)	b ₃ (N ²)	b ₄ (S ²)	b ₅ (N×S)	F	r
<u>MYERS 3W 1980</u>							
547.83	18.66					70.93	.876**
298.03	18.66	8.32				47.08	.912**
676.03	13.94	-4.27			0.157	44.92	.943**
81.64	27.32	8.32	-0.054			31.34	.921**
-69.19	27.32	30.95	-0.054	-0.377		30.33	.945**
308.80	22.59	18.35	-0.054	-0.377	0.157	50.18	.976**
<u>MYERS 4E 1980</u>							
686.08	20.69					75.52	.883**
637.63	18.33	1.61			0.078	29.19	.916**
448.83	20.69	7.90				45.46	.909**
121.33	33.79	7.90	-0.081			33.62	.926**
-52.24	33.79	33.94	-0.081	-0.433		35.01	.952**
136.55	31.43	27.65	-0.081	-0.433	0.078	27.91	.958**
<u>MYERS 5E 1980</u>							
2080.75	8.61					10.14	.503
1969.60	6.25	3.70			0.078	5.31	.665
1780.70	8.61	10.00				8.16	.644
1372.78	24.93	10.00	-0.101			7.18	.729
1115.70	24.93	48.56	-0.101	-0.642		19.09	.916**
1304.66	22.57	42.26	-0.101	-0.642	0.078	17.85	.937**

^{1/} kg/ha

*, ** Significant at the 0.05 and 0.01 levels, respectively.

Table 11. Multiple linear regression coefficients, values of F and r for $(N/S)_t$ ratios at varying levels of applied N and S, Myers 3W, 4E, and 5E locations.

b_0	b_1	b_2	b_3	b_4	b_5	F	r
	(N) ^{1/}	(S)	(N ²)	(S ²)	(N×S)		
<u>MYERS 3W 1980</u>							
8.08	0.056					2.86	.222
11.83	0.085	-0.125			-9.58	15.34	.851*
14.13	0.056	-0.201				20.44	.819**
13.43	0.084	-0.201	-0.0001			12.32	.822*
15.35	0.084	-0.489	-1.73	4.79		23.22	.929**
888.25	-48.50	16.06	0.34	-0.57	0.45	9.34	.886*
<u>MYERS 4E 1980</u>							
10.58	0.025					0.779	.072
15.43	0.025	-0.161				10.61	.702*
13.03	0.055	-0.081			-0.001	8.45	.760
13.48	0.102	-0.161	-0.0004			7.40	.735*
15.23	0.102	-0.424	-0.0004	0.004		13.17	.882*
12.83	0.132	-0.344	-0.0004	0.004	-0.001	19.00	.940**
<u>MYERS 5E 1980</u>							
14.58	0.020					0.437	.419
20.33	0.020	-0.191				16.04	.780*
17.53	0.055	-0.098			-0.001	14.72	.846*
20.33	0.020	-0.191	0			9.50	.780
22.08	0.020	-0.454	0	0.004		16.51	.904**
19.28	0.055	-0.360	0	0.004	-0.001	38.64	.969**

^{1/} kg/ha

*, ** Significant at the 0.05 and 0.01 levels, respectively.

Table 12. Results of analysis of variance on yield and (N/S)_t ratios from Myers 3W, 4E, and 5E locations, (harvest) 1980.

	F _T	F _B	LSD _{0.05}	LSD _{0.01}
YIELD _I /				
3W	32.57**	3.20*	513.2	690.2
4E	16.10**	2.02	822.1	1120.0
5E	6.29**	2.72	715.0	956.8
(N/S) _t				
3W	82.54**	2.69	1.94	2.61
4E	7.81**	0.48	4.93	6.72
5E	18.46**	0.11	3.46	4.65

_I/ kg/ha at 0.0% moisture.

*, ** Significant at the 0.05 and 0.01 levels, respectively.

Plant tissue samples were collected by plot during the growing season. Laboratory analyses were conducted on the samples to check the levels of major chemical constituents during crop maturation. This was accomplished to determine the effect stage of maturity and added N and S fertility had on the concentrations of N and S in the tissue.

The tissue analyses detected the effect of optimum N

fertilization without adequate S. Levels of N in the tissue without added S (Figure 7a) were significantly higher than treatments receiving S on the 6 June ($LSD_{0.05} 0.388$) and 3 July ($LSD_{0.05} 0.353$) sampling dates. This indicates an accumulation of N in the tissue probably due to inhibition of protein synthesis by the absence of adequate levels of S.

The results of tissue S analysis are displayed in Figure 7b. Significant differences due to treatments alone were observed in response to applied S. Sulfur uptake was optimized at the maximum N level with the 40 kg S/ha application on the two early sampling dates, however, the 40 kg S/ha level may have been exhausted by harvest.

Total N alone drastically decreases during maturation (Figure 7a) with the steepest decline occurring at the 140 kg N/ha level. The total S content of the forage (Figure 7b) remained fairly constant with time; however, the concentration of S in the tissue is very low allowing limited resolution of actual changes in the S level. The ratio of total N to total S seems to accurately depict the S status of the tissue (Figure 7c). At the highest N level, the crop S status was adequately maintained with S applications of greater than 20 kg S/ha. With at least 20

kg S/ha, forage tissue (N/S)_t ratios remained within the critical nutrient range for grasses (11-14) and were stabilized through the growing season.

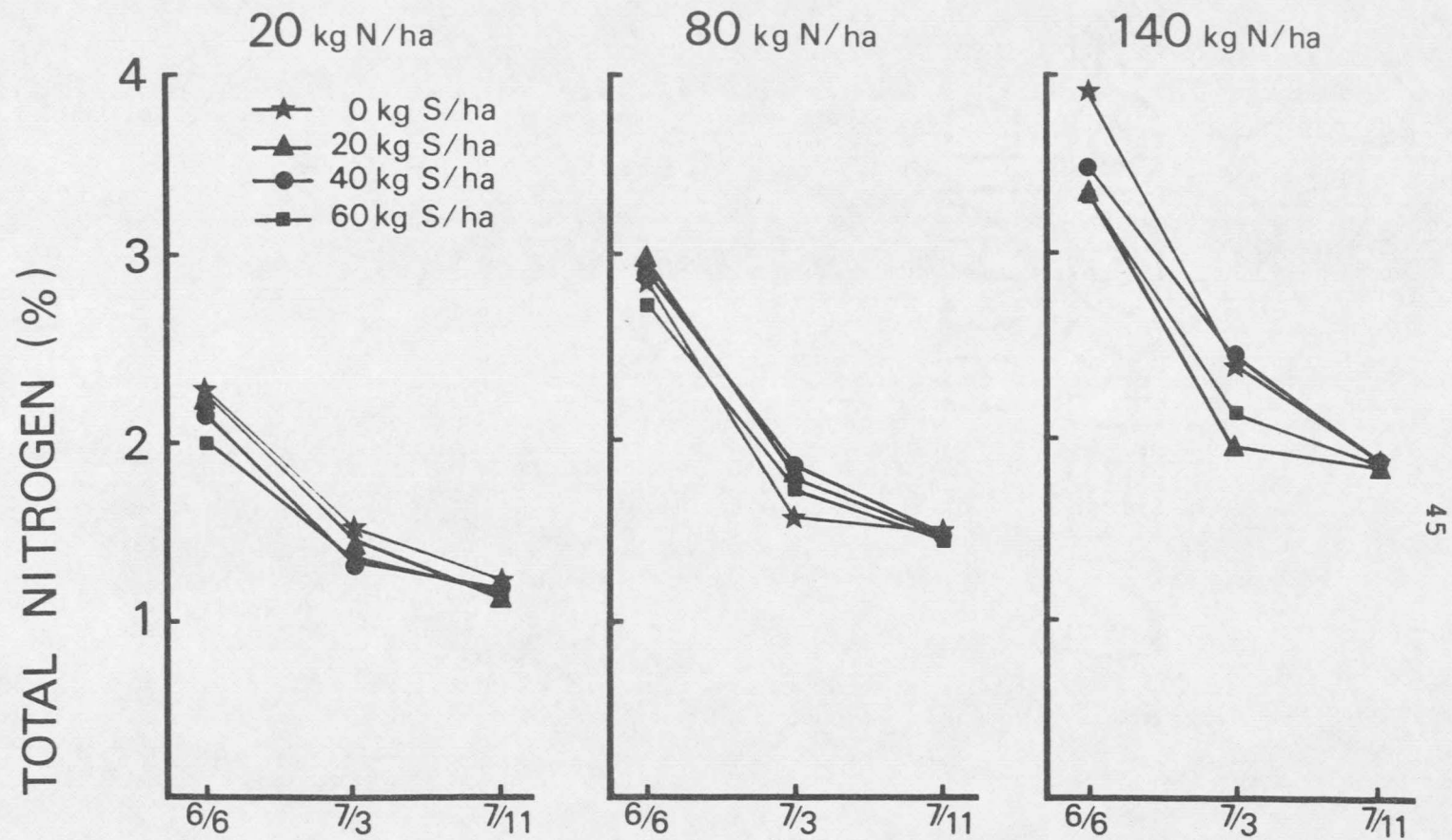


Figure 7a. Total N content of nonirrigated forage (Myers 3W location) at three sampling dates (6 June, 3 July, and 11 July, 1980) with three N and four S levels.

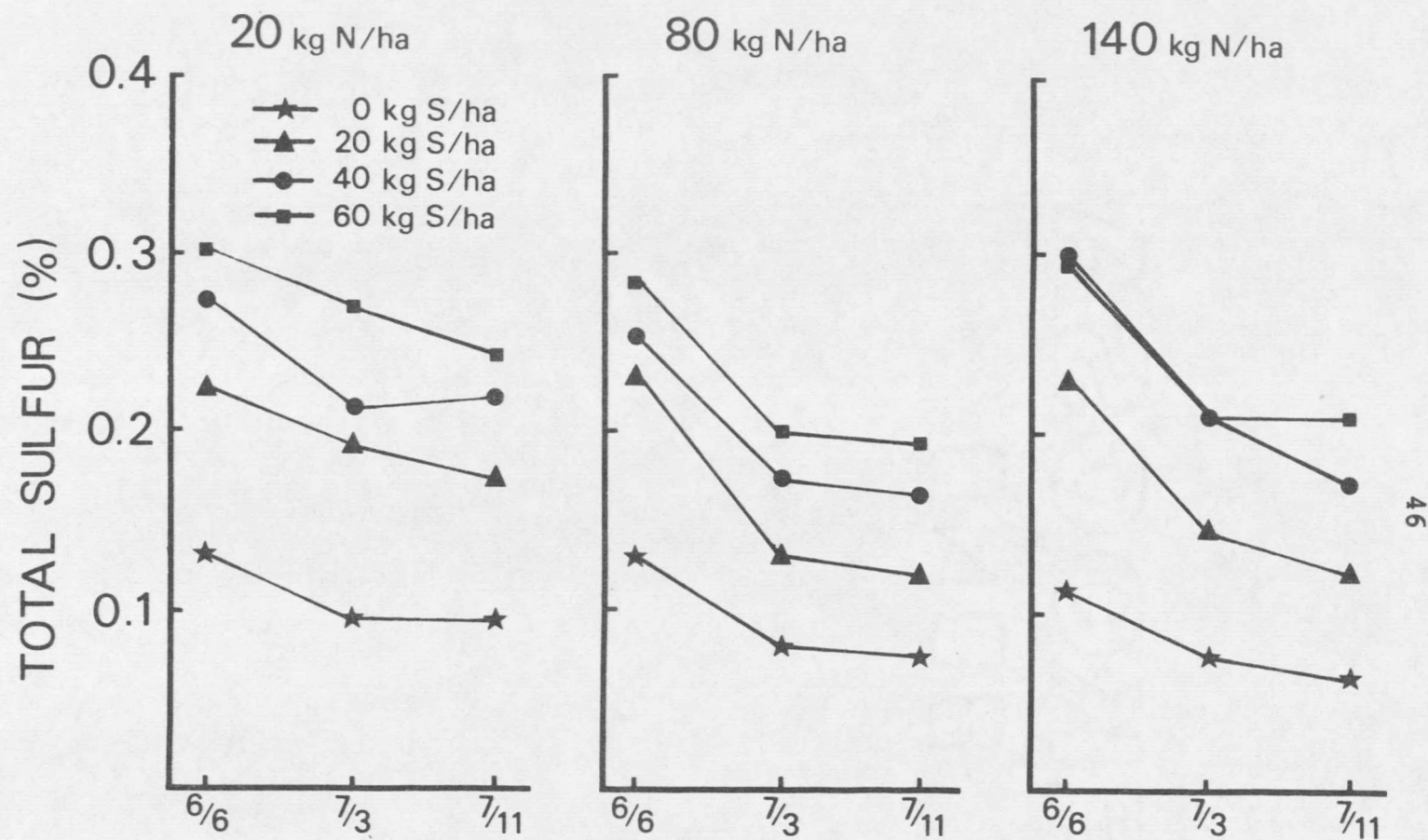


Figure 7b. Total S content of nonirrigated forage (Myers 3W location) at three sampling dates (6 June, 3 July, and 11 July, 1980) with three N and four S levels.

