AN ABSTRACT OF THE THESIS OF

WANEE AKRATANAKUL for the MASTER OF SCIENCE
(Name of student) (Degree)

in SOILS presented on Sept. 29, 1971
(Major) (Date)

Title: THE EFFECT OF SOIL TEMPERATURE AND SOIL MOISTURE STRESS ON S-UREA MINERALIZATION AND RYEGRASS YIELD

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Abstract approved: ______________________
Dr. M. D. Dawson

A growth chamber experiment was conducted to determine the rate of S-urea mineralization and effect of S-urea on the yield of ryegrass (Lolium multiflorum) grown in Steiwer soil as influenced by soil temperature (60, 75, and 90° F) and soil moisture stress (0.10, 0.35, and 2.50 bars). Plant yield, nitrogen and sulphur uptake and amount of S-urea mineralized were studied.

The optimum conditions for ryegrass growth appeared to vary due to the interaction between soil temperature and moisture status. Increasing root temperature indicated a higher soil moisture content was required for optimum ryegrass growth. High soil temperature and low soil water suction decreased the percent plant nitrogen in 31-day old seedlings. Ryegrass N-uptake was highest in the 31-day old seedlings maintained at 0.35 bar soil water suction and a root

temperature of 75° F.

Optimum conditions for S-urea mineralization to available $NH_4 + NO_3$ occurred at a soil temperature of 90° F and moisture stress of 0.10 bar. Moreover, the mineralization exceeded 60 percent of the S-urea added in only 9 days after application under these warm moist soil conditions. The amount of nitrogen mineralized was directly related to plant growth.

While SO_4-S mineralized from S-urea varied directly with soil temperature and moisture content unlike nitrogen mineralization no interaction between these two factors was observed.

Sulphur and nitrogen status in plants proved to have a close relationship. At low soil temperature and high soil moisture content luxury consumption of sulphate by ryegrass likely occurred.

The Effect of Soil Temperature and Soil Moisture Stress on S-Urea Mineralization and Ryegrass Yield

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1972

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Date thesis is presented Sept. 29, 1971

Typed by Opal Grossnicklaus for Wanee Akratanakul

ACKNOWLEDGEMENT

The author wishes to express her appreciation to Dr. M. D. Dawson for his advice and encouragement during the course of this study and in the preparation of this manuscript.

Acknowledgements are extended to Dr. L. Boersma for his constructive suggestions and use of facilities during this research, and to Dr. H. D. Reese for his guidance in chemical analysis.

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INTRODUCTION

Few crops have as high a demand for nitrogen in order to attain top production as does grass. Frequently high producing grass requires in excess of 500 lbs of N/acre/an for optimum yields. Numerous problems can emerge from supplying this rate of nitrogen to grasses using conventional nitrogen fertilizers. Slow release products such as S-urea were manufactured in an attempt to conserve applied nitrogen and thereby reduce its losses due to leaching, volatilization, denitrification or from luxury consumption by the grass itself. An adequate continuous supply of nitrogen for grass during the entire growing season with minimum loss, yet supplied in one or two applications would appear to be the characteristics of an ideal nitrogen fertilizer. Oxamide, urea formaldehyde and other urea polymers are the examples of nitrogen fertilizers having delayed release properties. However, the cost of these compounds is too high and nitrogen recovery from some of them is quite low. Sulphur-coated urea was developed by TVA (Tennessee Valley Authority) for low cost, slow release nitrogen fertilizer in expectation that it would meet the ideal characteristics previously described. Soil conditions and methods of application have been shown to affect the release rate of this fertilizer. However, little research has been conducted designed to determine the effect of both soil temperature and soil moisture on the mineralization of both nitrogen and sulphur from S-urea and its concurrent effect on plant growth and nutrient uptake. This investigation was therefore initiated with the following objectives:

1. To examine the rate of mineralization of S-urea applied to the Steiwer soil subjected to varying moisture stress and temperature.
2. To study the effect of S-urea on *Lolium multiflorum* yield when subjected to varying soil moistures stress and temperature.
3. To determine the uptake of nitrogen and sulphur in *Lolium multiflorum* when grown in S-urea treated soil subjected to varying moisture stress and temperature.

REVIEW OF LITERATURE

Nitrogen and Plant Growth

It is likely that the growth of plants is limited more often by a deficiency of nitrogen than any other nutrient. Viets (1965) calculated that plants contained more atoms of nitrogen derived from soil than of any other element except hydrogen. Nitrogenous compounds make up a significant part of the total weight of plants. In a plant that contains 1.6% nitrogen, for example, about 10% of plant weight is contributed by compounds containing nitrogen. Nitrogen occurs in both organic and inorganic forms in plants (Black, 1968). Sauchelli (1964) reported that nitrogen is utilized by the plant in the fabrication of protein, nucleoprotein, amino acids, amines, and various other nitrogenous compounds. And he further proposed that nitrogen is called the growth element and is present in largest amounts in the more tender, growing tissue such as buds, tip shoots, and developing leaflets.

Plants absorb most of their nitrogen in the ammonium and nitrate forms. The quantities of these two ions presented to the roots of plant depend largely on the amounts supplied as commercial nitrogen fertilizers and released from reserves of organically bound soil nitrogen. The amounts released depend on the balance that exists between the factors affecting nitrogen mineralization, immobilization, and losses from the soil (Tisdale and Nelson, 1966).

Terman et al. (1968) reported that ryegrass uptake of soil nitrogen increased as fertilizer nitrogen was depleted from the soil. Total yield of dry forage and uptake of nitrogen were linear for all rates of nitrogen applied from 0 to 900 mg N per pot (3 kg of soil). Reid (1970) found that in a perennial ryegrass sward the dry matter yield response to nitrogen rate was almost linear between the 0 and 300 lb N/acre then it decreased steadily and became nonsignificant at about the 500 lb N/acre.

Lewis and Lang (1957) and Dotzenko (1961) generally agreed that different species of grasses respond differently to the rate of nitrogen application. Hylton (1970) reported that tall wheatgrass grown in nutrient solutions to which nitrate had been added up to 32.0 meq of NO_3 per liter, significantly reduced the dry matter yield when less than 4.0 meq of NO_3 per liter was maintained. Accumulation and distribution of NO_3-N varied slightly between species.

Sulphur and Plant Growth

Sulphur occurs in plants as a constituent of (1) amino acids, cysteine, and methionone, (2) plays a role in the activation of certain vitamins, glutathion, and coenzyme A (3) occurs in some species as sulhydril(-SH) groups in plant tissue. Sulphur is essential in plant nutrition and a deficiency seriously affects crop quality (Coleman, 1966; Odelein, 1966). The requirement of this element varies among the different plant species. The cruciferae have particularly high requirements, as do the legumes, compared with the graminae which generally need less sulphur (Radet, 1966).

Matin (1966) stated that sulphur deficiency is being increasingly recognized as a limiting factor in forage production in many parts of the world. Beaton (1970) has stated that inadequate supplies of this element will seriously retard the growth of all plants including turf-grass, Woodhouse (1966) reported that coastal bermuda grass, which can tolerate very low levels of sulphur, will nevertheless respond quite dramatically to application of this element. In sulphur deficiency soils Anderson and Spencer (1950) found that sulphur deficiency in subterranean clover plants showed symptoms of nitrogen deficiency with a low percentage total nitrogen. Conrad (1950) and Burns (1967) found that sulphate was the principal form of sulphur found in surface runoff and percolating water. Under oxidation conditions sulphate losses from soil were quite large. McKell and Williams (1960) have shown that a large proportion of applied sulphate from gypsum moved out of the root zone in a single season. When leaching was a potential problem, sulphate retention by soil absorption reduced leaching losses very appreciably. Dawson (1969) reported that on soil subject to heavy leaching of sulphate like the Steiwer soil and Demint series, it would be more efficient to make annual applications of sulphur fertilizers each spring or apply some sulphur in the element form.

Nitrogen-Sulphur Relationships

Grass yield can be considerably increased by fertilizer nitrogen. However, high grass yields exert a large demand for other nutrients, including sulphur. Grass requires about one part of sulphur for every fourteen parts by weight of nitrogen for protein synthesis (Dijkshoorn et al., 1967). An insufficient supply of sulphur can affect both yield and quality of crops (Dijkshoorn et al., 1967 and Moir et al., 1967). Greenhouse studies showed that when sulphur became limiting, additional nitrogen did not affect either the yield or protein level of the plants, but the non-protein nitrogen increased. There was a close relationship between the amount of nitrogen and sulphur metabolized in plants. One part of sulphur was required for every twelve to fifteen parts nitrogen to increase maximum production of both dry matter and protein (Stewart and Porter, 1969). Walker (1957) reported that in the well drained grassland soils, most of the sulphur occurs in the organic matter and the average C:N:S ratio in the A horizon of normal soils is probably 100:8:1. In the absence of an outside source of sulphur nitrogen fixation in legume plants may cease.

Harward et al. (1962) reported a correlation coefficient of 0.897

between nitrogen content and sulphur content in alfalfa. Such a relationship might be expected considering the composition of plant protein. Vartha (1963) found that when both nitrogen and sulphur were applied together, the total herbage yield comprising that of the grasses, forbs and dead matter, showed a significant response to the application of nitrogen and sulphur. Dawson (1969) has shown that subterranean clover responded significantly to applied gypsum. Harward et al. (1962), Pumphrey (1965), and Sorensen (1968) have shown that nitrogen concentration and yield of alfalfa increased with the application of sulphur alone. O'Conner (1969) found that when the nitrogen supply in cockfoot and ryegrass was ample these grasses responded to sulphur applications. The effect of sulphur on perennial ryegrass was examined by Cowling and Jones (1970) who noted that sulphur additions had the greatest effect in soils with higher nitrogen levels. Thus dry matter yield increased from 6.5 to 19.0 grams per pot on the previously-cropped soil and from 10.6 to 15.8 grams per pot on the uncultivated soil. They further suggested that ryegrass at the higher rates of nitrogen, responded to added sulphur. When N/S ratio in ryegrass exceeded 20:1, yield was restricted by the supply of added sulphur. A nitrogen sulphur ratio of 1 has been proposed as normal for healthy graminous species. The higher N:S ratio indicated that a large portion of nitrogen in the plant had not been incorporated into protein and a high level of nitrate-N tended between nitrogen content and sulphur content in alfalfa. Such a relationship might be expected considering the composition of plant protein. Vartha (1963) found that when both nitrogen and sulphur were applied together, the total herbage yield comprising that of the grasses, forbs and dead matter, showed a significant response to the application of nitrogen and sulphur. Dawson (1969) has shown that subterranean clover responded significantly to applied gypsum. Harward et al. (1962), Pumphrey (1965), and Sorensen (1968) have shown that nitrogen concentration and yield of alfalfa increased with the application of sulphur alone. O'Conner (1969) found that when the nitrogen supply in cockfoot and ryegrass was ample these grasses responded to sulphur applications. The effect of sulphur on perennial ryegrass was examined by Cowling and Jones (1970) who noted that sulphur additions had the greatest effect in soils with higher nitrogen levels. Thus dry matter yield increased from 6.5 to 19.0 grams per pot on the previously-cropped soil and from 10.6 to 15.8 grams per pot on the uncultivated soil. They further suggested that ryegrass at the higher rates of nitrogen, responded to added sulphur. When N/S ratio in ryegrass exceeded 20:1, yield was restricted by the supply of added sulphur. A nitrogen sulphur ratio of 1 has been proposed as normal for healthy graminous species. The higher N:S ratio indicated that a large portion of nitrogen in the plant had not been incorporated into protein and a high level of nitrate-N tended to accumulate. Stewart and Whitfield (1964) determined the ratio of total nitrogen to total sulphur and protein-N to protein-S in wheat tissue. They propose that a total N:S ratio can be used as a very good criterion in assessing the sulphur status of plant.