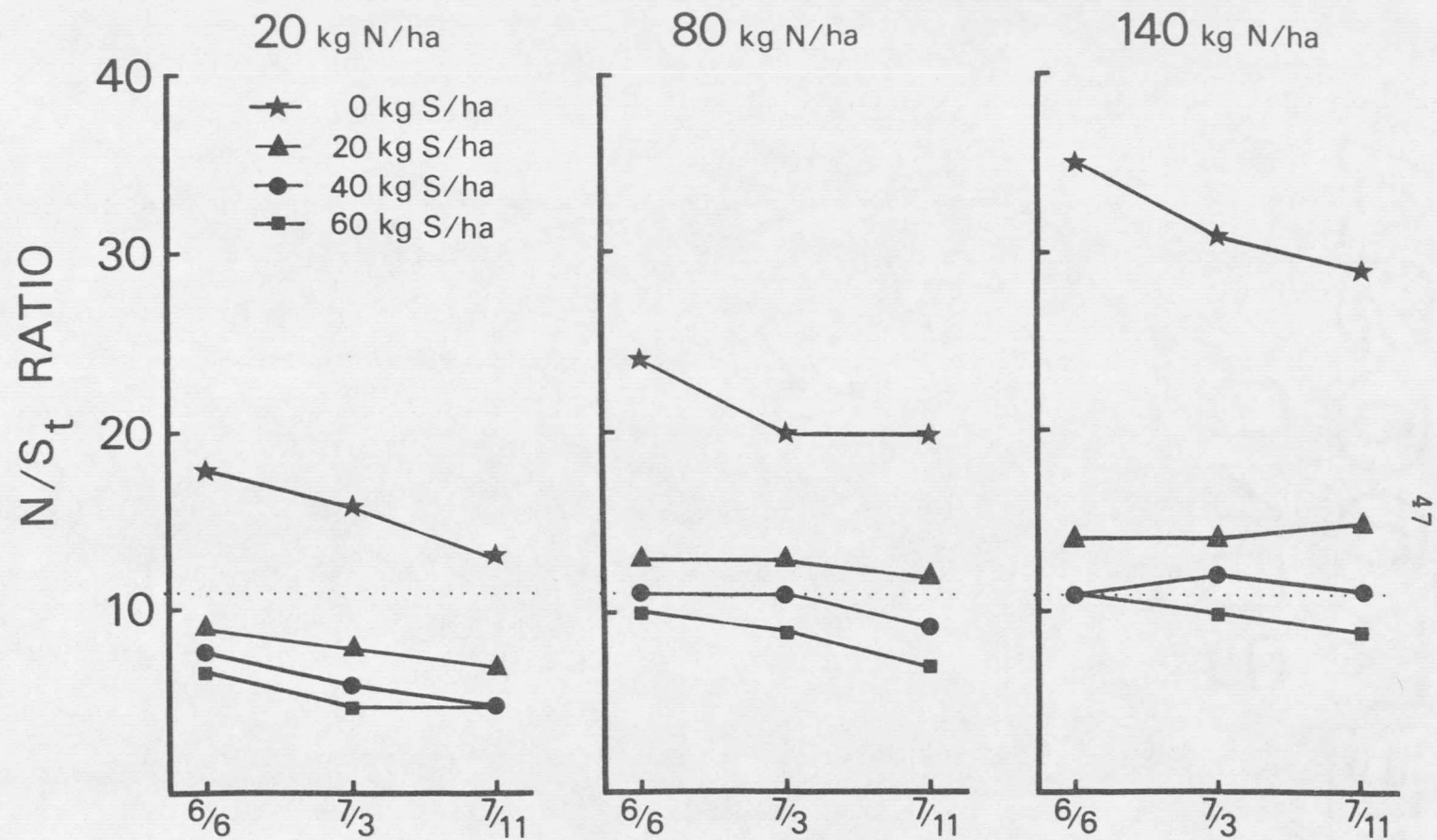


Figure 7c. Nitrogen to S ratios of nonirrigated forage (Myers 3W location) at three sampling dates (6 June, 3 July, and 11 July, 1980) with three N and four S levels.

CHAPTER 5

EFFECT OF SEVERAL SULFUR FERTILIZER SOURCES ON THE YIELD AND $(N/S)_t$ RATIO OF DRYLAND FORAGE; A TWO YEAR COMPARISON.

INTRODUCTION

Once a S deficiency has been recognized, the choice of a nutrient source becomes important. The effectiveness of a fertilizer nutrient source is dependent upon both its relative cost and its agronomic effectiveness. Relative cost includes availability at a particular location, cost per pound of nutrient, and application cost. Agronomic effectiveness is dependent upon the availability of the nutrient to the plant. In the case of S, availability is controlled to a large extent by the chemical form of S in the root zone and the solubility of the particular S compound.

Elemental S must undergo microbiological transformation to sulfate ($SO_4^{=}$) before it can be taken up by the plant. The rate of this process is dependent on a number of factors which include soil temperature, soil water content, pH, and availability of other nutrients. For these reasons, the availability of elemental S is initially low. The soil conditions must be warm, moist, and slightly acidic for the soil microbial population to rapidly convert elemental S to the plant available

(sulfate) form. The cool soil temperatures occurring in crop production areas at relatively high elevations limit the rate of elemental S conversion. Dry soil conditions which are synonymous with nonirrigated crop production can also reduce the levels of sulfate produced from elemental S.

Because sulfate supplying fertilizers require no microbiological conversion they are less dependent on moisture and temperature conditions to be plant available. Fertilizer formulations providing S in the sulfate form allow for almost immediate S availability to the plant. Due to different manufacturing processes, substantial solubility differences occur between forms of sulfate fertilizers.

The objective of this study was to compare the agronomic effectiveness of several S fertilizer sources on the yield and chemical composition of nonirrigated high elevation hayland. The selected S sources were ammonium nitrate-sulfate (30-0-0-6.5), gypsum or calcium sulfate (0-0-0-17), ammonium thiosulfate (12-0-0-26), and sulfur-coated urea (35-0-0-21). The yield response to selected S sources was observed in the year of fertilizer application and in the year following application. Forage chemical

composition was measured during the growing season of fertilizer application and the following year.

MATERIALS AND METHODS

Field plots designed to compare the agronomic effectiveness of several S sources were established with an experimental design intended to allow measurement of forage yield response to varying S fertilizer rates. The field plots were established at two locations designated Myers 1W and 2E, approximately 1 km apart 15 km southeast of Bozeman, Montana. Soils at the selected sites are fine, mixed Argic Cryoborolls (Appendix II) at approximately 1525 m above sea level. Vegetation consisted of a mixed species grass stand predominately orchardgrass (Dactylis glomerata L.), timothy (Phleum pratense L.) and brome-grasses (Bromus sp.).

The S sources compared were gypsum (0-0-0-17), ammonium nitrate-sulfate (30-0-0-6.5), ammonium thiosulfate (12-0-0-26), and sulfur-coated urea (35-0-0-21). Treatments summarized in Table 13 were applied in a randomized complete block design to 3.05 m by 6.09 m plots with three replications.

A soil sample was collected from each replication before fertilizer application (Table 3). Soil organic matter was determined colorimetrically (Sims and Haby, 1970); pH with a glass electrode (soil/water ratio of 1:2); K from ammonium acetate extraction (Bower et al., 1952);

P by the acid fluoride method of Smith et al. (1957); acetate soluble S turbidimetrically (Bardsley and Lancaster, 1965). Plant tissue samples (leaves only) were collected through the growing season. A 0.609 m by 6.75 m area of each plot was harvested with a Rem forage plot harvester.

Table 13. Sulfur sources applied at Myers 1W and 2E locations, May, 1979.

Treatment No.	Fertilizer Rate kg/ha				N and S Sources
	N	P ₂ O ₅	K ₂ O	S	
4	168	112	56	0	AN
5	168	112	56	34	Gypsum
8	168	112	56	34	ANS
9	168	112	56	34	APS
10	168	112	56	34	Amm.Thio.
14	168	112	56	0	Urea
15	168	112	56	100	Gypsum
16	168	112	56	100	SCU

Plant material harvested from each plot was weighed in the field. A subsample was weighed, dried at 65 degrees C for 72 hours, and reweighed for moisture content determination. Plant tissue samples were ground in a Wiley mill to pass a 40 mesh screen and stored in manila envelopes pending chemical analyses.

Plant tissue analyses were accomplished on all treatments at each sampling date. Dried, ground plant tissue was analyzed for total N and total S (Appendix III). The total S procedure for plant material was provided by Dr. D. T. Westermann, USDA, ARS, Snake River Conservation Research Center, Kimberly, Idaho, and is described in its entirety in Appendix III.

A nitric-perchloric acid digest (Appendix III) was used to prepare selected plant tissue samples for further analyses. Calcium, Mg, K, Zn, and Mn levels were determined using flame atomic absorption spectrophotometry. Phosphorus analysis (Appendix III) was accomplished colorimetrically from aliquots of the nitric-perchloric acid digest.

Two-factor analysis of variance, and least significant difference (LSD) values were calculated for comparison of treatments.

RESULTS AND DISCUSSION

Experimental sites were established in 1979 to compare the initial and residual effects of four different S sources on the yield and chemical composition of nonirrigated grass. Selected treatment results from the Myers 2E location (Table 14) show the variability in S availability the year of application. Ammonium thiosulfate and ammonium nitrate-sulfate (ANS) produced greater forage yield responses than did either gypsum or ammonium phosphate-sulfate (16-20-0-14) at the 34 kg S/ha rate. However, only the yield increase due to ANS was statistically significant. Gypsum and ammonium phosphate-sulfate produced similar yields although the $(N/S)_t$ ratios were substantially different. The ammonium phosphate-sulfate application did not reduce the $(N/S)_t$ ratio to the normal range of 11 - 14 indicating that this S source may be less soluble. The residual response of the most soluble S sources was limited. Ammonium nitrate-sulfate produced the least forage the second year of the study, however, it was not statistically less than the other sources. The gypsum and ammonium phosphate-sulfate sources displayed residual properties reflecting their lack of solubility the year of application. Ammonium thiosulfate maintained yield levels through the study. Ratios of N to S were more nearly equal

the second year of the study. However, all $(N/S)_t$ ratios were above the normal range of 11-14 in the plant tissue suggesting that 34 kg S/ha did not adequately supply S the second year. Additional S application is necessary to maintain the proper nutritional balance and to optimize yield.

Table 14. Initial and residual response of nonirrigated grass hay to four S sources at the Myers 2E location.

S Source ^{1/}	Yield ^{2/}		$(N/S)_t$ Ratio	
	<u>1979</u>	<u>1980</u>	<u>1979</u>	<u>1980</u>
Gypsum	2630	3131	13	16
ANS	3412	2900	11	17
APS	2672	3260	16	17
Amm.Thio.	3080	3022	12	18
LSD _{0.05}	637	889		

^{1/} See Table 13 for complete fertilizer rates.

^{2/} Yield expressed in kg/ha at 0.0% moisture.

Results in 1979 (Tables 15 and 16) at the Myers 1W and 2E locations indicated that SCU was the least effective treatment in providing adequate N or S to increase yield. Both AN and urea produced more hay at both sites than did SCU in 1979. Urea with gypsum provided the maximum yield and also the only $(N/S)_t$ ratio within the normal range.

Table 15. Yield and $(N/S)_t$ ratio response of nonirrigated grass hay to different N and S sources at the Myers 1W location.

Source ^{1/}	Yield ^{2/}		$(N/S)_t$ Ratio	
	<u>1979</u>	<u>1980</u>	<u>1979</u>	<u>1980</u>
AN	2671	1590	31	30
Urea	2533	2160	25	26
Urea + Gyp.	3151	2615	11	13
SCU	1756	2142	33	20
LSD _{0.05}				5.39

^{1/} See Table 13 for complete fertilizer rates.

^{2/} Yield expressed in kg/ha at 0.0% moisture.

Table 16. Yield and $(N/S)_t$ ratio response of nonirrigated grass hay to different N and S sources at the Myers 2E location.

Source ^{1/}	Yield ^{2/}		$(N/S)_t$ Ratio	
	<u>1979</u>	<u>1980</u>	<u>1979</u>	<u>1980</u>
AN	2369	1916	25	31
Urea	2681	2268	24	30
Urea + Gyp.	3018	3114	10	12
SCU	2067	3036	21	18
LSD _{0.05}			11.98	8.99

^{1/} See Table 13 for complete fertilizer rates.

^{2/} Yield expressed in kg/ha at 0.0% moisture.

Because of the dry conditions found at this location in 1979 (Appendix IV), the experimental area was treated with background levels of N and P and harvested in 1980 to obtain a second year of data. The results of the 1980 data at the 2E location (Table 16) showed that SCU was more available in the second year, probably due to the increased moisture availability in 1980 and the slow release characteristics of the product. Forage production as a result of SCU application exceeded either N source alone at the 2E location in 1980. Sulfur-coated urea did not bring

the $(N/S)_t$ ratio into balance in either 1979 or 1980. The urea plus gypsum treatment out-yielded the SCU treatment and consistently held the $(N/S)_t$ ratio in the proper balance. The application of 168 kg N/ha as urea with 100 kg S/ha of gypsum appeared to adequately supply second year residual S requirements at the 2E location.

The results of these studies indicate a difference in initial and residual S availability between these S sources. Ammonium nitrate-sulfate is more available than gypsum or ammonium phosphate-sulfate at the 34 kg/ha level. Plots treated with gypsum out-yielded the SCU treated plots at the 100 kg S/ha level and kept the crop $(N/S)_t$ ratio balanced. The specific application of this data may be in the selection of S sources for their initial and residual S supplying potential. A study conducted in California on annual grassland (Vaughn et al., 1979) emphasized the residual characteristics of SCU and the relative unavailability in the year of application. Mays (1970) found that a mixture of a soluble N source with SCU (relatively insoluble) provided the most desirable tall fescue (Festuca arundinacea) yield curves. A similar source combination would allow for available S the year of application from soluble S sources and residual S the

second year from a less soluble source. Minimal maintenance applications of soluble S could then provide plant available S each growing season once the organic matter - microbial population S sink was satisfied.

CHAPTER 6

QUANTITATIVE ASSESSMENT OF SOIL SULFATE-SULFUR LEVELS AS A FUNCTION OF APPLIED FERTILIZER SULFUR.

INTRODUCTION

Sulfur deficiency of forages has been reported in western Montana primarily on coarse textured soils (Stoltenberg, 1969). Graham (1973) suggested that S deficiencies can also be expected on shallow, medium-textured, intensively farmed soils and on fine-textured soils developed under forest.

Soil tests for S have been less than satisfactory (Bardsley and Lancaster, 1965). Generally, soils testing less than 5 ppm $\text{SO}_4\text{-S}$ are considered likely to respond. Acetate extractable S soil tests measure primarily soluble SO_4 and therefore neglect or omit organic S. Stoltenberg (1969) was able to correlate forage yield with acetate extractable sulfate ($r = 0.729$), to a depth of 30 cm, by grouping the soil test results from three locations. No improvement in the correlation of yield with acetate extractable sulfate was obtained by including soil samples from profile depths below 30 cm. Prefertilizer soil S levels were not presented. Additionally, Graham (1973) offered no prefertilizer S soil concentrations.

This study was initiated to quantitatively assess the

post-harvest soil sulfate-S levels as a function of spring applied treatment S at two southwestern Montana locations.

MATERIALS AND METHODS

To investigate the potential correlation of post-harvest soil sulfate-S ($\text{SO}_4\text{-S}$) levels with levels of spring applied fertilizer S, similar randomized complete block experiments were established at two nonirrigated sites approximately 1 km apart, 15 km southeast of Bozeman, Montana.

The treatment set shown in Table 4 was applied to an orchardgrass (Dactylis glomerata L.), timothy (Phleum pratense L.), bromegrass (Bromus sp.) mixed hay stand. One experiment designated Myers 3W, measured 28 m by 30 m with four replications. The second experimental location, Myers 4E, was 21 m by 30 m with three replications. The Bridger series soils (fine, mixed Argic Cryoborolls) are high elevation soils approximately 1525 m above sea level (Appendix II), and were the dominant soils at these sites.

Prefertilizer soil samples were collected by replication from each site (Table 17) followed by fertilizer topdressing between 2 May and 6 May, 1980. Soil samples were analyzed for pH by glass electrode (soil/water ratio of 1:2); organic matter colorimetrically (Sims and Haby, 1970); K from ammonium acetate extraction (Bower et al., 1952); P by the acid fluoride method of Smith et al., (1957); acetate-soluble S turbidimetrically with J.

Kunard's modification of the method of Bardsley and Lancaster (1965), (see Appendix III).

Table 17. Prefertilizer soil analyses (by replication) at Myers 3W and 4E sites, May, 1980.

Site by Rep.	Depth cm	Texture	pH	OM %	P -----	K ppm	SO ₄ -S -----
Myers 3W							
I	0-20	sil	5.4	7.2	51	357	8
II	0-20	sil	5.3	7.2	53	334	5
III	0-20	sil	5.2	6.5	53	318	7
IV	0-20	sil	5.2	7.2	63	318	8
Myers 4E							
I	0-20	sil	5.3	6.3	47	201	8
II	0-20	sil	5.2	5.9	40	201	7
III	0-20	sil	5.2	5.7	43	186	8

The plots were harvested 11 and 15 July, 1980 and dry matter yields determined. Post-harvest soil samples were collected from each plot and analyzed for sulfate-S by the modified method of Bardsley and Lancaster (1965) as shown in Appendix III.

Yield data were analyzed using two-factor analysis of variance to determine treatment differences. Post-harvest soil sulfate-S data were analyzed using linear regression.

RESULTS AND DISCUSSION

Prefertilizer soil sulfate-S ($\text{SO}_4\text{-S}$) levels (by replication) at the Myers 3W and 4E locations averaged slightly more than 7 parts per million (ppm) in the surface 20 cm of soil (Table 17). In general, these sites would probably not be expected to respond to S fertility because soil $\text{SO}_4\text{-S}$ levels exceed the 5 ppm recommended response level. However, both sites responded to S fertilizer when adequate levels of N were supplied, indicating that the critical soil test level of 5 ppm S failed to predict the deficient S situation (Figures 1 and 2).

The S soil test on post-harvest samples accurately identified incrementally increasing levels of spring applied S as gypsum (Figure 8). The treatments receiving no S in the spring contained six ppm $\text{SO}_4\text{-S}$ following harvest which is essentially equivalent to the prefertilizer mean level of 7 ppm (Table 17). Spring applied S levels of 20, 40, and 60 kg S/ha appeared as 8, 10.5, and 12 ppm $\text{SO}_4\text{-S}$ respectively in the topdressed soil after harvest (Figure 8). The data indicate that the S soil test can measure the soluble soil S fraction, that is the SO_4 portion in the soil. Since a majority of soil S is in the organic fraction (Tisdale and Nelson, 1975), and therefore not readily plant available, it seems a difficult

task to predict S deficiency with only a portion of the potentially usable S.

This study showed that the soil test for $\text{SO}_4\text{-S}$ was sensitive to increasing levels of applied gypsum. This relationship may prove useful for measuring residual $\text{SO}_4\text{-S}$. However, the failure of soil analysis for soluble S to correlate with fertilizer responses may be due to S mineralization or immobilization during the growing season.

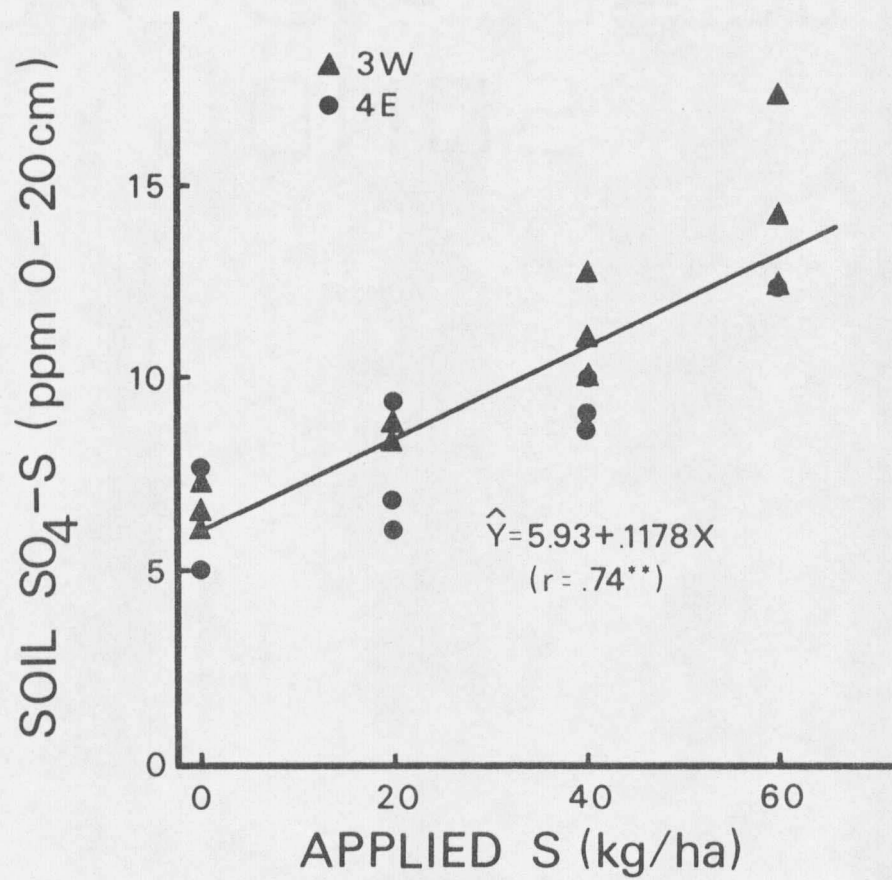


Figure 8. Relationship of post-harvest soil sulfate-S to levels of spring applied S as gypsum at the Myers 3W and 4E locations, 1980.

CHAPTER 7

GENERAL CONCLUSIONS

Sulfur deficient irrigated and nonirrigated grass hayland sites were selected for experiments designed to determine the levels of fertilizer N and S required to optimize forage yield and chemical composition.