Sulphur-Urea Fertilizer

Most nitrogen fertilizers are water soluble, hence they are readily available to crops (Allison, 1955). But solubility has several drawbacks. For one, soluble nitrate is easily leached. Second, too much soluble nitrogen may damage seedlings and plants. Third, when it is applied early in the season, soluble nitrogen may cause luxury consumption by plant followed by nitrogen deficiency in the crop late in the season especially with forages harvested two or more times during the crop season. A relatively uniform growth response coupled with efficient usage of nitrogen fertilizer are characteristics desired by forage crops.

The Tennessee Valley Authority researchers have made an extensive study manufacturing a slow release S-urea fertilizer where sulphur was used to coat water soluble urea. Sulphur was considered a promising coating agent for several reasons. It is inexpensive as compared with polymeric materials such as polyethylene, polyurethane, or natural resins, and is easily handled in the molten state necessary for coating granules. It may also have residual value on sulphur deficiency soils (Rindt et al., 1968). Slow release nitrogen fertilizers would make it possible for one application to replace repeated nitrogen applications to crops with long growing periods (Allen et al., 1968). Lunt (1967) stated that using sulphur as a coating material had the additional advantage of supplying plant nutrient sulphur. The coating of the element sulphur gradually breaks down under the action of soil microorganisms, releasing plant available sulphate ions. Lunt further suggested that the chief effect from using S-urea was twofold (1) to delay forage production until later in the season and (2) to produce a better distribution of protein throughout the season. Beaton et al. (1967) and TVA (1968) have shown that heavy rates of urea (360 lbs N/acre) nearly killed bermuda-grass turf, while sulphur coated urea at the same rate of nitrogen caused no damage and gave maximum increase in yield. Mays and Terman (1969) found that uncoated ammonium nitrate, urea and other readily soluble nitrogen fertilizers resulted in higher plant nitrogen uptake than when S-coated urea applied. But S-urea provided higher yields in the later-cutting than did the soluble nitrogen materials.

S-Urea Dissolution and Transformation

Burns (1967) stated that the temperature range within which biological oxidation occurs in soil was about 4° C to 55° C. Low soil temperatures often limit sulphur oxidation in the field. Nicolson (1970) found that increasing soil temperature from 10 to 20° C increased plant growth yet had little effect on soil sulphur transformation. Mineralization from the soil organic matter was too small to correct sulphur deficiency. Ahmed et al. (1963) studied capsule fertilizer and found that the release rate of fertilizer from capsules was directly related to temperature. Brown (1966) observed that release rate of sulphur coated urea were controlled by the thickness of the coating and the temperature of the medium. Between 5 and 35° C the increased release of urea was related to increase in temperature. He further suggested that raising temperature increased the surface area through which diffusion must take place. Allen et al. (1968) reported that dissolution of a sulphur coated urea granule layer in the soil was relatively rapid at 20 or 30° C but very slow at 10° C. TVA (1968) has reported that the dissolution rate of sulphur coated urea in water at 100° F was about 15% in the first 24 hours but only 1% per day thereafter. The rate of nitrogen release from sulphur coated urea appears highly soil temperature dependent.

Soil Temperature and Plant Growth

The level of food reserves in grasses has been found to depend partly upon temperature. In general, the accumulation of reserves has been reported to vary inversely with temperature (Hamid et al.,

(1966) and Sullivan et al., 1949). Nielson et al. (1960) and Brouwer (1962) stated that soil temperature and nitrogen influence the growth and chemical composition of plants. Generally, plant growth was best over a narrow range of root temperatures. Freind et al. (1962) suggested that the optimum temperature for overall absolute growth rate of wheat between emergence and anthesis was between 20 and 25° C. Under greenhouse conditions, Nielsen and Cunningham (1964) found that top growth of Italian ryegrass was near optimum at 19.5° C while root optimal growth was at 11° C. Raising the soil temperature greatly increased the percentage of Ca and Mg but had little influence on concentration of N, P, S, Na, and K. Beevers and Cooper II (1964) found that the percentage of total nitrogen was greatest in plants continuously grown at 12° C day temperature. A decrease in nitrogen was reported in the 25° C day and 12° C night temperature while lowest nitrogen content was noted at 25° C continuous temperature. The nitrate content decreased with decreasing temperature while ammonium-N increased with decreased temperatures. Beevers and Cooper I (1964) reported that reduced temperature greatly lowered dry matter yield of the plants and Italian ryegrass generally produced more dry matter than did the Irish ryegrass. Both species yielded near maximum in the 25° C day and 12° C night regimes. Davidson and Milthorpe (1965) found that the initial growth rates of cockfoot was increased by increasing temperature from 14 to 26° C. They also observed that the reduction in the relative growth rate with time at 22 and 26° C was associated with increase in the size which was partly reflected by reduction in the leaf-area ratio. Templeton et al. (1969) reported somewhat similar results with orchard grass. In continuous 70 to 80° F conditions a somewhat faster rate of leaf appearance and length of exposed leaf blades was reported. Tiller development was greater under alternative conditions of 70 to 80° F for 10 hours and 50° F for 14 hours. Stewart and Whitfield (1964) pointed out that temperatures between 55 to 65° F had no effect on the growth of winter wheat unless fertilizer was added. When N, P, S, fertilizer was added to treatments exposed to 65° F the yield almost doubled that obtained at 55° F.

Soil Moisture and Plant Growth

Dean and Gledhill (1956) postulated that soil moisture stress possibly affects the physiology of the plant or the availability of nutrients in the soil and thus nutrient absorption by roots. Mederski and Wilson (1960) found that corn yield of both tops and roots grown in soil decreased linearly with increasing soil water suctions. Mattas and Pauli (1965) reported total nitrogen per plant increased rapidly during initial stress and remained fairly constant thereafter. Moisture stress decreased soluble protein content. Sabey (1969) using ammonium-N saturated soil subjected to 0.0, 0.1, 0.33, 1.0, 5.0, and 15 bar soil moisture tension, found that nitrate-N accumulation in ppm per day was greatest at 0.1 bar in all soils. Cummins et al. (1967) found that with either low temperature or low moisture higher forage yields were obtained with a single nitrogen application. Under both high soil temperature and high soil moisture, split nitrogen application proved advantageous. Generally, low soil moisture increased nitrogen content of forage compared with high soil moisture.

Burns (1967) pointed out that moisture and aeration affect the biochemical oxidation of sulphur to sulphate. Sulphur oxidation was most rapid at moisture contents greater than field capacity. The heavier soil (more clay) oxidized sulphur more rapidly than sandy soil. Moser and Olsen (1953) suggested that sulphur oxidation might be expected to occur more rapidly in irrigated soils kept at high moisture contents. Giordano and Mortvedt (1970) studied the rate of nitrogen release from S-urea and subsequently uptake of nitrogen by rice. They reported the rate of nitrogen release was much greater in moist than in flooded soils. When the flooded soil was dried to field capacity, oxidation of the FeS coating appeared to seal the granules so that very little nitrogen was released. In general, the release of nitrogen was slightly greater when S-urea was applied to limed soil fertilized with phosphorus.

Nutrition and Root-Shoot Ratio

Differential yield and quality responses of perennial ryegrass strains to nitrogen under field conditions has been shown by Holmes (1955) and Hunt (1956). Hylton et al. (1965) reported that when the nitrogen supply was low, top growth and root growth of ryegrass was nearly equal. But as the nitrogen supply was increased, the tops grew at an accelerated rate and increased the ratio of tops to roots from 1.22 to a high value of 2.76. It was shown by Harris (1914) that the ratio of tops to roots of wheat seedlings was always greater in dilute soil extracts. Wheat harvested at different stages showed relatively more roots during an early stage of plant growth, but there was a little effect with age up to 30 days old on the root-shoot ratio values (Brouwer, 1966). Humphries (1958) has suggested that roots and shoots are in competition for minerals absorbed by the roots and carbohydrates manufactured by the shoots. When the nutrient supply was limiting, the root grew relatively more than the shoot, while a reduction photosynthetic product had a direct effect on root growth. Vose (1962) suggested that perennial ryegrass strains with narrow shoot-root ratios tended to give higher yields than strains providing a high shoot-root ratio. Low moisture supply increased root production while increase in nitrogen led to an increased shoot-ratio primarily due to enhanced shoot growth.

Temperature and Root-Shoot Ratio

An increase in root-shoot ratios with higher temperatures has been reported for many grasses. Ketellapper (1960) showed that shoot growth of *Phalaris tuberosa* L. was more strongly influenced by root temperature than by air temperature. However, the effect on the root growth itself was not considered. Troughton (1957) has shown with grass seedlings under field conditions during a period of increasing soil temperature that the relative size of root decreases with increasing age and size. Under uniform temperature, however, the shoot-root ratio in eight grass species was shown to decrease with increase in age (Sprague, 1944). Davidson (1969) found that the ryegrass root-shoot ratio values were constant when the root temperature increased from 20 to 27.7° C. The growth of grass roots was slowest in summer and increased through autumn (Stuckey, 1941 and Jacques, 1957). Soper (1957) suggested that a combination of lower light intensity and higher temperature reduced both root and shoot weights of perennial ryegrass, but had a greater effect on root weight. By contrast, a return to full light and lower temperature resulted in a larger increase in the root-shoot ratio that exceeded plants grown continuously under similar conditions.

Soil Moisture-Air and Root-Shoot Ratio

Vose (1962) stated that plants grown without aeration have higher shoot-root ratio than those grown with aeration. Although there was a lower weight of roots in the non-aerated treatments, the actual number of roots was very significantly increased. The number of tillers was greater in aerated than in non-aerated treatments. Harris (1914) found that roots of corn plants grown in sand showed a greater root growth with lower amounts of soil water. Davidson (1969) pointed out the interaction between soil nutrients and soil moisture. Ryegrass showed better growth at lower soil moisture tensions than when moisture suction approached pF 3. Yields of ryegrass shoots were depressed by nitrogen in the absence of phosphorus at low soil moisture levels which resulted in low shoot-root ratio. The relative weight of roots was inversely proportional to soil moisture as well as the nitrogen and phosphorus concentration. Moisture had a small effect on the root-shoot ratio when nutrients were adequate. Under such conditions the root-shoot ratio approximated 0.41.

MATERIALS AND METHODS

Growth Chamber Experiment

The experiment which was designed to study the transformation of S-urea in soil planted to ryegrass (Lolium multiflorum) was conducted in a growth chamber. A factorial design was used in a randomized block with two replications. Ryegrass was grown in cells bathed in osmotic solutions and maintained at varying temperatures.