Comparison of sources showed variable initial and residual S availability. Ammonium nitrate-sulfate provided more available S the year of application than did gypsum, ammonium thiosulfate (liquid), or ammonium phosphate-sulfate. Sulfur-coated urea tended to be unavailable the first year when compared to urea plus gypsum at the same S level.

Optimum yields were obtained only in plots receiving adequate N and S. The minimum N and S levels required for optimum yield on nonirrigated grass hayland appeared to be 110 kg N and 37 kg S/ha respectively. For residual S response at least 67 kg S/ha must be applied the first year. Because of the variability in S source availability the selection of a relatively available, cost competitive S source is important. Additionally, the application of a less soluble S source in combination with an available source would provide adequate S both the first and second growing seasons.

The utilization of tissue analysis to identify a potential S deficiency is recommended only where adequate levels of N have been applied. Abnormally high N/S_t ratios are apparent primarily in tissue that is properly fertilized with N and deficient in S.

The S soil test is not an adequate diagnostic tool for the identification of potential S deficient soil systems. Although levels of soluble SO_4-S can be measured, use as a predictive tool is limited.

APPENDIX I: FORAGE YIELD AND RESULTS OF CHEMICAL
ANALYSES.

Appendix Table 1. Yield and chemical composition of forage samples from field plot experiments, 1978-1980. Means of 3 and 4 replications (R).

Treat. NO.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	ppm	-----
Boyd 26 June 1978 (R=3)										
1		63	3.03	0.048	1.80	0.24	0.22	0.42		
2		96	4.62	0.048	2.00	0.21	0.22	0.52		
3		94	4.55	0.048	1.70	0.20	0.21	0.45		
4		91	4.39	0.048	2.30	0.15	0.20	0.42		
5		91	4.39	0.048	2.90	0.20	0.25	0.45		
6		15	4.58	0.304	3.80	0.08	0.24	0.41		
Boyd 25 July 1978 (R=3)										
1		51	2.45	0.048						
2		86	4.14	0.048						
3		79	3.80	0.048						
4		67	3.22	0.048						
5		71	3.42	0.048						
6		9	2.72	0.288						
Boyd 1 Aug. 1978 (R=3)										
1		41	2.31	0.056						
2		78	3.74	0.048						
3		70	3.95	0.056						
4		51	3.05	0.060						
5		58	3.28	0.056						
6		12	2.48	0.204						
Boyd 1 Aug. 1978 (R=3) Harvest										
1	2345	34	1.63	0.048						
2	1744	53	2.76	0.052						
3	1360	53	2.76	0.052						
4	3489	47	2.65	0.056						
5	3252	53	2.55	0.048						
6	5499	11	2.30	0.212						
Boyd 14 June 1979 (R=3)										
1		23	2.00	0.088	2.81	0.38	0.15	0.25	16	108
2		37	3.29	0.088	2.79	0.37	0.18	0.33	32	87
3		33	2.77	0.084	2.62	0.39	0.17	0.32	30	82
4		31	2.71	0.088	2.66	0.38	0.19	0.32	23	92
5		32	2.80	0.088	2.72	0.37	0.18	0.34	24	100
6		15	2.10	0.138	3.04	0.36	0.14	0.26	16	129

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----		%	-----			-- ppm --	
Boyd 17 June 1979 (R=3)										
1		19	1.21	0.064						
2		36	2.34	0.064						
3		35	2.19	0.064						
4		37	2.27	0.060						
5		38	2.27	0.060						
6		13	1.14	0.084						
Boyd 26 June 1979. (R=3)										
1		24	1.25	0.052	2.47	0.60	0.18	0.24	13	127
2		39	1.90	0.048	2.69	0.58	0.24	0.32	20	142
3		39	2.05	0.052	2.56	0.59	0.25	0.35	18	134
4		40	1.94	0.048	2.59	0.56	0.26	0.41	18	159
5		41	1.97	0.048	2.77	0.62	0.29	0.44	20	186
6		18	1.43	0.064	2.31	0.46	0.16	0.20	12	159
Boyd 26 June 1979 (R=3) Harvest										
1	977	20	1.27	0.064						
2	633	25	1.50	0.060						
3	916	21	1.62	0.076						
4	685	31	1.87	0.060						
5	700	25	1.53	0.060						
6	2080	15	1.04	0.068						
Myers 1W 13 June 1979 (R=3)										
1		11	1.98	0.184						
2		37	5.21	0.140						
3		21	5.12	0.248						
4		21	4.54	0.220						
5		13	5.06	0.388						
6		12	4.84	0.322						
7		9	4.57	0.484						
8		11	4.72	0.436						
9		12	4.49	0.528						
10		9	4.94	0.520						
11		22	4.77	0.220						
12		10	5.06	0.520						
13		30	4.98	0.168						
14		26	4.89	0.188						
15		12	5.49	0.464						
16		15	4.05	0.268						

Appendix Table 1. (cont'd)

Treat.	Yield	(N/S)t	N	S	K	Ca	Mg	P	Zn	Mn
No.	kg/ha	Ratio	-----	-----	-----	-----	-----	-----	--- ppm ---	---

Myers 1W 29 June 1979 (R=3)

1	10	1.66	0.164
2	32	3.61	0.112
3	21	2.94	0.140
4	21	3.31	0.156
5	9	3.29	0.372
6	10	3.64	0.368
7	7	3.22	0.460
8	11	3.28	0.292
9	12	3.46	0.284
10	12	3.18	0.268
11	18	3.43	0.189
12	9	3.24	0.360
13	32	3.46	0.108
14	25	3.64	0.144
15	9	3.46	0.372
16	17	2.73	0.160

Myers 1W 17 July 1979 (R=3)

1	9	1.39	0.156
2	24	2.32	0.099
3	22	2.43	0.112
4	22	2.31	0.104
5	9	2.23	0.252
6	10	2.55	0.264
7	7	2.23	0.308
8	11	2.64	0.236
9	10	2.32	0.240
10	9	2.61	0.276
11	19	2.44	0.128
12	8	2.40	0.280
13	25	2.34	0.092
14	23	2.34	0.100
15	8	2.46	0.300
16	17	1.60	0.096

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	ppm	ppm

Myers 1W 25 July 1979 (R=3)

1		13	1.57	0.116						
2		34	2.06	0.060						
3		30	2.05	0.068						
4		26	2.17	0.084						
5		14	2.10	0.148						
6		15	2.33	0.152						
7		10	2.04	0.196						
8		18	1.98	0.108						
9		16	2.30	0.144						
10		13	2.27	0.172						
11		26	2.19	0.084						
12		16	2.06	0.132						
13		31	2.33	0.076						
14		25	1.84	0.072						
15		17	2.31	0.136						
16		34	1.65	0.059						

Myers 1W 25 July 1979 (R=3) Harvest

1	213	16	1.71	0.104	2.52	0.53	0.19	0.26	13	247
2	1912	26	2.21	0.084	3.24	0.40	0.19	0.21	26	141
3	2242	23	2.02	0.088	3.27	0.41	0.16	0.19	24	101
4	2671	31	2.15	0.072	3.64	0.40	0.16	0.24	25	126
5	3026	12	1.87	0.156	3.90	0.34	0.17	0.23	22	118
6	3131	13	2.20	0.164	3.45	0.43	0.15	0.20	27	103
7	3000	10	2.06	0.204	3.88	0.36	0.17	0.21	20	139
8	2977	13	2.10	0.100						
9	3028	14	2.13	0.156						
10	2837	13	2.09	0.172						
11	2599	21	2.12	0.100						
12	3179	12	2.09	0.172						
13	1477	33	2.22	0.068						
14	2533	25	2.21	0.088	3.00	0.49	0.17	0.20	27	96
15	3151	11	2.25	0.204	3.59	0.42	0.15	0.22	25	98
16	1756	33	1.85	0.056	3.76	0.38	0.17	0.27	27	138

Appendix Table 1. (cont'd)

Treat. NO.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	--- ppm ---	---

Myers 2E 13 June 1979 (R=3)

1	16	1.95	0.120
2	46	5.14	0.112
3	23	5.00	0.212
4	24	4.87	0.204
5	10	5.14	0.492
6	7	4.67	0.668
7	7	4.84	0.648
8	9	4.97	0.528
9	9	4.79	0.532
10	9	5.03	0.536
11	15	4.92	0.328
12	8	4.87	0.624
13	25	4.66	0.188
14	22	4.96	0.220
15	9	5.36	0.576
16	16	3.69	0.232

Myers 2E 29 June 1979 (R=3)

1	14	1.66	0.120
2	27	3.54	0.132
3	22	3.20	0.148
4	26	3.29	0.128
5	10	3.41	0.324
6	7	3.26	0.480
7	7	3.35	0.480
8	10	3.50	0.360
9	9	3.32	0.380
10	12	3.38	0.284
11	22	3.20	0.148
12	8	3.45	0.420
13	30	3.97	0.132
14	25	4.00	0.160
15	7	4.42	0.604
16	19	3.34	0.176

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----		%	-----			ppm	---

Myers 2E 17 July 1979 (R=3)

1	13	1.19	0.088
2	25	2.21	0.088
3	24	2.14	0.088
4	17	2.10	0.124
5	8	2.06	0.248
6	6	2.29	0.376
7	6	2.09	0.336
8	9	2.28	0.260
9	8	2.06	0.240
10	10	2.31	0.240
11	21	1.89	0.088
12	8	2.06	0.244
13	27	2.21	0.080
14	27	2.46	0.092
15	8	2.24	0.284
16	21	2.24	0.104

Myers 2E 26 July 1979 (R=3)

1	15	1.22	0.080
2	30	2.18	0.072
3	28	2.32	0.084
4	26	2.19	0.084
5	13	2.40	0.184
6	10	2.22	0.216
7	9	2.38	0.248
8	13	2.35	0.180
9	12	2.24	0.180
10	14	2.24	0.156
11	21	2.24	0.104
12	13	2.36	0.184
13	31	1.71	0.056
14	35	2.10	0.060
15	9	2.08	0.224
16	15	1.35	0.088

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----		%	-----			-- ppm --	

Myers 2E 26 July 1979 (R=3) Harvest

1	315	16	1.53	0.090						
2	1984	21	1.82	0.088						
3	2906	32	1.92	0.060						
4	2369	25	1.94	0.076						
5	2630	13	2.02	0.152						
6	3202	10	1.98	0.188						
7	2760	10	2.11	0.208						
8	3412	11	1.94	0.176						
9	2672	16	2.07	0.132						
10	3080	12	2.08	0.176						
11	2945	27	2.08	0.076						
12	3011	11	2.04	0.192						
13	1238	24	2.13	0.088						
14	2681	24	2.05	0.084						
15	3018	10	2.15	0.208						
16	2067	21	1.85	0.088						

Myers 1W 6 June 1980 (R=3)

1	9	1.93	0.216	3.11	0.41	0.15	0.36	23	163
2	36	3.82	0.106	3.46	0.27	0.15	0.39	36	130
3	28	3.46	0.123	3.23	0.35	0.13	0.33	31	110
4	28	3.67	0.130	3.54	0.32	0.13	0.37	28	130
5	16	3.26	0.200	3.58	0.30	0.12	0.34	36	99
6	14	3.08	0.213	3.54	0.33	0.09	0.32	26	101
7	12	3.06	0.246	3.66	0.29	0.11	0.33	29	131
8	18	3.08	0.173						
9	18	3.19	0.176						
10	18	3.22	0.176						
11	24	3.46	0.143						
12	16	3.09	0.186						
13	39	3.90	0.100	3.16	0.35	0.15	0.27	31	115
14	25	3.08	0.123	3.41	0.35	0.12	0.25	30	91
15	13	2.86	0.226	3.56	0.31	0.11	0.25	28	128
16	26	3.55	0.136						