Specifically, tetraploid ryegrass seeds were germinated in a growth chamber for four days. Ten seedlings were transplanted into each cell (Figure 1) filled with 240 gms. of Steiwer soil previously fertilized with KH_2PO_4 at rate which provided an equivalent of 80 kgs. P and 100.7 kgs. K/hec. All cells were placed into a growth chamber on trays containing distilled water to a level of 1.5 cm. The growth chamber was set at day temperature of 78° F and a night temperature of 73° F. After fourteen days the grass seedlings were removed from the growth chamber and the plastic side of each cell was removed to prepare for the application of S-urea fertilizer. Pellets (1 to 2 mm. diameter) of S-urea fertilizer (34.5%, N, 20.5% S with dissolution rate 27.0% in 7 days, 29.2% in 13 days, 31.8% in 21 days) were carefully placed in the soil at 1.5 cm. distance from the frame of the cell at the rate equivalent to 300 kgs. N and 178 kgs. S/hec. The

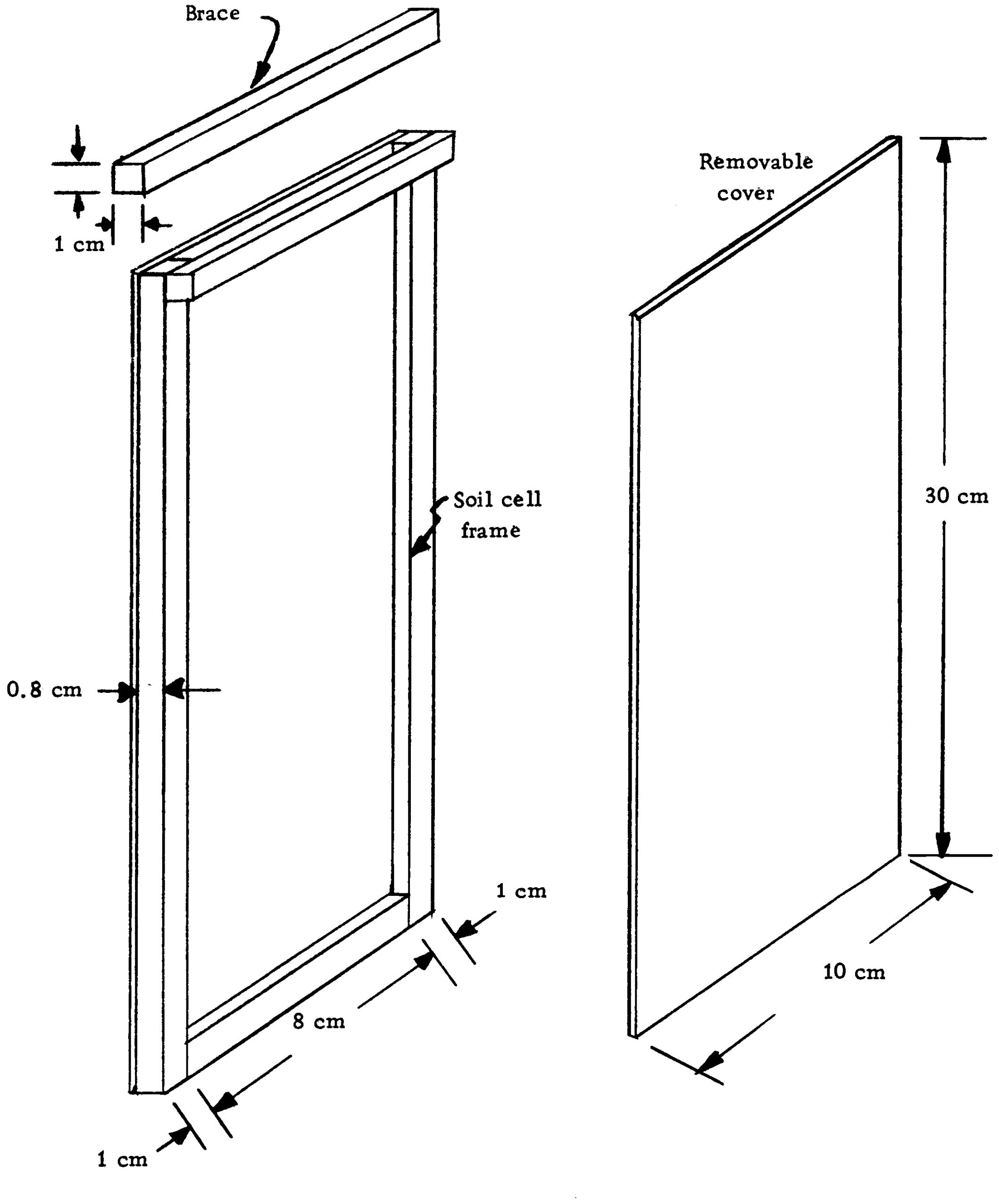


Figure 1. Schematic diagram of the plastic cell used, showing removable cover and braces.

fertilized cell units were covered with plastic sides and put in the growth chamber for a further five days. Twelve cells containing grass and soil were randomly selected for sampling and dry weight determination. Thereafter the plastic sides of each cell were removed and each cell unit was put into a semipermeable cellulose acetate membrane as described by Kuo (1970). The cells were then immersed in the chamber containing a range of osmotic solutions adjusted to provide suctions of 0.10, 0.35, and 2.50 bars (Figure 2). Three different temperatures (60, 70, and 90° F) were used at each level of moisture suction. The technique for controlling the soil water suction, soil temperature and design of the osmotic bath used in this study was suggested by Zur (1961) and developed by Cox (1966).

The osmotic solutions were prepared with carbowax 6000 (polyethylene glycol) dissolved in distilled water at the desired concentrations so that unit cells containing grass seedlings were subjected to the desired water suction. The solution was stirred with a stirrer rod by hand twice a day in order to avoid the development of concentration gradients in the osmotic solutions.

Soil temperature was controlled by the use of chambers surrounded by a water-jacket which was connected to a constant temperature water bath. The room temperature was set at 75° F and relative humidity ranged from 40 to 50 percent. The light from the fluorescent tubes and incandescent lamps was maintained at 1800

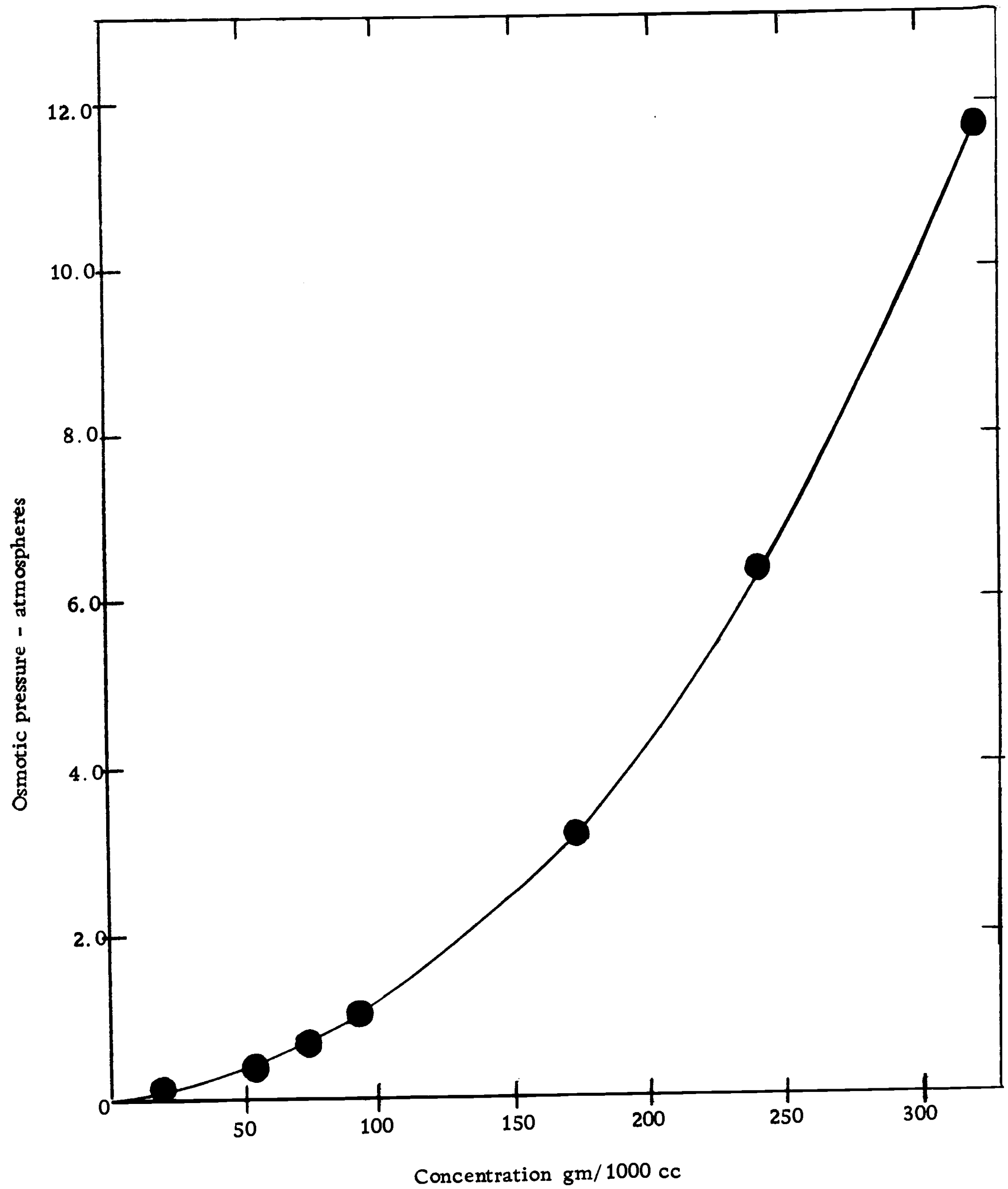


Figure 2. Osmotic pressure of a carbowax 6000 solution as a function of concentration (After Zur, 1961).

ft-candle on the top of the plants. Air movement was continuously forced by electric fan during the experiment.

Plants were removed for dry weight determination and chemical analysis at four day intervals (0, 4, 8, and 12 days). At the same intervals samples of soil from individual cells and a water sample from the osmotic bath were taken for subsequent available N and SO_4-S determination. Plant dry weight was determined after oven drying at 72° C for 48 hours. The dry samples were ground separately with a blending mill to a uniform meal-like fineness. The ground samples were then redried in the oven at 52° C for 24 hours and kept in a desiccator until subsequent chemical analysis.

Soil samples for chemical analysis were carefully removed at each harvest interval from the middle of each cell from the top to bottom to avoid plant roots and fertilizer granules previously banded in the soil. The soil samples were kept in glass bottles with plastic covers. Samples taken from the osmotic solutions were transferred from each chamber into individual bottles and covered with caps. Both the soil and solution samples were stored in the refrigerator until chemical analysis was performed.

Soil Incubation Study

Incubation studies were carried out using a technique suggested by Vlassak (1970). Fifty grams of air-dried Steiwer soil were put into 150 ml flasks and moistened to 65% of water holding capacity. The flasks were closed with plastic covers and incubated at 30° C. The soil samples were removed at 0, 2, 4, 8, 16, 24, and 32 days and placed in glass bottles fitted with plastic covers and stored in the refrigerator ready for chemical analysis.

Root-Shoot Ratio Determination

A similar technique was used in the root-shoot ratio experiment except ryegrass seedlings were grown in perlite filled cells. The plants were provided water and nutrient solution on alternate days for a nineteen day period. Each bank of six cells containing grass seedlings was then immersed in the plant nutrient osmotic solutions adjusted to provide water suctions of 0.35 and 2.50 bars respectively and maintained at 75° F. Plant shoots and roots were individually removed from the perlite cells and dried in the oven at 72° C for 48 hours. Dry weight of shoots and roots for each soil water suction was measured, and root-shoot ratios were calculated. Dry weight of shoots and roots for each soil water suction obtained from the perlite experiment were used together with the dry matter yield and total nitrogen and sulphur analyzed from the shoots of plants grown in soil to calculate total plant nitrogen and sulphur for each treatment.

The influence of moisture suction and temperature on the rate of nitrogen mineralization of S-urea was determined from the following formula:

$$Nm = \frac{n_1 + n_2 + n_3 + n_4 - n_5}{Nf} \times 100$$

Where Nm = percent N mineralized from S-urea

n_1 = nitrogen content of shoots

n_2 = nitrogen content of roots

n_3 = NH_4-N + NO_3-N in osmotic solution

n_4 = NH_4-N + NO_3-N in fertilized soil

n_5 = NH_4-N + NO_3-N mineralized from unfertilized soil

Nf = total nitrogen content of S-urea fertilizer

Similarly the rate of sulphur mineralization from S-urea was calculated from the formula:

$$S_m = \frac{s_1 + s_2 + s_3 + s_4 - s_5}{Sf} \times 100$$

Where S_m = percent S mineralized from S-urea

s_1 = sulphur content of shoots

s_2 = sulphur content of roots

s_3 = SO_4-S in osmotic solution

s_4 = SO_4-S in fertilized soil

s_5 = SO_5-S mineralized from unfertilized soil

S_f = total sulphur content of S-urea fertilizer

Soil Chemical Analysis

Available nitrogen and sulphate sulphur were determined from the sampled soil. The available soil nitrogen (combined ammonium and nitrate nitrogen) procedure used in this study were modified by Soil Testing Laboratory, Oregon State University from the extraction-distillation method proposed by Bremner and Keeney (1966). Ten grams of air-dried soil was extracted with 50 ml of 2 M KCl. The extract was analyzed by steam distillation in which magnesium oxide was used for distillation of ammonium and ball-milled Deverda alloy for reduction of nitrate to ammonium. A 30 ml aliquot of the distillate was taken for the determination of ammonium nitrogen by titrating with 0.005 N HCl from a microburette.