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----			%	-----		--- ppm ---	

Myers 1W 8 July 1980 (R=3)

1		8	1.57	0.200
2		31	2.26	0.073
3		26	1.83	0.070
4		24	1.88	0.076
5		16	1.69	0.106
6		14	1.89	0.133
7		10	1.57	0.153
8		17	1.96	0.113
9		16	1.60	0.096
10		16	1.78	0.113
11		23	2.02	0.086
12		14	1.59	0.113
13		35	2.34	0.066
14		24	1.94	0.080
15		12	1.72	0.140
16		20	1.84	0.090

Myers 1W 8 July 1980 (R=3) Harvest

1	110	10	1.74	0.180
2	1223	34	2.37	0.070
3	1344	24	1.79	0.073
4	1590	30	1.98	0.066
5	2092	16	1.56	0.096
6	2346	15	1.53	0.100
7	3018	13	1.70	0.126
8	2287	17	1.59	0.093
9	2129	18	1.59	0.086
10	2033	18	1.97	0.106
11	2261	23	1.76	0.076
12	2369	15	1.64	0.106
13	1222	34	2.41	0.073
14	2160	26	1.92	0.070
15	2615	13	1.52	0.116
16	2142	20	1.66	0.083

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	ppm	-----

Myers 2E 13 June 1980 (R=3)

1	17	1.80	0.106
2	40	3.49	0.086
3	30	3.04	0.100
4	36	3.15	0.086
5	18	2.60	0.146
6	17	2.49	0.150
7	14	2.69	0.190
8	16	2.49	0.153
9	19	2.67	0.143
10	18	2.75	0.150
11	26	2.85	0.110
12	17	2.65	0.156
13	42	3.77	0.090
14	32	2.95	0.093
15	13	2.61	0.196
16	26	2.66	0.103

Myers 2E 8 July 1980 (R=3)

1	13	1.26	0.093
2	29	2.03	0.070
3	26	1.85	0.070
4	28	1.90	0.066
5	15	1.75	0.116
6	14	1.65	0.116
7	12	1.59	0.136
8	15	1.64	0.110
9	14	1.75	0.123
10	17	1.66	0.100
11	21	1.77	0.083
12	13	1.57	0.120
13	33	2.54	0.076
14	30	2.14	0.070
15	9	1.93	0.206
16	19	1.76	0.090

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----			-----			ppm	
Myers 2E 11 July 1980 (R=3) Harvest										
1	333	20	1.78	0.090						
2	1026	36	2.42	0.066						
3	2100	28	1.71	0.060						
4	1916	31	1.87	0.060						
5	3131	16	1.48	0.090						
6	2794	15	1.56	0.106						
7	3194	13	1.52	0.120						
8	2900	17	1.45	0.086						
9	3260	17	1.57	0.090						
10	3022	18	1.47	0.083						
11	2114	29	1.82	0.063						
12	2661	17	1.45	0.086						
13	972	29	2.13	0.073						
14	2268	30	1.88	0.063						
15	3114	12	1.54	0.130						
16	3036	18	1.63	0.090						
Myers 3W 6 June 1980 (R=4)										
1		18	2.29	0.130						
2		9	2.11	0.225						
3		8	2.12	0.272						
4		7	2.00	0.302						
5		22	2.83	0.130						
6		13	2.94	0.232						
7		11	2.84	0.255						
8		10	2.76	0.285						
9		35	3.90	0.112						
10		14	3.38	0.232						
11		11	3.47	0.300						
12		11	3.34	0.297						
Myers 3W 3 July 1980 (R=4)										
1		16	1.49	0.095						
2		8	1.46	0.190						
3		6	1.36	0.212						
4		5	1.36	0.270						
5		20	1.57	0.080						
6		13	1.80	0.132						
7		11	1.87	0.175						
8		9	1.72	0.200						
9		31	2.40	0.077						
10		14	1.96	0.142						
11		12	2.47	0.212						
12		10	2.13	0.212						

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----		%	-----			-- ppm --	

Myers 3W 11 July 1980 (R=4)

1		13	1.21	0.095
2		7	1.18	0.175
3		5	1.20	0.220
4		5	1.13	0.242
5		20	1.49	0.075
6		12	1.41	0.120
7		9	1.44	0.165
8		7	1.42	0.195
9		29	1.86	0.065
10		15	1.83	0.125
11		11	1.89	0.172
12		9	1.87	0.212

Myers 3W 11 July 1980 (R=4) Harvest

1	704	14	1.31	0.090
2	1009	10	1.55	0.147
3	840	7	1.36	0.197
4	872	7	1.43	0.215
5	1833	22	1.54	0.070
6	2394	13	1.36	0.105
7	2466	10	1.39	0.137
8	1991	8	1.42	0.172
9	2293	27	1.92	0.070
10	3198	14	1.56	0.107
11	3245	11	1.58	0.142
12	3649	11	1.68	0.150

Myers 4E 13 June 1980 (R=3)

1		14	1.66	0.120
2		10	1.66	0.156
3		10	1.72	0.166
4		8	1.64	0.196
5		21	2.61	0.126
6		15	2.51	0.166
7		13	2.55	0.193
8		12	2.28	0.187
9		27	2.94	0.106
10		16	2.95	0.183
11		13	2.96	0.226
12		11	3.17	0.273

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	ppm	-----
Myers 4E 3 July 1980 (R=3)										
1		14	1.36	0.100						
2		11	1.46	0.130						
3		10	1.49	0.143						
4		7	1.40	0.206						
5		21	1.79	0.086						
6		12	1.86	0.150						
7		12	1.84	0.153						
8		10	1.76	0.166						
9		30	2.50	0.083						
10		15	2.44	0.163						
11		11	2.38	0.206						
12		12	2.36	0.190						
Myers 4E 11 July 1980 (R=3)										
1		13	1.25	0.093						
2		8	1.23	0.156						
3		8	1.27	0.153						
4		6	1.19	0.190						
5		18	1.6	0.093						
6		13	1.75	0.136						
7		9	1.54	0.173						
8		10	1.54	0.160						
9		25	2.16	0.086						
10		13	1.99	0.153						
11		9	1.96	0.206						
12		9	1.83	0.200						
Myers 4E 11 July 1980 (R=3) Harvest										
1	638	14	1.31	0.090						
2	1025	10	1.033	0.126						
3	1155	9	1.32	0.143						
4	1189	9	1.42	0.150						
5	2517	23	1.71	0.073						
6	2657	12	1.30	0.103						
7	2719	11	1.37	0.126						
8	2260	10	1.27	0.123						
9	2584	21	1.61	0.076						
10	3788	14	1.75	0.123						
11	3748	11	1.61	0.150						
12	3821	9	1.56	0.163						

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----			%	-----		-- ppm --	

Myers 5E 13 June 1980 (R=4) Sainfoin

1	25	3.39	0.135
2	19	3.60	0.187
3	16	3.73	0.227
4	14	3.62	0.257
5	24	3.23	0.135
6	20	3.72	0.187
7	18	3.74	0.212
8	14	3.79	0.267
9	26	3.51	0.135
10	20	3.71	0.182
11	19	4.20	0.222
12	16	3.78	0.240

Myers 5E 3 July 1980 (R=4) Sainfoin

1	28	2.48	0.087
2	25	2.77	0.112
3	24	2.79	0.117
4	21	2.68	0.127
5	30	2.47	0.082
6	26	2.72	0.102
7	25	2.81	0.112
8	21	2.64	0.122
9	29	2.51	0.085
10	26	2.74	0.102
11	21	2.83	0.130
12	22	2.79	0.127

Myers 5E 15 July 1980 (R=4) Sainfoin

1	28	2.21	0.077
2	25	2.49	0.097
3	24	2.52	0.102
4	24	2.54	0.107
5	26	2.26	0.085
6	28	2.48	0.087
7	24	2.46	0.102
8	20	2.33	0.115
9	30	2.37	0.080
10	25	2.47	0.097
11	24	2.47	0.102
12	22	2.64	0.120

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N -----	S -----	K -----	%	Ca -----	Mg -----	P -----	Zn -- ppm --	Mn --
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Myers 5E 13 June 1980 (R=4) Grass

1		16	1.88	0.120							
2		10	1.92	0.185							
3		9	1.92	0.210							
4		8	1.93	0.230							
5		24	2.70	0.112							
6		13	2.56	0.190							
7		14	2.66	0.220							
8		11	2.54	0.235							
9		32	3.49	0.110							
10		16	3.12	0.200							
11		13	3.30	0.250							
12		11	3.28	0.282							

Myers 5E 3 July 1980 (R=4) Grass

1		15	1.51	0.097							
2		9	1.54	0.162							
3		8	1.64	0.192							
4		7	1.58	0.227							
5		22	2.01	0.092							
6		13	1.82	0.135							
7		10	2.07	0.200							
8		10	2.04	0.200							
9		29	2.38	0.082							
10		17	2.65	0.157							
11		13	2.57	0.195							
12		11	2.41	0.215							

Myers 5E 15 July 1980 (R=4) Grass

1		13	1.35	0.100							
2		8	1.40	0.180							
3		7	1.55	0.232							
4		6	1.35	0.225							
5		20	1.66	0.082							
6		13	1.65	0.130							
7		10	1.83	0.180							
8		8	1.82	0.215							
9		26	2.25	0.085							
10		14	2.04	0.145							
11		10	2.02	0.192							
12		10	2.15	0.222							

Appendix Table 1. (cont'd)

Treat. No.	Yield kg/ha	(N/S)t Ratio	N	S	K	Ca	Mg	P	Zn	Mn
			-----	-----	-----	-----	-----	-----	--- ppm ---	

Myers 5E 15 July 1980 (R=4) Harvest

1	1792	20	1.45	0.072
2	2165	15	1.50	0.102
3	2669	14	1.66	0.115
4	1897	12	1.62	0.135
5	2314	24	1.66	0.067
6	3343	17	1.64	0.097
7	3225	14	1.53	0.112
8	3178	12	1.60	0.127
9	2485	28	1.83	0.065
10	3419	17	1.62	0.095
11	3343	14	1.67	0.120
12	3413	12	1.66	0.135

APPENDIX II: SOIL PROFILE DESCRIPTIONS.

Appendix Table 2. Pedon description for the Bridger series at the Myers 1W and 3W sites.

***** SITE DESCRIPTION *****

Soil Series: Bridger Site Number: 100 County: Gallatin
 Location: 1/4, 1/4, SE 1/4 Section 32 Township 2 S, Range 6 E
 Classification: fine, mixed Argic Cryoborolls

 Date Sampled: 09/03/80 Elevation: 5000ft, 1524m Precipitation: 18 in, 457 mm
 Site Codes/Co: 06/PM: 20/Veg: 21/LU: 08/Drain: 05/Perm: 04/Ersn: 02/Postn: 07/LF: 04/
 Material: crystalline alluv. Vegetation: perennial forage Land use: dryland hay
 Drainage: well Permeability: medium Erosion: slight
 Slope: 4 %, 2degrees Aspect: S220W Position: level slope
 Soil temp. C, 32F Number of Horizons: 7 Landform: alluvial fan

**** PROFILE DESCRIPTION ****

HOR.	NO.	DEPTH (cm)	COLOR		TEXT	RF	STR		CONS	RT	PR		pH	EFF	BND	*
			MOIST	DRY			gsk	dmsh			asl	ask				
A1		0-15	10YR 2/1	10YR 3/1	09 sil	0	333	3223	22				6.0	1	21	
A3		15-33	10YR 2/1	10YR 3/1	09 sil	0	333	3223	22				6.0	1	32	
B1		33-48	10YR 3/1	10YR 3/1	12 sicl	0	23	4223	22				6.5	1	32	
B2lt		48-68	10YR 4/4	10YR 4/4	12 sicl	0	235	5444	12		754		7.0	1	22	
B22t		68-96	10YR 4/4	10YR 5/6	12 sicl	0	235	5444	12				7.0	1	31	1
B3ca		96-130	10YR 5/4	10YR 5/6	09 sil	0	234	4223	11				8.0	1	31	1
IIC		130-160	10YR 5/4	10YR 4/3	12 sicl	0	3	5444	11				8.0	1		1
		-	/	/												

RF=rock fragment(%) STR=structure grade,size,kind
 CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
 PR=pore amount, size, kind EFF=effervesence BND=boundary
 COMMENTS (*): 1:common clay films. Described by J. C. Wallace.