In the soil sulphate method, ten grams of air-dried soil samples were extracted with 20 ml of 500 ppm P KH_2PO_4 solution. The sulphate in the extractant was digested as described by Johnson and Nishita (1952) with a reducing mixture composed of hydriodic acid, formic acid and hypophosphoric acid. The resulting hydrogen sulphide was determined by spectrophoto-metrically as methylene blue colorimetric procedure using Bausch and Lomb Spectronic 20 spectrophotometer at a wavelength of 670 mμ.

Plant Analysis

Total plant nitrogen and sulphur were determined according to method used in the Plant Analysis Laboratory in the Oregon State University Soils Department (1964). The plant material was digested in a volumetric flask with nitric and perchloric acid and the sulphate content of an aliquot of the digest was determined turbidimetrically as barium sulphate by barium chloride. Twenty minutes later the turbidity was read in the colorimeter using a wavelength of 500 mμ.

Total nitrogen was determined by the modified microKjeldahl procedure described by Jackson (1958).

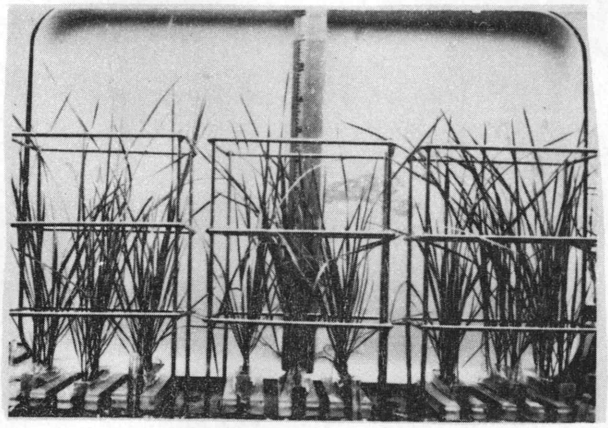


Figure 3a. 27-day old plants subjected to 60°F root temperature and soil water suctions of 0.10, 0.35, and 2.50 bars respectively (left to right).

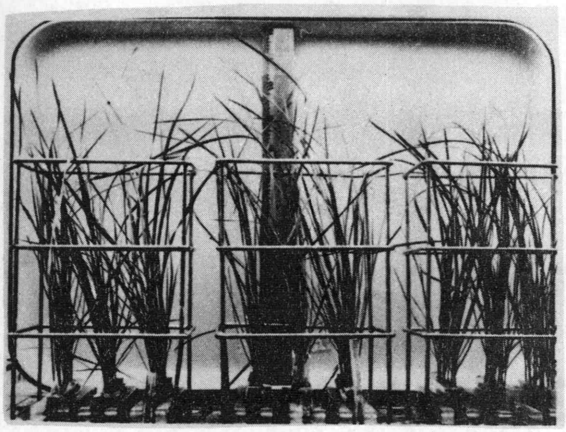


Figure 3b. 31-day old plants subjected to 75°F root temperature and soil water suctions of 0.10, 0.35, and 2.50 bars respectively (left to right).

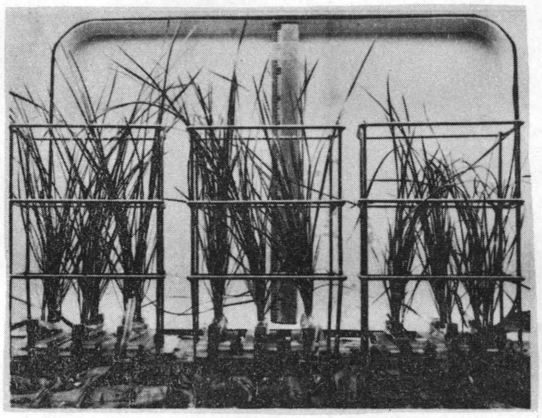


Figure 3c. 31-day old plants subjected to 90°F root temperature and soil water suctions of 0.10, 0.35, and 2.50 bars respectively (left to right).

Figure 3. Ryegrass grown in controlled osmotic chambers.

RESULTS

Shoot Dry Matter Yield

Ryegrass shoot dry matter yields as influenced by temperature, moisture, and cutting date are presented in Table 1. Highly significant differences in yields were noted due to each variable, namely, soil temperature, water suction, and date of cutting. Furthermore, highly significant moisture-temperature interactions as expressed in dry matter yields were evident (Appendix Table 2).

The influence of temperature and moisture suction on shoot dry weight at 4 day intervals beginning with 19-day old seedlings is presented in Figure 4-9. Highly significant differences in mean shoot yields were obtained between each 4 day harvest interval at all temperature treatments (Table 1).

As might be expected no differences in yield were observed at the first harvest since seedlings had just been exposed to osmotic solutions in the growth chamber. At the second interval the highly significant differences in mean ryegrass yields were apparent between plants subjected to 60° and 75° F at each moisture suction. Moreover, at both 0.35 bar and 2.5 bars the plants grown at 90° F yielded significantly more than ryegrass roots maintained at 60° F.

The effect of different root temperatures on the third interval

Table 1. Average shoot dry matter yield (mg/chamber) of 19-day old ryegrass seedlings as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature ^{o}F		
		60	75	90
	5*	384	419	421
0.10	9	465	555	502
	13	654	822	946
	17	869	1074	1177
0.35	9	421	539	510
	13	608	772	839
	17	1079	1293	995
2.50	9	418	514	526
	13	568	644	771
	17	680	923	932

*check, pre-osmotic treatment

$LSD_{0.01}$ = 75.4 mg per chamber

$LSD_{0.05}$ = 56.0 mg per chamber

CV = 4.2%

Table 2. Average accumulative ryegrass shoot dry matter yeidl (mg) obtained during the osmotic chamber experiment as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature ^{o}F		
	60	75	90
0.10	2372	2870	3046
0.35	2492	3014	2765
2.50	2050	2500	2650

$LSD_{0.01}$ = 173.6 mg per treatment

$LSD_{0.05}$ = 119.3 mg per treatment

CV = 2.0%

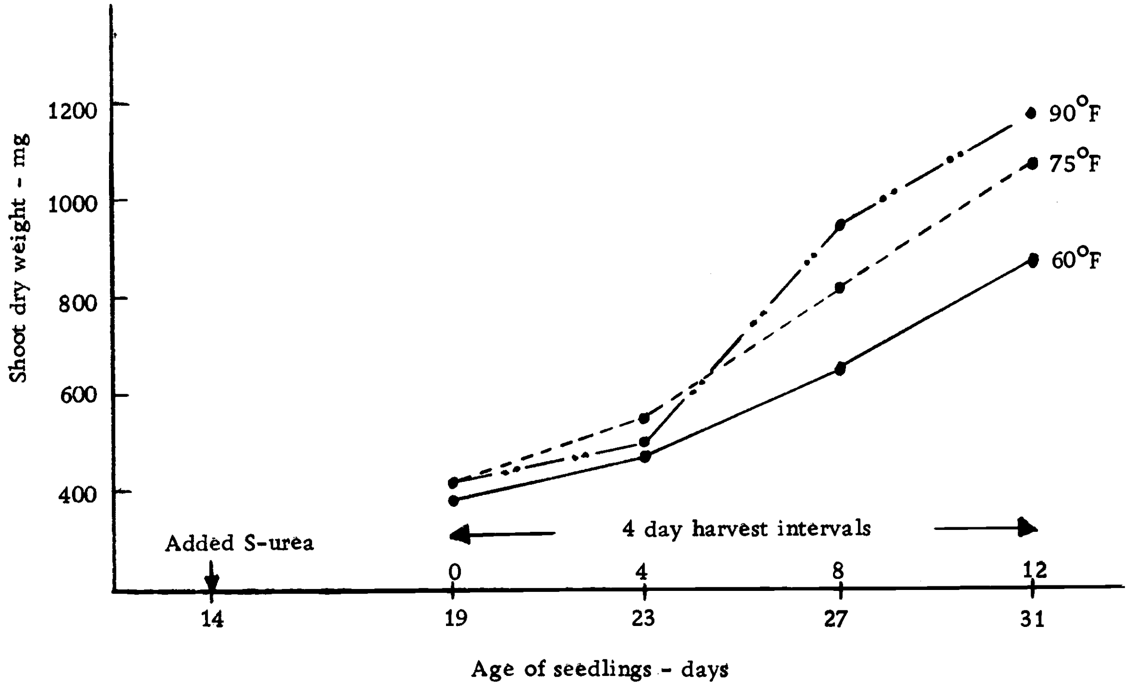


Figure 4. Shoot dry weight (mg/chamber) of 19-day old ryegrass seedlings as influenced by soil temperatures of 60, 75, and 90°F at a soil water suction of 0.10 bar.

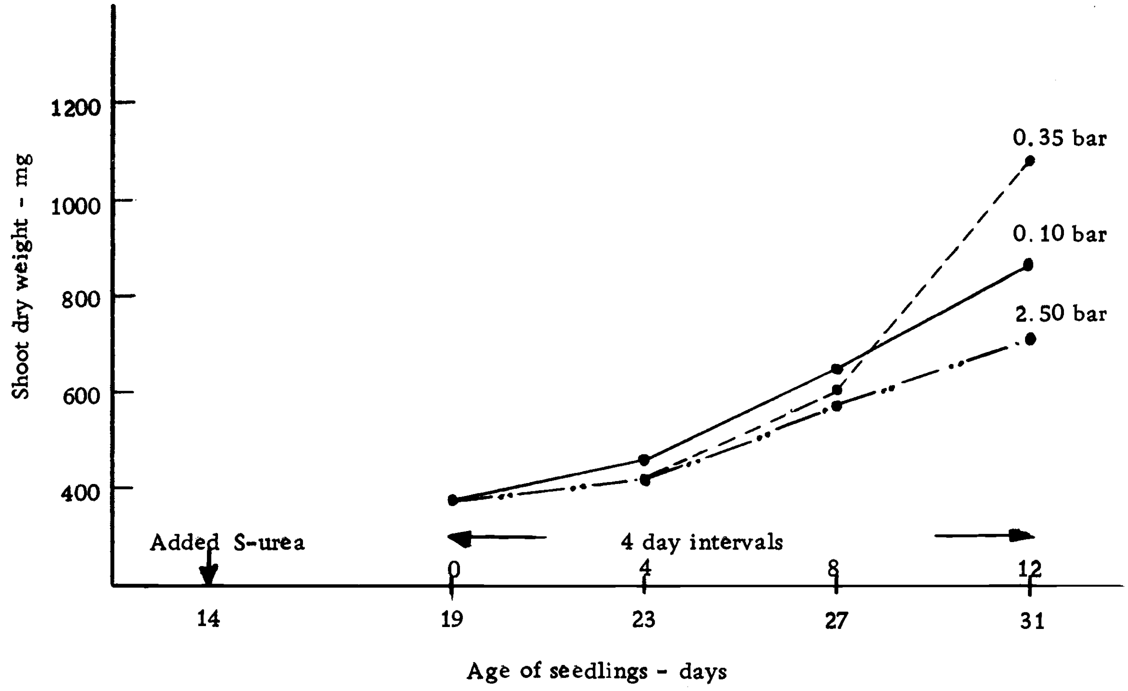


Figure 5. Shoot dry weight (mg/chamber) of 19-day old ryegrass seedlings as influenced by soil water suctions of 0.10, 0.35, and 2.50 bars at a soil temperature of 60°F.