Appendix Table 3. Pedon description for the Bridger series at the Myers 2E and 4E sites.

***** SITE DESCRIPTION *****

Soil Series: Bridger Site Number: 101 County: Gallatin
 Location: 1/4, 1/4, SW1/4 Section 33 Township 2 S, Range 6 E
 Classification: fine, mixed Argic Cryoborolls
 Date Sampled: 09/04/80 Elevation: 5000 ft, 1524m Precipitation: 18 in, 457 mm
 Site Codes/Co: 06/PM: 20/Veg: 21/LU: 08/Drain: 05/Perm: 04/Ersn: 02/Postn: 07/LF: 04/
 Material: crystalline alluv. Vegetation: perennial forage Land use: dryland hay
 Drainage: well Permeability: medium Erosion: slight
 Slope: 4 %, 2degrees Aspect: N 0 Position: level slope
 Soil temp. C, 32F Number of Horizons: 5 Landform: alluvial fan

**** PROFILE DESCRIPTION ****

HOR.	NO.	DEPTH (cm)	COLOR		TEXT	RF	STR	CONS	RT	PR	pH	EFF	BND	*
			MOIST	DRY										
A11		0-9	10YR 2/1	10YR 3/1	08 l	0	233	3223			5.5	1	21	
A12		9-21	10YR 2/1	10YR 3/2	09 sil	0	233	3223			6.0	1	41	
B21t		21-52	10YR 5/6	10YR 5/6	09 sil	0	234	4423			6.5	1	31	1
B22t		52-74	10YR 6/6	10YR 5/6	14 c	0	336	5443			7.0	1	31	1
IIC		74-115	10YR 6/6	10YR 4/6	14 c	0	235	5443			7.0	1		1
		-	/	/							.			
		-	/	/							.			
		-	/	/							.			

RF=rock fragment(%) STR=structure grade,size,kind
 CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
 PR=pore amount, size, kind EFF=effervesence BND=boundary
 COMMENTS (*): 1:clay films and flows on ped faces. Described by J. C. Wallace.

Appendix Table 4. Pedon description for the Michelson series at the Myers 5E site.

***** SITE DESCRIPTION *****

Soil Series: Michelson Site Number: 102 County: Gallatin
 Location: 1/4, 1/4, SE1/4 Section 33 Township 2 S, Range 6 E
 Classification: fine-loamy, mixed Argic Cryoborolls
 Date Sampled: 09/04/80 Elevation: 5000 ft, 1524m Precipitation: 18 in, 457 mm
 Site Codes/Co:06/PM:20/Veg:21/LU:09/Drain:05/Perm:04/Ersn:02/Postn:04/LF:04/
 Material: crystalline alluv. Vegetation: perennial forage Land use: pasture
 Drainage: well Permeability: medium Erosion: slight
 Slope: 7%, 4degrees Aspect: S210SW Position: midslope
 Soil temp. C, 32F Number of Horizons:5 Landform: alluvial fan

**** PROFILE DESCRIPTION ****

HOR.	NO.	DEPTH (cm)	COLOR		TEXT	RF	STR	CONS	RT	PR	pH	EFF	BND	*
			MOIST	DRY										
A1		0-18	10YR 2/1	10YR 2/2 08 1	0 323 3343						7.0 2	32	1	
B1		12-28	10YR 4/3	10YR 4/4 12 sicl	0 333 3333						8.0 2	31	2	
B2t		28-46	10YR 4/4	10YR 6/4 11 cl	0 235 5434						8.0 2	31	3	
B3		46-62	2.5Y 6/4	2.5Y 7/4 09 sil	0 234 1233						8.2 3	21		
Cca		62-115	10YR 4/4	10YR 4/2 08 1	0 3 3323						8.2 3		4	
		-	/	/							.			
		-	/	/							.			
		-	/	/							.			

RF=rock fragment(%) STR=structure grade,size,kind
 CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
 PR=pore amount, size, kind EFF=effervesence BND=boundary
 COMMENTS (*): 1:many worm casts, some B material on channels. 2:some mixing of A and B on transitional horizon. 3:common organic stains on ped faces. 4:much fine lime, mostly concentrated on ped faces. This soil could be Bridger series if bulk of pedon had higher clay content in the Argillic horizon (>35%). Described by J. C. Wallace.

Appendix Table 5. Pedon description for the Beaverton series at the Boyd site.

***** SITE DESCRIPTION *****

Soil Series: Beaverton Site Number: 104 County: Gallatin
 Location: 1/4, 1/4, SE1/4 Section 35 Township 2 S, Range 5 E
 Classification: loamy-skeletal, mixed Typic Argiborolls
 Date Sampled: 09/21/81 Elevation: 4600 ft, 1402m Precipitation: 18 in, 457 mm
 Site Codes/Co:06/PM:14/Veg:21/LU:07/Drain:05/Perm:04/Ersn:02/Postn:07/LF:04/
 Material: alluvial Vegetation: perennial forage Land use: irrigated hay
 Drainage: well Permeability: medium Erosion: slight
 Slope: 2 %, 1degrees Aspect: N Position: level slope
 Soil temp. C, 32F Number of Horizons:5 Landform: alluvial fan

**** PROFILE DESCRIPTION ****

HOR.	NO.	DEPTH (cm)	COLOR MOIST	DRY	TEXT	RF	STR	CONS	RT	PR	pH	EFF	BND	*
A1		0-20	10YR 2/2	10YR 5/2	09 sil	0	622	2222	73		.	1	11	
B2t		20-43	10YR 3/4	10YR 4/3	12 sicl	0	624	3333	73		.	1	21	
B3		43-49	10YR 3/4	10YR 4/2	08 1	20	334	2222	73		.	1	11	
IIC1		49-75	10YR 3/3	2.5Y 5/2	05 sl	70		1111	53		.	1	21	
II2C2 c		75-	10YR 3/3	/	05 sl	80		1111	53		.	2	66	
		-	/	/							.			
		-	/	/							.			
		-	/	/							.			

RF=rock fragment(%) STR=structure grade,size,kind
 CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
 PR=pore amount, size, kind EFF=effervescence BND=boundary
 COMMENTS (*): Described by P. McDaniel.

Appendix Table 6. Index for county codes.

Code	County	Code	County	Code	County
01	Silver Bow	19	Chouteau	37	Daniels
02	Cascade	20	Valley	38	Glacier
03	Yellowstone	21	Toole	39	Fallon
04	Missoula	22	Big Horn	40	Sweet Grass
05	Lewis & Clark	23	Musselshell	41	McCone
06	Gallatin	24	Blaine	42	Carter
07	Flathead	25	Madison	43	Broadwater
08	Fergus	26	Pondera	44	Wheatland
09	Powder River	27	Richland	45	Prairie
10	Carbon	28	Powell	46	Granite
11	Phillips	29	Rosebud	47	Meagher
12	Hill	30	Deer Lodge	48	Liberty
13	Ravalli	31	Teton	49	Park
14	Custer	32	Stillwater	50	Garfield
15	Lake	33	Treasure	51	Jefferson
16	Dawson	34	Sheridan	52	Wibaux
17	Roosevelt	35	Sanders	53	Golden Valley
18	Beaverhead	36	Judith Basin	54	Mineral
				55	Petroleum
				56	Lincoln

Appendix Table 7. Index for parent material, vegetation, and land use codes.

Code	Parent Material	Code	Vegetation	Code	Land Use
01	volcanic ash	01	mixed coniferous	01	commercial forest
02	loess	02	ponderosa pine	02	non-comm. forest
03	glacial outwash	03	lodgepole pine	03	forest
04	glacial till	04	spruce-fir	04	range
05	lacustrine	05	larch-fir	05	dryland crop
06	peat	06	Douglas-fir	06	irrigated crop
07	muck	07	mixed deciduous	07	irrigated hay
08	residual sandst.	08	cottonwood	08	dryland hay
09	residual shale	09	aspen	09	pasture
10	residual siltst.	10	trees	10	residential
11	residual limest.	11	dryland crop	11	urban
12	resid. crystalline	12	irrig. field crop	12	disturbed land
13	mixed alluvium	13	row crops	13	strip mine
14	alluvial	14	horticultural crop	14	mill tailings
15	colluvial	15	riparian	15	mine dump
16	soliflucate	16	mixed shortgrass	16	wildland
17	sandst. alluvium	17	mixed midgrass	17	landfill
18	shale alluvium	18	shrubs & grasses		
19	siltst. alluvium	19	halophytic		
20	crystalline alluv.	20	sedges & rushes		
21	limestone alluv.	21	perennial forage		
		22	tame pasture		

Appendix Table 8. Index for drainage, permeability, and erosion codes.

Code	Drainage	Code	Permeability	Code	Erosion
01	very poor	01	very slow	01	none
02	poor	02	slow	02	slight
03	poor to moderate	03	slow to medium	03	moderate
04	moderate	04	medium	04	severe
05	well	05	medium to rapid	05	slight-wind
06	well to excessive	06	rapid	06	moderate-wind
07	excessive	07	very rapid	07	severe-wind
08	'altered, drained'				
09	'altered, wetted'				

Appendix Table 9. Index for landscape position and landform codes.

Code	Landscape Position	Code	Landform
01	crest	01	sedimentary upland
02	ridge	02	mountains
03	upper midslope	03	playa
04	midslope	04	alluvial fan
05	lower midslope	05	sand dune
06	footslope	06	glacial outwash
07	level slope	07	ground moraine
		08	alpine till
		09	terrace
		10	floodplain
		11	plateau
		12	solifluction lobe
		13	patterned ground
		14	backswamp
		15	landslide
		16	badlands
		17	disturbed land
		18	talus

Appendix Table 10. Index for structure grade,
size, and kind codes.

Code	Structure grade	Code	Structure kind
01	massive	01	massive
02	weak: peds barely observable in place and when disturbed peds remain	02	platy
03	weak to moderate	03	granular
04	moderate: peds easily observable and when disturbed most of material consists of peds.	04	subangular blocky
05	moderate to strong	05	angular blocky
06	strong: peds distinctly visible, when disturbed entire soil mass is aggregated	06	prismatic
		07	columnar
		08	wedge

Code	Size Class	Diameter of granules	Thickness of plates (mm)	Diameter of blocks	Diameter of prisms
01	very fine	<1	<1	<5	<10
02	fine	1-2	1-2	5-10	10-20
03	medium	2-5	2-5	10-20	20-50
04	coarse	5-10	5-10	20-50	50-100
05	very coarse	>10	>10	>50	>100

Appendix Table 11. Index for soil consistence codes.

Code	Dry consistence	Code	Moist consistence
01	loose	01	loose
02	soft: easily crushes to powder	02	very friable: crushes under gentle pressure
03	slightly hard: easily broken between thumb and finger	03	friable: crushes easily under moderate pressure between 0 and finger
04	hard: easily broken in hand	04	firm: crushes under moderate pressure between thumb and finger
05	very hard: broken in hands with difficulty	05	very firm: barely crushable between thumb and finger
06	extremely hard: cannot be broken in hands	06	extremely firm: crushes under strong pressure in hand
07	indurated	07	induratedg
Code	Wet stickiness	Code	Wet plasticity
01	nonsticky: no adherence	01	nonplastic: no wire formed
02	slightly sticky: adheres to thumb and finger but comes off one cleanly	02	slightly plastic: wire forms but easily deformed
03	sticky: soil adheres and stretches before pulling apart	03	plastic: wire forms, moderate pressure required to deform
04	very sticky: soil adheres to both fingers	04	very plastic: wire forms, much pressure required to deform

Appendix Table 12. Index for root abundance, size, and location codes.

Code	Size	Code	Location
01	none	01	none
02	very fine (0.1-1mm)	02	throughout horizon
03	fine and very fine	03	between peds
04	fine (1-2mm)	04	flattened in cracks
05	medium and fine	05	flattened around rocks
06	medium (2-5mm)	06	mat at top of horizon
07	coarse and medium		
08	coarse (>5mm)		
09	fine and coarse		

Code	Abundance CLASS	Very fine	Fine (NUMBER/DM**2)	Medium	Coarse
01	none				
02	trace				
03	few	<10	<10	<1	<1
04	few to common				
05	common	10-100	10-100	1-10	1-5
06	common to many				
07	many	>100	>100	>10	>5

Appendix Table 13. Index for pore size and kind codes.

Code	Size	Code	Kind
01	none	01	none
02	micro and very fine	02	irregular and tubular
03	very fine (.1-.5mm)	03	tubular
04	fine and very fine	04	tubular continuous
05	fine (.5-2mm)	05	tubular discontinuous
06	medium and fine	06	vesicular
07	medium (2-5mm)	07	vesicular and tubular
08	coarse and medium	08	interstitial voids between peds
09	coarse (>5mm)	09	interstitial voids between rocks

Appendix Table 14. Index for effervescence in HCl, and horizon boundary codes.

Code Effervescence		Lower Horizon Boundary	
		Code Distinctness	Code Shape
01 noncalcareous		01 abrupt (<1in.)	01 smooth
02 slight		02 clear (1-2.5in.)	02 wavy
03 moderate		03 gradual (2.5-5in.)	03 irregular
04 violent		04 diffuse (>5in.)	04 broken
		05 arbitrary	05 arbitrary
		06 not reached	06 not reached

APPENDIX III: SELECTED PLANT TISSUE AND SOIL ANALYSIS
PROCEDURES.

TOTAL S PROCEDURE FOR PLANT MATERIAL^{1/}

EQUIPMENT:

1. Spectrophotometer with flow-through cuvette
2. 50 ml beakers
3. Manostat auto-pipettes - 10 ml and 4 ml
4. Hot Plate
5. Muffle Furnace
6. Whatman #42 filter papers (11 cm)
7. 50 ml volumetric flasks with stoppers
8. Long stem funnels
9. Funnel racks
10. 50 ml Erlenmeyer flasks
11. 10 ml pipette

REAGENTS:

1. 95% ethanol.
2. Saturated magnesium nitrate solution: 950 g/l of $\text{Mg}(\text{NO}_3)_2 \cdot 6 \text{H}_2\text{O}$.
3. Acid solution: add 50 ml concentrated HCl to 50 ml acetic acid. Shake before use.
4. Turbidity solution: combine 200 ml distilled water at 65°C with 0.6 g of gelatin (Knox), cool, then swirl in 4.0 g $\text{BaCl}_2 \cdot 2 \text{H}_2\text{O}$ crystals. Refrigerate when not in use.

^{1/}

Procedure provided by Dr. D. T. Westermann, USDA, ARS, Snake River Conservation Res. Ctr., Kimberly, Id.

Procedure:A. Dry-ash

1. Place 0.5 g dry, ground plant sample into 50 ml beaker.
2. Add 2.0 ml of 95% ethanol.
3. Add 3.0 ml $\text{Mg}(\text{NO}_3)_2$ solution. Then place beakers on warm hot plate to dry. Avoid excess heating.
4. Ash at 500° to 550°C for 2 hours in muffle furnace. (Allow a full 2 hours when furnace reaches 500°C).
5. Remove beakers (allow to cool) and dissolve ash in 10 ml of 3N HCl. Heating on warm hot plate aids in dissolution.
6. Rinse beakers with 5 ml of 3N HCl then with 10 ml deionized distilled water.
7. Filter through Whatman #42 filter paper and bring to 50 ml volume with deionized distilled water.

B. Turbidity

1. Pipette a 10 ml aliquot from the volumetrics into a 50 ml Erlenmeyer flask.
2. Add 1 ml of acid solution, swirl, and allow to stand 1 hour.
3. Add 1 ml of room temperature turbidity solution, swirl, and allow to stand 30 min. (Timing here is critical.)
4. Swirl samples 15 seconds and read turbidity at 500 nm.

COMMENTS:

1. Blanks should be included (from Step 2 of dry ash procedure) to allow for spectrophotometric zeroing. If the instrument drifts, use a blank to zero midway through the analysis.
2. Standard curves (in working range of samples run) are constructed by:
 - a. Adding 54.34 g K_2SO_4 to a 1000 ml volumetric flask brought to volume with distilled water. This is the 10,000 ppm stock solution.
 - b. Making standards (in the working range) from the 10,000 ppm stock solution in 100 ml volumetrics. This is accomplished weekly to reduce the incidence of standard degradation, as the 10,000 ppm solution is stable with time where as the 100 ppm, or less, is not.
 - c. Standard curve solutions, of appropriate concentrations, are not ashed. Begin with the turbidity portion of the procedure by pipetting a 10 ml aliquot.
3. Use automatic pipettes (Manostat) for dry-ash Steps 2, 3, and 5, and turbidity Steps 2 and 3.
4. Carefully pipette the 10 ml aliquot in turbidity Step 1.
5. Do not deviate from the time schedule described in the turbidity procedure.
6. Turbidity solution can be stored only 2 weeks. Solution degradation causes increase in turbidity after that time.

NITRIC-PERCHLORIC ACID DIGESTION FOR MICRONUTRIENT

ANALYSIS OF PLANT MATERIAL^{1/}

EQUIPMENT:

1. Hot Plate
2. 2-3 mm Glass Beads
3. 125 ml Erlenmeyer flasks

REAGENTS:

1. Nitric Acid (HNO_3) concentrated
2. Perchloric acid (HClO_4) concentrated

SAFETY:

In addition to normal laboratory safety, certain precautions are necessary for using perchloric acid. A stainless steel fume hood which may be washed internally with running water between digests or at frequent intervals is required. Glass beads are added to the plant material before adding any acid to smooth boiling and prevent bumping. While the digestion flasks are on the hot plate, close supervision is required in case of problems which might occur with the boiling acid. Perchloric acid easily becomes explosive, particularly with organic materials or if HEATED TOO FAST.

^{1/} Procedure modified from that described by Kresge, P.O. 1977. Diagnosis and correction of copper deficiency of small grains in Oregon. Ph.D. Thesis, Oregon State University.

PROCEDURE:

Dry and grind plant tissue samples to pass 40 mesh screen.

1. Weigh 0.5 g of plant tissue (with analytical balance) into 125 ml Erlenmeyer flasks. With a small scoop place 6-10, 2-3 mm glass beads into flask to control boiling.
2. Add 8.0 ml concentrated HNO_3 to the flasks and allow to stand overnight or equivalent period (minimum 2 hours).
3. Place flasks on hot plate heated to at least 300°C . Remove flasks from hot plate when dense red smoke emission begins to subside.
4. Cool flasks to room temperature and add 3.0 ml concentrated HClO_4 . Place flasks on hot plate at 300°C then increase plate temperature and evaporate to dryness. Dryness includes the sides of the Erlenmeyer flasks.

NOTE: Be sure there are no black carbon flakes in the solution prior to adding HClO_4 . If there are, or if digestion is not complete, add 5-8 ml of HNO_3 and repeat steps beginning at No. 3.

5. Cool to room temperature.
6. Add 10 ml 3 N HCl .
7. Allow to stand overnight (at least 12 hours).
8. Product is 1:20 dilution.

COMMENTS:

Analysis of digestant is usually completed with an atomic absorption spectrophotometer. Generally, Cu and Zn require no dilution while Ca, Mg, Mn, and K will be diluted.

TOTAL NITROGEN DIGESTION AND DISTILLATION PROCEDURE

FOR PLANT MATERIAL^{1/}

EQUIPMENT:

1. Aluminum digestion block with temperature controller
2. Stainless steel test tube racks
3. Suitable fume hood
4. 25 x 200 mm test tubes
5. Titration apparatus (Manostat Digi-Pet)
6. Manostat Dispenser (10 ml)
7. 50 ml Erlenmeyer flasks
8. 125 ml Erlenmeyer flasks
9. Magnetic stir bars and stirrer
10. 4 l glass container for boric acid solution
11. Rheostat (Variable transformer)
12. Steam generation unit
13. 25 ml automatic stopcock type pipette
14. Thomas pinch-clamps
15. 3-way stopcocks
16. Vacuum source

^{1/}

Similar to semi-micro Kjeldahl method of Bremner, J.M. 1965. Total Nitrogen. In C.A. Black (ed.) Methods of Soil Analysis. Agron. 9:1171-1175. Amer. Soc. of Agron., Madison, WI

REAGENTS:

1. Salicylic acid - sulfuric acid solution: Dissolve 55.6 g salicylic acid in concentrated sulfuric acid (use 9 lb bottle of H_2SO_4 with a magnetic stirrer).
2. Sodium thiosulfate: $Na_2S_2O_3 \cdot (5H_2O)$ crystals.
3. Catalyst: Grind thoroughly a 100:10:1 mixture of K_2SO_4 : $CuSO_4 \cdot (5H_2O)$: Se.
4. Sodium hydroxide: Dissolve 900 g NaOH in 2 l of distilled water (add in small amounts because of heat release). Add 1.75 g phenolphthalein (use magnetic stirrer).
5. Boric acid-indicator solution: Combine 80.0 g of boric acid (H_3BO_3) with 3800 ml of distilled water in a 4 l flask; swirl until H_3BO_3 dissolves. Add 80 ml of mixed indicator solution prepared by dissolving 0.099 g of bromocresol green and 0.066 g of methyl red in 100 ml ethanol. Add 0.1 N NaOH cautiously (approx. 190 drops) until a color change from pink to pale green is just detectable when 1.0 ml of solution is treated with 1 ml of water. Bring H_3BO_3 solution to 4 l volume with distilled water.
6. Hydrochloric or sulfuric acid titration solution: Make up 1.85 N HCl or H_2SO_4 acid solution. Store in sealed glass container. Check normality periodically with THAM procedure.
7. THAM^{1/}: Place 0.03 g (approx.) THAM in 2 125 ml Erlenmeyer flasks. Add 50 ml distilled water to the THAM flasks plus a blank flask.

^{1/} Tris(hydroxymethyl) aminomethane [2-amino-2(hydroxy-methyl) 1,3-propanediol]

7. Cont'd. Add 6 drops of indicator^{1/}; titrate each solution and blank with plant titration acid.

RECORD:

	<u>WT.</u>	<u>ML. TITRATED</u>
Blank	_____	_____
THAM 1	_____	_____
THAM 2	_____	_____

CALCULATE:

$$\text{Normality} = \frac{\text{Wt.}}{(\text{Acid-blank}) \times .1211}$$

DIGESTION:

1. Weigh 0.1 g of ground plant sample into clean, dry 25 x 200 mm test tube.
2. Add 5.0 ml salicylic-sulfuric acid solution to each tube and allow to stand at least 2 hours.
3. Add 1.0 g sodium thiosulfate (use calibrated spoon) and place tubes on 500°F (260°C) digestion block for 2 hours or until "frothing"^{2/} is complete.
4. Remove tubes from block and allow to cool.
5. Add 1.0 g catalyst (use same calibrated spoon from #3). Then wash down inner tube with 4.0 ml distilled water.
6. Place tubes on digestion block (block must be less than 100° C) and allow to digest at 600° F (315° C) until clear (approx. 4 hours).