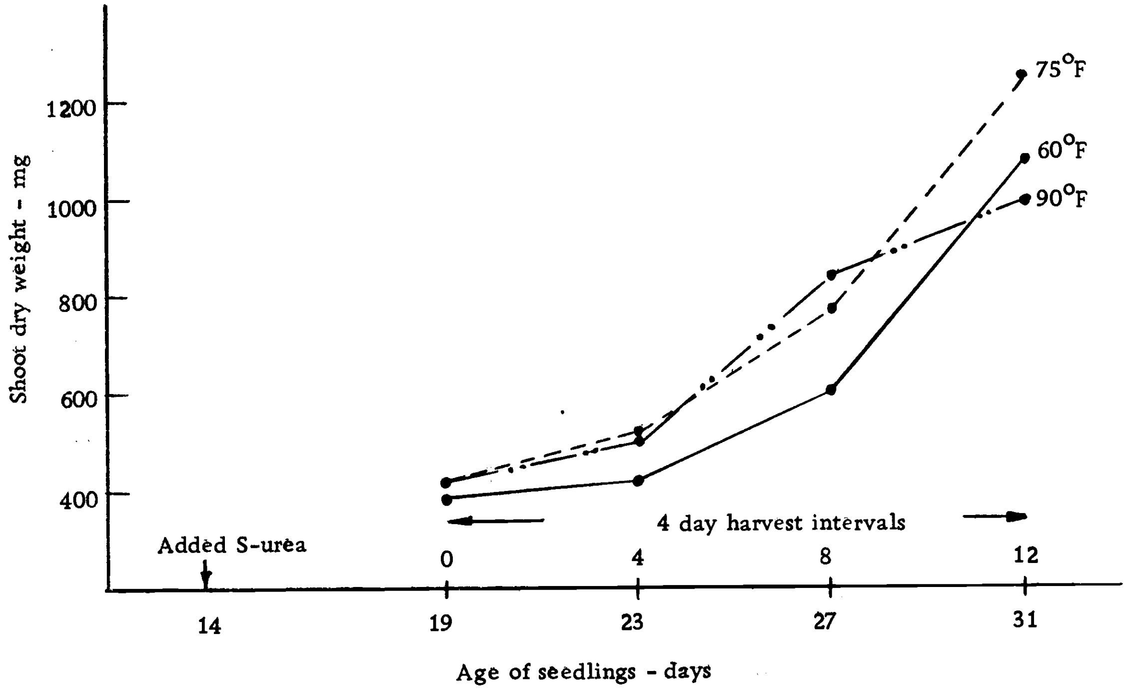


Figure 6. Shoot dry weight (mg/chamber) of 19-day old ryegrass seedlings as influenced by soil temperatures of 60, 75, and 90°F at soil water suction of 0.35 bars.

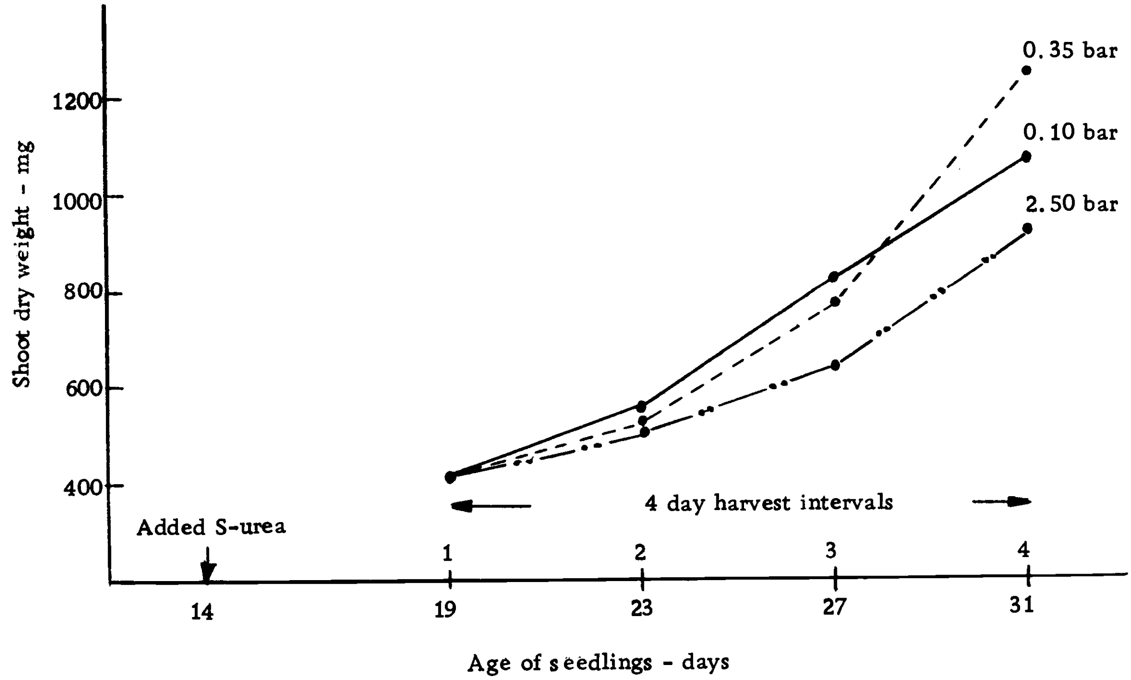


Figure 7. Shoot dry weight (mg/chamber) of 19-day old ry.grass seedlings as influenced by soil water suctions of 0.10, 0.35 and 2.50 bars at a soil temperature of 75°F.

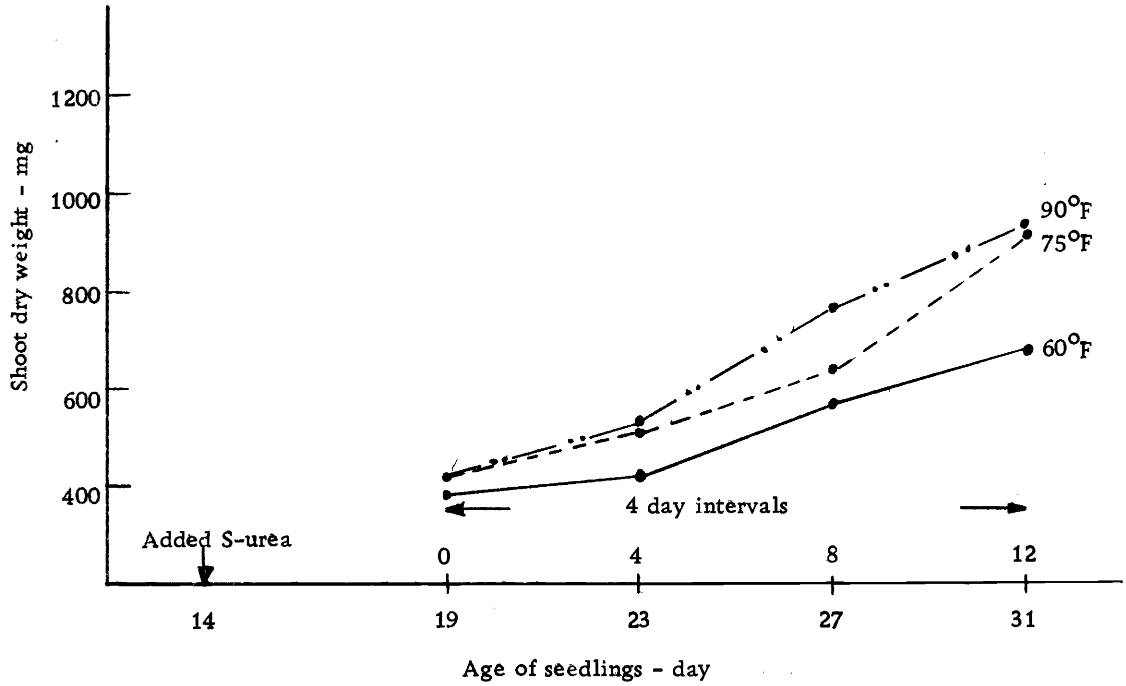


Figure 8. Shoot dry weight (mg/chamber) of 19-day old ryegrass seedlings as influenced by soil temperatures of 60, 75 and 90°F at a soil water suction of 2.50 bars.

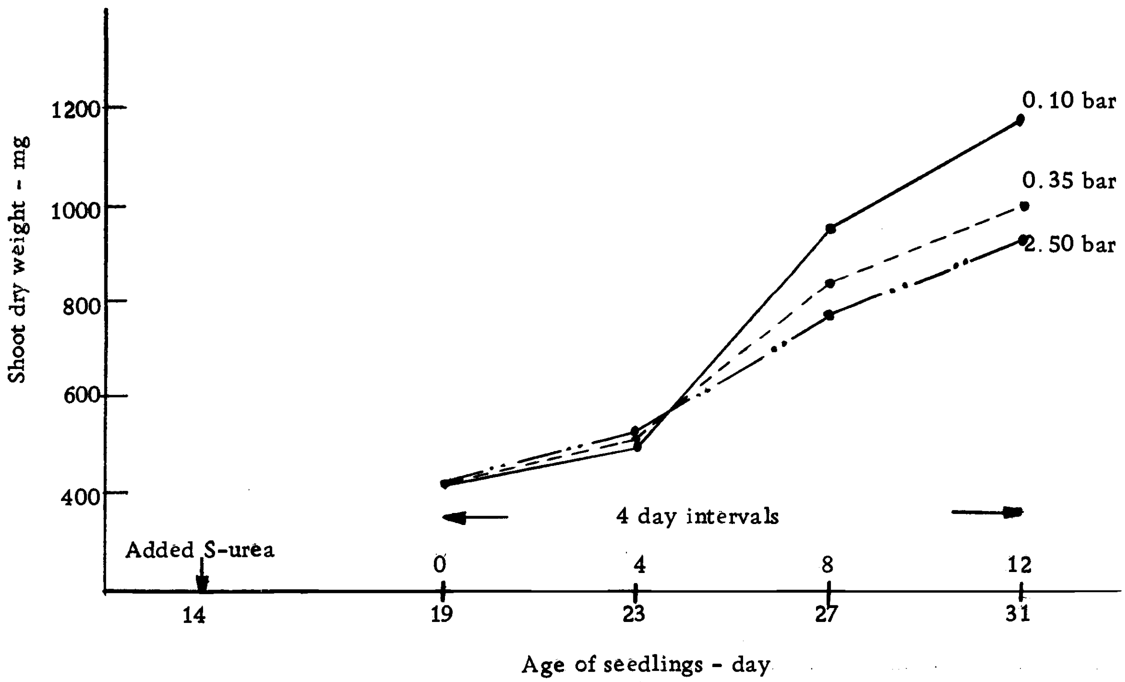


Figure 9. Shoot dry weight (mg/chamber) of 19-day old ryegrass seedlings as influenced by soil water suctions of 0.10, 0.35 and 2.50 bars at a soil temperature of 90°F.

harvest (27-day old seedlings) was highly significant at all moisture suctions. Highest shoot yield was observed in plants subjected to 0.10 bar suction and a temperature of 90° F. At 60 and 75° F there was a highly significant increase in grass yield at 0.10 bar over plants grown in 2.50 bar soil water suction. Furthermore, at 75° F root temperature there was also a significant increase in yield between the 0.35 and 2.50 bar treatments yet no yield difference was observed between 0.35 and 0.10 bar. Soil moisture suction exerted greatest influence on shoot yield at 90° F root temperature where differences due to suction were significant.

At the fourth interval harvest (31-day old seedlings) highest yield was recorded in the 75° F root temperature regime at 0.35 bar soil water suction. In both 75 and 90° F treatments shoot yield was significantly increased over those at 60° F. This was true at all soil moisture suctions except at 0.35 bar where the 60° F root temperature favored more growth than those at 90° F. However, at 0.10 bar soil moisture the 90° F root temperature treatment resulted in greater yields than either the 60° F or 75° F root temperatures with least yield at the lowest temperature. A significantly lower ryegrass yield was recorded in treatments subjected to 2.50 bar soil water suction at 60° F root temperature than at the higher root temperatures.

At the fourth interval harvest a highly significant soil moisture-temperature interaction effect on 31-day old seedling yields was evident (Appendix Table 2). The optimum root temperature for ryegrass yield apparently depended upon the soil water suction. Thus when roots were exposed to 90° F, plants subjected to 2.50 bar soil water suction yielded less than at either 0.35 or 0.10 bar.

The effect of root temperature and soil water suction on the average accumulative yield is shown in Table 2 and Appendix Table 3. Highly significant effects from root temperature changes occured at each soil moisture level. In the 60° F treatment, a soil water suction of 0.35 bar gave significantly more shoot growth than at either 0.10 or 2.50 bars. At 75° F root temperature while there was a non significant difference in accumulative shoot yield between 0.10 and 0.35 soil water suctions, there was significantly less yield when roots were maintained at 2.50 bars. At 90° F root temperature and 0.10 bar soil water suction significantly greater accumulative shoot yield resulted than at higher soil water suctions.

Plant Nitrogen Status

The percent nitrogen content of ryegrass shoots as influenced by soil moisture and root temperature is presented in Appendix Table 4. The percent nitrogen decreased from 23 to 31 day old seedlings. Data in Table 3 and Appendix Table 6 indicated a highly significant effect from both root temperature and soil moisture on the percentage of plant nitrogen at the last harvest. However, no significant soil moisture-temperature interaction was noted. In the 60° F root temperature a 2.50 bar soil water suction resulted in highly significant increase in percent plant nitrogen over roots subjected to either 0.10 or 0.35 bar suction. At 75° F and 90° F root temperatures there was not significant effect among the different soil water suctions. However, there was a significant decrease in percent plant nitrogen with increasing root temperature from 60 to 90° F under both 0.10 or 0.35 bar soil water suction. At a soil water suction of 2.50 bars, the 60° F root temperature treatment resulted in a higher percent plant nitrogen than either 75 or 90° F.

The content of plant nitrogen uptake was computed from the product of percent plant nitrogen and yield of dry matter for the fourth interval harvest (31 day old seedlings). Nitrogen uptake data for each treatment is shown in Table 4. Soil temperature and moisture had a highly significant effect on total nitrogen content (Appendix Table 7). Moreover, there was a highly significant soil moisture-temperature interaction effect. Thus at 60° F root temperature plants subjected to 0.35 bar soil water suction resulted in shoot nitrogen content being significantly greater than at either 0.10 or 2.50 bar soil water suctions. The highest plant nitrogen content occurred at 75° F root temperature and soil water suction of 0.35 bar. Plant roots subjected to 75° F and soil water suction of 2.50 bars exhibited

Table 3. Mean percentage of nitrogen in 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F		
	60	75	90
0.10	3.51	3.16	3.14
0.35	3.70	3.38	3.29
2.50	4.22	3.39	3.33

Table 4. Mean nitrogen content (mg/chamber) of 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F		
	60	75	90
0.10	30.51	40.43	36.92
0.35	39.90	42.25	32.80
2.50	29.04	31.29	30.99

$LSD_{0.01}$ = 6.05 mg N per chamber

$LSD_{0.05}$ = 4 16 mg N per chamber

CV = 5.16%

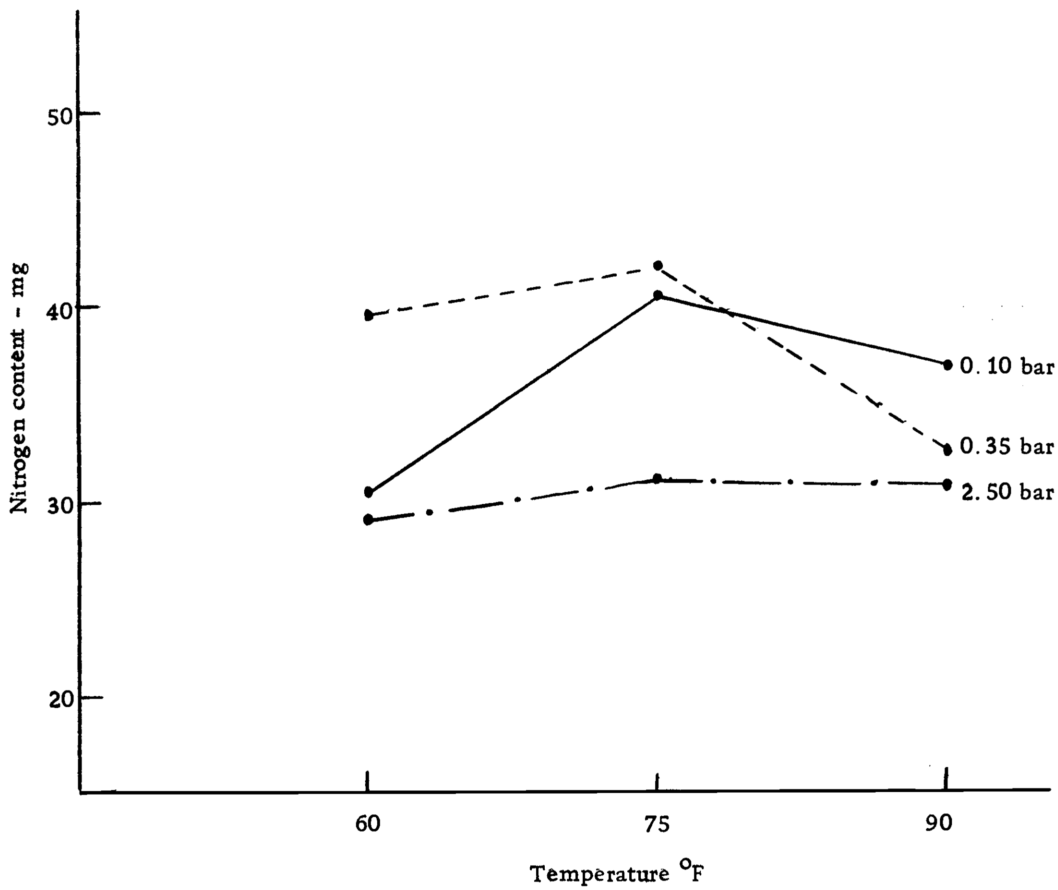


Figure 10. Nitrogen content (mg/chamber) of ryegrass shoots at the 12-day harvest as influenced by different root temperatures and soil water suctions.

significantly lower plant nitrogen content than other treatments. Furthermore, a highly significant increase in plant nitrogen content resulted when soil water suction was lowered from 2.50 to either 0.10 or 0.35 bar. A similar though even more pronounced effect occurred in the 90° F treatment.

By contrast, at 0.10 bar soil water suction and root temperature of either 75 or 90° F the plant nitrogen content was significantly greater than in the 60° F treatment. Moreover, at 0.35 bar soil water suction the 60 and 75° F treatments resulted in significantly higher nitrogen content than under the 90° F root temperature treatment. Soil temperature appeared to have little influence on nitrogen content when the moisture was maintained at 2.50 bars.

An interesting soil moisture-temperature interaction occurred following the increase of root temperature from 75 to 90° F in the 0.35 bar soil water suction treatment. Such an increase in root temperature resulted in a significant lowering of plant nitrogen content. Indeed, at the higher root temperature the plants subjected to a soil water suction of 0.10 bar resulted in a significantly greater nitrogen content than at 0.35 bar.

Plant Sulphur Status

The percent plant sulphur as influenced by soil moisture and root temperature is presented in Table 5. There was a highly significant effect from both soil temperature and moisture on the percentage of plant sulphur at the 12 day cutting (31-day old ryegrass seedlings). A highly significant soil moisture-temperature interaction was observed (Appendix Table 10). At 60° F root temperature, a soil water suction of 0.10 bar resulted in highly significant increases of percent plant sulphur over roots subjected to 0.35 bar soil water suction. There was a highly significant lower percent sulphur in plants grown at 2.50 bar suction than at either 0.10 or 0.35 bar. By contrast, at the 75° F root temperature, plants grown at the lower soil moisture stress showed highly significant lower percent sulphur than those grown at 2.50 bar suction. In the 90° F treatment, plants subjected to 0.35 bar soil water suction resulted in significantly less percent sulphur than those grown at either 0.10 or 2.50 bars.

At 0.10 bar soil water suction the plants grown at 60° F contained significantly higher percent sulphur than at either 75° F or 90° F root temperature. Indeed, there was a highly significant increase in percent sulphur with the lowering of root temperature from 90 through 75 to 60° F. At a soil moisture of 2.50 bars there was a significant decrease in percent plant sulphur associated with the increase in root temperature from 60 through 75 to 90° F.

Content of plant sulphur was computed from the product of percent plant sulphur and dry matter yield. The mean of 31-day old plant sulphur content is presented in Table 6. Data in Appendix 11

Table 5. Mean percentage of sulphur in 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F		
	60	75	90
0.10	0.37	0.29	0.30
0.35	0.35	0.29	0.26
2.50	0.29	0.33	0.30

Table 6. Mean sulphur content (mg/chamber) of 31-day old ryegrass shoots as influenced by root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F		
	60	75	90
0.10	3.24	4.33	3.53
0.35	3.74	3.72	2.62
2.50	2.17	3.03	2.80

$LSD_{0.01}$ = 0.41 mg S per chamber

$LSD_{0.05}$ = 0.28 mg S per chamber

CV= 3.79%

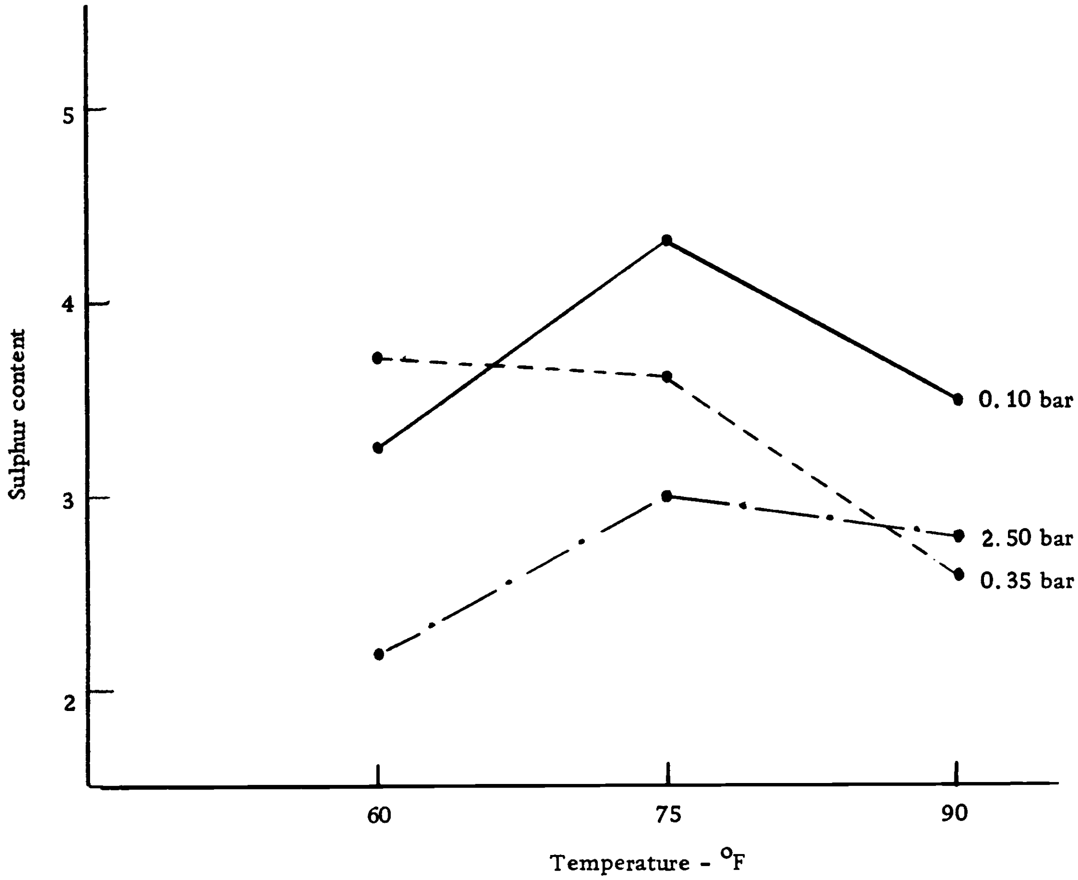


Figure 11. Sulphur content (mg/chamber) of ryegrass shoots at the 12 day harvest as influenced by different root temperatures and soil water suctions.

and also graphically shown in Figure 11 indicated that soil temperature and moisture had a highly significant effect on sulphur content. Moreover, a highly significant soil moisture-temperature interaction effect was noted.