- ^{1/} Triturate 100 mg bromocresol green with 1.45 ml of 0.1 NaOH and dilute to 100 ml CO₂ free water. Dissolve 100 mg Alizarin red S in 100 ml CO₂ free water. Mix 1 part bromocresol green-NaOH solution with 1 part Alizarin red S solution.
- ^{2/} Active bubbling (small bubbles) at glass, water, air intersection in tube.

7. Remove tubes and allow to cool (approx. 10 min.). Then add 10 ml distilled water.
8. Refrigerate tubes between digestion and distillation when stored over 24 hours.

DISTILLATION:

1. Assemble 50 ml Erlenmeyer flasks and dispense 8.0 ml boric acid solution into each.
2. Place test tube on distillation apparatus, dispense 1:1 (vol : vol) NaOH solution into each test tube (approx. 15 ml) and allow to distill to 30 ml volume in 50 ml Erlenmeyer containing boric acid solution.

TITRATION:

1. Titrate each 50 ml Erlenmeyer flask (green color) to neutral (just to pink color) and record amount of acid added as accurately as possible (recommended to thousandths of a ml).

CALCULATION:

1. Subtract ml acid per blank from ml acid per sample. Multiply this difference by N acid and .014. Divide product by sample wt (g) and multiply quotient by 100. This calculation equals % N.

COMMENTS:

1. The steam generation units used were 1000 ml Pyrex No. 5000. Two distillation apparatus were attached to one steam unit.
2. Automatic stopcock type pipettes used were 25 ml Kimax (Kimble No. 37075F).

3. Rheostats (variable transformers) are necessary to allow for equality in steam generation throughout the system. When more than one steam unit is required, the rate of distillation must be regulated.
4. The aluminum digestion block and stainless steel racks were designed and constructed by Mr. Gordon Williamson.^{1/}
5. The distillation units used were a modification of the Kemmerer-Hallett^{2/} unit. Mr. Gordon Williamson^{1/} adapted them for use with 25 x 200 mm test tubes by;
 - a. Removing the stopcock reservoir, leaving only the tubular unit. (This connects to the stopcock type automatic pipette for NaOH addition.)
 - b. Cutting the steam tube (originating from the steam generation flask) to allow for easy adaption of the high pressure tubing from 3-way stopcock.
 - c. Reconstructing a 125 ml (Pyrex No. 4060 with a 29/42 ground glass joint) flask to accomodate a quick release hook-up for the 25 x 200 mm test tubes.
 - d. Grinding a Thomas pinch-clamp to fit the upper lip of the 25 x 200 mm test tube and the lower portion of the boiling chamber (c above).
6. The 3-way stopcocks are utilized to provide steam and vacuum for the distillation apparatus.
7. Thomas pinch-clamps hold the 25x200 mm test tubes to the distillation apparatus.

^{1/} Technical Services, Ryon Lab, Montana State Univ., Bozeman, MT. 59717

^{2/} Fisher Scientific Catalog 77, p 849, No. 21-150.

8. Tubes may be cooled in the block if 50 g of sand are placed in the bottom of the aluminum block cavities. This keeps tubes from breaking during blocks concentration when cooling.

PHOSPHORUS PROCEDURE FOR PLANT MATERIAL^{1/}

EQUIPMENT:

1. 30 ml test tubes
2. Spectrophotometer (with dipping probe or flow-through type cuvette)
3. Automatic dispenser
4. Automatic pipette
5. Diluter/dispenser
6. Pipette

REAGENTS:

1. Stannous chloride stock solution: Dissolve 10 grams of reagent grade $\text{SnCl}_2 \cdot (2\text{H}_2\text{O})$ in 25 ml of concentrated HCl. Keep the solution in a black, glass-stoppered bottle. Store in refrigerator. Prepare a fresh solution every 6 weeks.
2. Ammonium molybdate solution: Dissolve 15 grams of reagent grade $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot (4\text{H}_2\text{O})$ in 350 ml deionized distilled water. Add slowly 350 ml of 10 N HCl while stirring. Cool to room temperature, add deionized distilled water to 1 liter volume. Store in dark stoppered glass bottle. Prepare fresh solution every 2 months.
3. Stannous chloride dilute solution: Mix 1 ml of SnCl_2 stock solution with 333 ml of deionized distilled water. Make fresh solution every 2 hours as needed.

^{1/}

T. Goodman's modification of the quantitative determination phase of Olsen, S.R. and L.A. Dean. 1965. Phosphorous. In C.A. Black (ed.) Methods of Soil Analysis. Agronomy 9:1040-1041. Am. Soc. of Agron., Madison, Wis.

PROCEDURE:

1. Dilute 1:10 (vol:vol) digestant:water with pipette into test tube. (Product from the wet nitric-perchloric acid digest, the 1:20 dilution, is now 1:200 dilution).
2. Dilute 1:10 (vol:vol) digestant (1:200): water with diluter into 30 ml (or appropriate substitute) test tube. (product is now 1:2000 dilution).
3. Add 12.5 ml ammonium molybdate with auto-dispenser and swirl.
4. Vigoursly add 2.5 ml dilute stannous chloride solution.
5. Allow solutions to react for 5 to 6 minutes, but not more than 20 minutes.
6. Read % T at 650 mu.
7. Standard curve solutions should be prepared to 2.0 ppm. (At least 5 curve solutions should be run with each analysis).
8. Final product (assuming 1:20 original dilution) is 1:5000.

CALCULATION:

1. Use standard curve regression coefficients (log curve) to calculate % P in plant from:
 - a. multiplying ppm (from regression) by dilution factor which equals ppm in plant.
 - b. multiplying ppm in plant by a % conversion factor which equals % P in plant.

SULFATE-SULFUR PROCEDURE FOR SOIL^{1/}

EQUIPMENT:

1. Spectrophotometer with flow-through cuvette
2. Shaker
3. Filter racks
4. 50 ml Erlenmeyer flasks
5. Test tubes and rack
6. 1 1000 ml volumetric flask with stopper
7. 100 ml volumetric flasks
8. Whatman #42 filter paper (11 cm)
9. 1, 250 ml volumetric flask with stopper

REAGENTS:

1. Extracting solution: Dissolve 156 g of ammonium acetate ($\text{NH}_4\text{C}_2\text{H}_3\text{O}_2$) in 4 liters of 0.25N acetic acid. (For 4 liters 0.25N acetic acid, dissolve 57.2 ml conc. acetic acid in distilled deionized water to a volume of 4 liters).
2. Sulfate-free charcoal: Wash Darco G60 carbon with extracting solution until blanks read 99% T or better (Usually two washes will clean charcoal sufficiently; dry charcoal before use).
3. Acid "seed" solution: 6N HCl containing 20 ppm sulfur as K_2SO_4 . Pipette 50 ml of 100 ppm S solution into a 250 ml volumetric flask, add 125 ml of conc. HCl and bring to volume with deionized distilled water.

^{1/} J. Kunard's modification of the acetate-soluble sulfur method, Bardsley, C. E., and J. D. Lancaster. 1965. Sulfur. IN C. A. Black (ed.) Methods of Soil Analysis. Agronomy 9:1111-1113. Am. Soc. of Agron., Madison, Wis.

4. Barium Chloride: $\text{BaCl}_2 \cdot (2\text{H}_2\text{O})$ 20 mesh crystals. Before beginning each analysis, weigh out 0.50 g BaCl_2 for each sample including blanks and standard solutions. Use analytical balance for accurate weight and place BaCl_2 for each sample in a separate test tube.
5. Sulfur stock solution: Makeup 100 ppm solution weekly from 10,000 ppm S. (Use 54.34 g of K_2SO_4 to make one liter of 10,000 ppm.) Curve solutions containing 0, 0.5, 1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 30, 40, and 50 ppm S can be made using different proportions of 100 ppm S solution and distilleddeionized water. Any of these solutions used to check the curve should be madeup from 100 ppm S solution.

PROCEDURE:

1. Weigh 10 g of soil into the proper extraction racks. Soil should be well mixed before weighing.
2. Add 25 ml extracting solution to each.
3. Shake samples for 30 min.
4. Add 0.25 g of charcoal to the standards and to each sample and shake for 3 more minutes. (Charcoal should either be pre-weighed into separate test tubes or use an accurately calibrated scoop.)
5. Filter solutions through Whatman #42 filter papers in filter racks.
6. Pipette 10 ml of each solution into separate 50 ml Erlenmeyer flasks.
7. Add 1 ml of acid "seed" solution to each sample and swirl.

8. Analyze 10 samples at a time. Using a blank to start each group of 10 will help detect problems such as movement of the flowthrough cuvette, accumulation of precipitate on the inside of the cuvette, contamination, etc.
 - a. Add 0.50 g BaCl_2 to each sample 30 seconds apart.
 - b. After adding BaCl_2 to the third sample, the first sample will have been allowed to sit for one minute with the BaCl_2 crystals in it. Swirl the first sample for 30 seconds.
 - c. Treat each sample in the same manner: add BaCl_2 , sit one minute, swirl for 30 seconds. If the time schedule has been followed correctly, each sample will be read 5 minutes from this point.
 - d. When swirling the last of the 10 samples, be prepared to read your first sample immediately on the spectrophotometer.
 - e. Read samples in one minute increments at 420 μm .

CALCULATION:

The ratio of extracting solution to soil can be varied thus changing the dilution factor. The normal dilution factor is 2.5 from:

$$(\text{ppm in solution}) \times 25 \text{ ml}/10 \text{ g} = \text{ppm S in soil.}$$

COMMENTS:

1. In all analytical work concerning S, care should be taken to avoid contamination from water, detergents, rubber tubing, rubber stoppers, and filter papers or chemicals which may contain some S as impurities.

2. Clean equipment and glassware are essential, but avoid using soap. Brush with water, rinse with dilute HCl and follow with a thorough distilled water rinse.
3. Timing is critical; the barium chloride must be allowed to sit in the sample solution for exactly one minute or a higher % T reading will be obtained. Some samples may continue to develop heavier precipitation if not read on schedule.
4. Rinsing the flow-through cuvette with deionized distilled water between samples will help prevent accumulation of precipitate. Acid rinsing may be needed occasionally, especially after heavily concentrated samples.
5. Three to four standard curve solutions and at least one standard soil should be run with each analysis. Curve solutions, as well as acid "seed" solution should be made-up weekly as small concentrations of S in solution will deteriorate.

APPENDIX IV: ACCUMULATED GROWING SEASON PRECIPITATION.

Appendix Table 15. Precipitation received at Bozeman, Montana from 1 April through 4 August, 1979.

Month	Week	Precip. (mm)
April	01 - 07	381
	08 - 14	1067
	15 - 21	1600
	22 - 28	1118
	29 -	
May	- 05	152
	06 - 12	330
	13 - 19	76
	20 - 26	152
	27 -	
June	- 02	4877
	03 - 09	914
	10 - 16	0
	17 - 23	8331
	24 - 30	51
July	01 - 07	0
	08 - 14	0
	15 - 21	0
	22 - 28	1092
	29 -	
August	- 04	406

Appendix Table 16. Precipitation received at Bozeman, Montana from 1 April through 2 August, 1980.

Month	Week	Precip. (mm)
April	01 - 05	51
	06 - 12	406
	13 - 19	254
	20 - 26	152
	27 -	
May	- 03	330
	04 - 10	3861
	11 - 17	1397
	18 - 24	610
	25 - 31	7442
June	01 - 07	2134
	08 - 14	864
	15 - 21	2870
	22 - 28	1321
	29 -	
July	- 05	1092
	06 - 12	406
	13 - 19	610
	20 - 26	203
	27 -	
August	- 02	1118

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Gavlak, R. G.

Effect of nitrogen and sulfur fertilization on forages in the Gallatin Valley of Montana

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