Lower soil moisture stress resulted in a highly significant increase in plant sulphur content at each root temperature except at 60° F where sulphur content appeared highest at 0.35 bar.

By contrast, at the soil water suction of 0.10 bars, plants grown in 75° F root temperature resulted in a highly significant increase in sulphur content over either 60 or 90° F treatments. At 0.35 bar soil water suction, the plants subjected to 90° F root temperature exhibited a highly significant decrease in sulphur content compared with 60 or 75° F treatments. However, a different pattern emerged in the 60° F treatment where at 2.50 bar suction a highly significant drop in plant sulphur content was noted compared with the higher temperatures at this moisture stress.

When the root temperature was increased from 60 to 90° F at 0.35 bar soil suction a highly significant decrease in plant sulphur content was noted (Table 6 and Appendix Table 11). Moreover, at 60° F root temperature the 0.35 bar soil water suction treatment resulted in a higher plant sulphur content than at 0.10 bar. However, after increasing the root temperature from 60 to 75° F, ryegrass grown at 0.35 bar exhibited a lower plant sulphur content than at

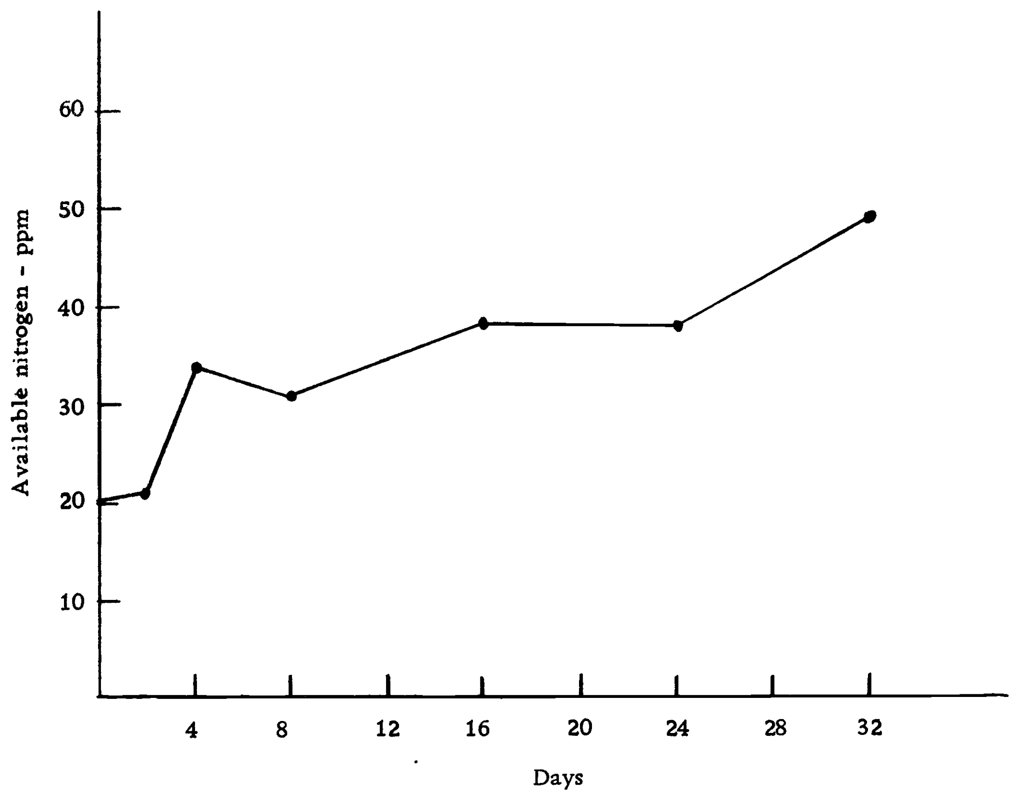


Figure 12. Available nitrogen (NH_4-N + NO_3-N) in ppm mineralized from unfertilized soil during 32-day incubation.

0.10 bar treatment (Figure 11).

Nitrogen Mineralization from S-Urea

The rate of N-mineralization from S-urea was calculated by the formula given on page 23. The data so obtained is shown in the Appendix Tables 12 to 19.

The available nitrogen (NH_4+NO_3) mineralized from unfertilized soil during incubation is shown in Figure 12. Complete mineralization data appears in Appendix Table 12. It is of interest to note that during the 32 day incubation treatment on the non fertilized soil there was a steady release of NH_4 + NO_3 from 20 ppm up to 49 ppm. Available nitrogen content from fertilized soil is presented in the Appendix Table 13. It appears that from the first to the last harvest interval ammonium and nitrate content of fertilized soil ranged from 25.58 to 64.58 mg N per chamber. In addition, nitrogen losses in NH_4-N and NO_3-N forms from soil to carbowax solution are shown in Appendix Table 14. It is worthy of note that losses of nitrogen to carbowax solution increased as the temperature was raised. Results of root-shoot ratio (Appendix Table 15) were used to calculate root dry weights and root nitrogen content are shown in Appendix Tables 16 and 17, respectively.

Available nitrogen (NH_4+NO_3) mineralized from S-urea (Table 6) was calculated from the following formula (page 23):

$$Nm = \frac{n_1 + n_2 + n_3 + n_4 - n_5}{Nf} \times 100$$

The effect of soil temperature and moisture on the rate and degree of S-urea mineralization were highly significant (Appendix Table 18a). At the second harvest interval (9 days after S-urea application) different soil water suctions did not significantly affect the rate of nitrogen release at both soil temperatures of 60 and 75° F. But in the 90° F soil temperature, at 0.10 bar water suction, significantly more nitrogen was mineralized from S-urea than at the higher suctions of 0.35 and 2.50 bars respectively. By contrast, increasing temperature at any given moisture suction resulted in a highly significant increase in the available nitrogen release from S-urea except between 75 and 90° F root temperatures at 2.50 bar soil water suction.

Mineralized S-urea in 27 day old harvested plants grown at a root temperature of 60° F was significantly less at 2.50 bars than the lower suctions. While moisture suction differences in the treatments subjected to the 75° F root temperature appeared to have little effect on S-urea mineralization, at the higher 90° F root temperature a highly significant increase in ammonium and nitrate content was associated with increased moisture status.

It is interesting to observe that at all moisture levels (0.10, 0.35, and 2.50 bars) highly significant increase in the mineralization of S-urea was associated with the raising of root temperature from

Table 7. Mean percentage of nitrogen mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F		
		60	75	90
	5*	25.7	25.3	24.7
0.10	9	31.9	41.0	62.4
	13	35.5	43.5	60.9
	17	29.0	50.0	61.2
0.35	9	30.4	39.0	43.3
	13	35.5	51.2	51.9
	17	42 9	53.6	53.5
2.50	9	29.3	40.2	40.5
	13	32.1	44.5	50.1
	17	33.1	43.1	53.3

*check, pre-osmotic treatment

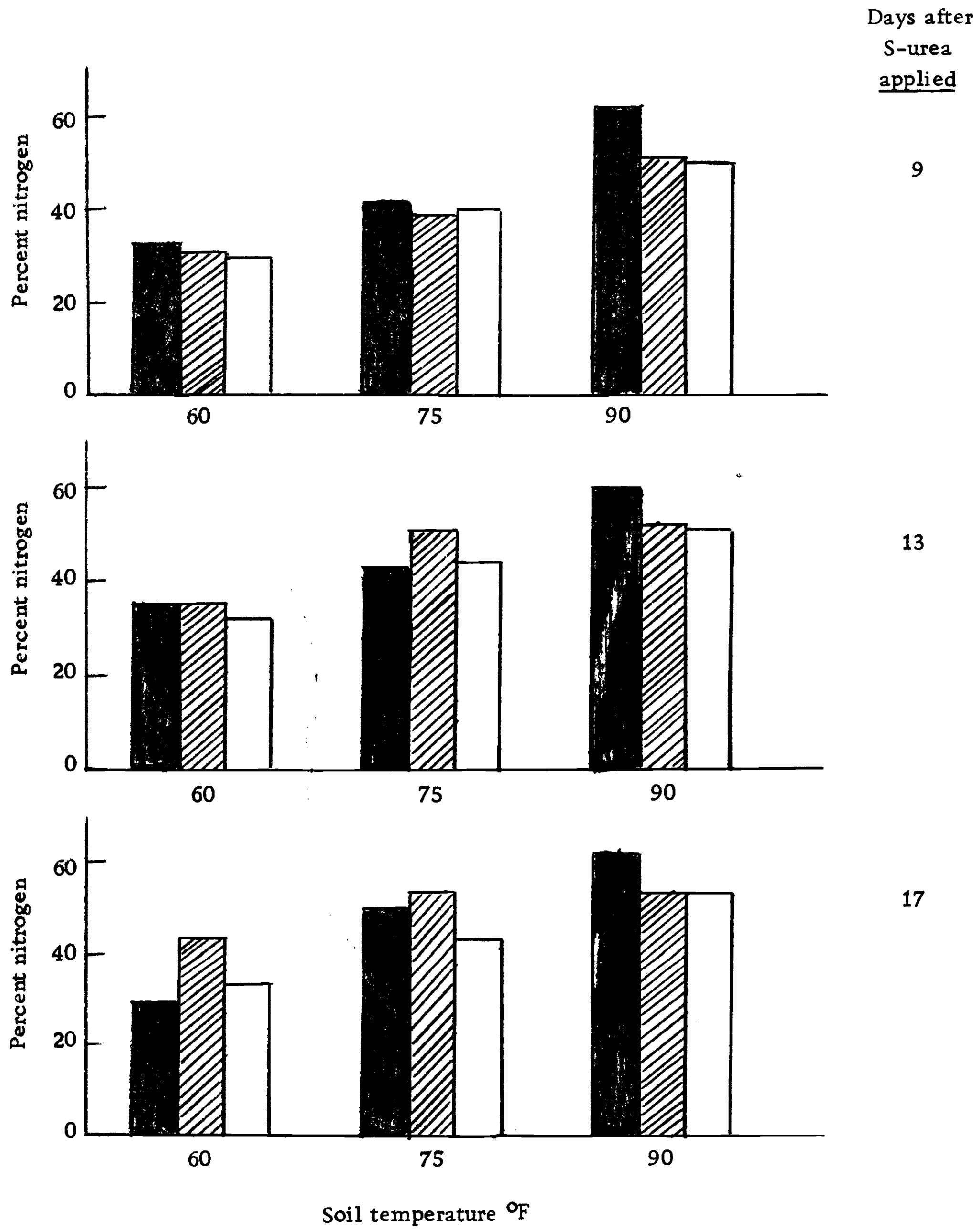
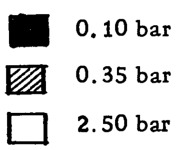


Figure 13. Percent nitrogen mineralization from S-urea as influenced by soil temperatures of 60, 75, and 90°F and soil water suctions of 0.10, 0.35, and 2.50 bars.



60 to 90° F.

At the 12 day cutting (31 day old seedlings), treatments exposed to 60° F soil temperature yielded significantly more ammonium and nitrate at 0.10 bar than at the higher soil water suctions. A similar effect was noted in the 75° F treatment where S-urea mineralization was significantly less at 2.50 bars than under conditions of lower moisture stress. At 90° F root temperature in the 12 day harvest the most pronounced effect from moisture stress on S-urea transformation to ammonium and nitrate was noted. Under this high root temperature regime a highly significant increase in S-urea mineralization occurred at 0.10 bar.

It is interesting to observe from Figure 13 that the rate of nitrogen release was highest during the first 5 to 9 days after fertilization and decreased thereafter.

Sulphur Mineralization from S-Urea

The rate of S-mineralization from S-urea was calculated by the formula shown on page 23. The data so obtained is shown in Appendix Tables 19 to 23.

The sulphate sulphur mineralized from unfertilized soil during incubation is shown in Figure 14 and Appendix Table 19. It appears that during the 32 day incubation sulphate sulphur mineralized from unfertilized soil ranged from 1.55 up to 6.00 ppm. Similarly sulphate

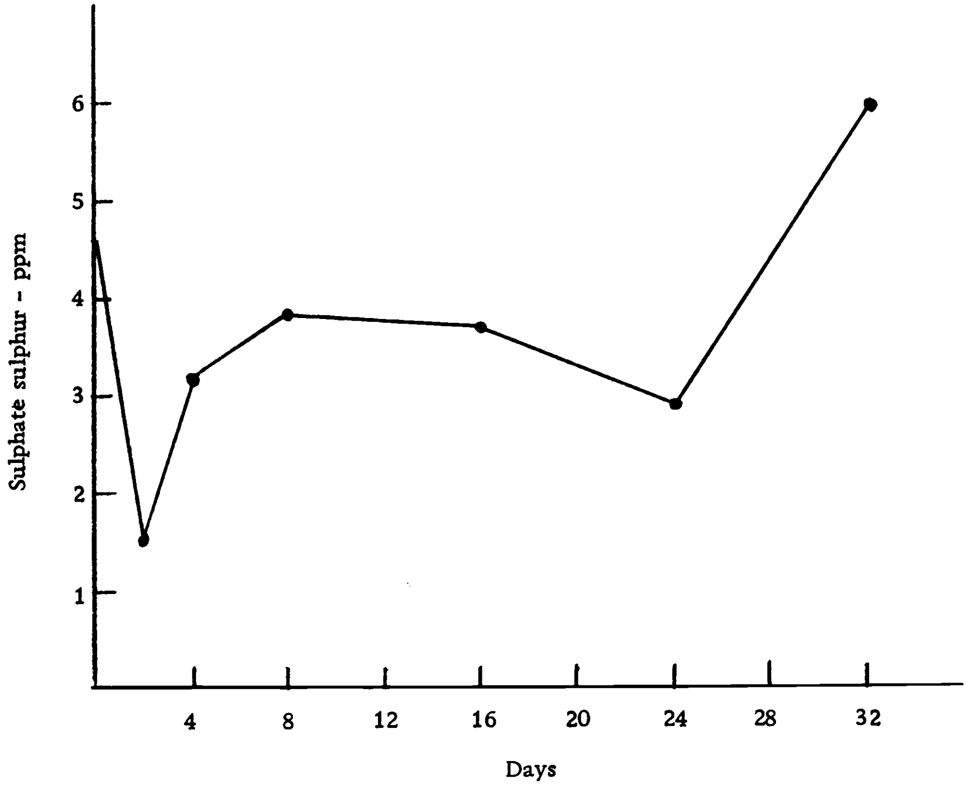


Figure 14. Sulphate sulphur content in ppm mineralized from unfertilized soil during 32-day incubation.

sulphur from fertilized soil is presented in Appendix Table 20. From the first to the last harvest interval (19 to 31 day old seedlings) it is interesting to note that the mean sulphate sulphur content of fertilized soil ranged from 0.972 to 4.968 mg S per chamber. The highest value was obtained from the treatment subjected to the root temperature of 90° F and soil water suction of 0.10 bar at the last harvest interval. Sulphur losses in sulphate form from soil to osmotic solution are shown in Appendix Table 21. It was observed that the content of sulphate losses increased with the higher soil temperatures and soil moisture status. Root-shoot ratio data (Appendix Table 15) used to calculate root-sulphur content is shown in Appendix Table 22.

Available sulphur (SO_4) mineralized from S-urea (Table 8) was calculated from the following formula (page 23):

$$Sm = \frac{s_1 + s_2 + s_3 + s_4 - s_5}{Sf} \times 100$$

Data in Appendix Table 23a indicate that at both 60 and 90° F root temperatures significantly less sulphur was mineralized at 2.50 bars than at the lower soil water suctions. Differences in soil moisture stress appeared to have less effect on the rate of sulphur mineralization than the soil temperature. It is interesting to observe that at all soil moisture levels (0.10, 0.35, and 2.50 bars) a highly significant increase in sulphur mineralization was associated with the raising of root temperature from 60 to 90° F. In but one instance, namely between 75 and 90° F at soil water suction of 2.50 bars no difference in sulphur mineralization was observed.

There was no soil temperature-moisture interaction effect on the amount of sulphur mineralized from S-urea (Appendix Table 23b).

From 5 to 17 days after the application of S-urea, the percent sulphur release ranged from 4.765 to 40.146 respectively (Table 10). There was a highly significant effect from both soil temperature and moisture stress on the rate and degree of S-urea mineralization.

At 9 days after fertilization (second harvest interval) there appeared to be little effect from the different soil water suctions on the rate of sulphur mineralization at soil temperatures of 60 or 90° F (Appendix Table 23b). However, at 75° F root temperature a highly significant increase in the sulphur mineralized to sulphate occurred at the lower moisture stress compared with the 2.50 bar treatment. At both soil water suctions of 0.10 and 0.35 bars, the 75 and 90° F root temperature treatments showed a highly significant increase in the rate of sulphur mineralized to sulphate over the 60° F treatments. Also at this second harvest interval in a soil water suction of 2.50 bars, 60 and 75° F treatments resulted in highly significant decreases in the rate of sulphur mineralized compared with the 90° F treatment.

Some 13 days after the application of S-urea (third harvest interval) the only significant effect from moisture stress occurred at the higher soil temperatures. A highly significant increase in sulphur mineralized to sulphate was noted at 75° F root temperature when moisture suction was lowered from 2.50 bars to 0.35 bar. In the 90° F treatment again a highly significant increase in sulphur mineralized to sulphate was noted when moisture stress was lowered from 2.50 bars to either 0.35 or 0.10 bar.

Similarly the effect of soil temperature and soil moisture on the rate of sulphur mineralization at 17 days after the application of S-urea fertilizer resulted in the same pattern described for 13 days.

It is interesting to note that the highest rate of sulphur mineralization from S-urea occurred during 5 to 9 days after the fertilizer application and drastically decreased thereafter.

Table 8. Mean percentage of sulphur mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature ^{o}F		
		60	75	90
	5*	4.9	5.8	4.8
0.10	9	15.2	21.7	24.5
	13	14.8	24.2	36.0
	17	17.4	27.7	39.3
0.35	9	14.8	22.8	21.6
	13	15.0	26.5	32.7
	17	18.1	26.7	40.1
2.50	9	11.7	15.7	21.4
	13	12.2	21.5	23.4
	17	11.9	24.6	26.0

*check, pre-osmotic treatment

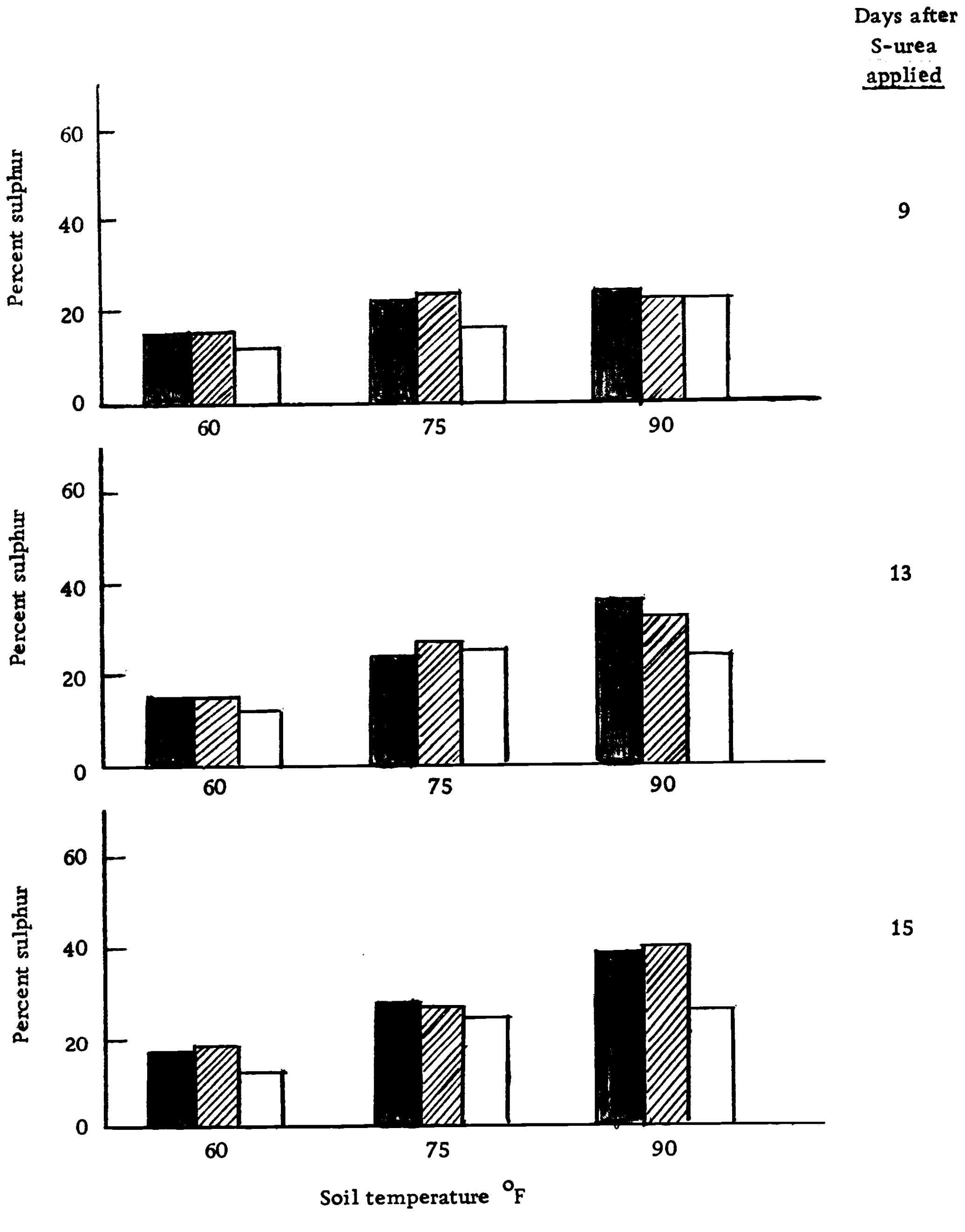


Figure 15. Percent sulphur mineralization from S-urea as influenced by soil temperatures of 60, 75, and 90°F and soil water suctions of 0.10, 0.35 and 2.50 bars.

DISCUSSION

Dissolution rates for different S-urea fertilizers have been studied quite extensively however, before an accurate evaluation of the potential usefulness of this fertilizer can be given factors affecting both NH_4+NO_3 and SO_4-S mineralization from the S-urea fertilizer deserve consideration. That S-urea is both temperature and moisture dependent insofar as transformation of urea to NH_4 + NO_3 and S to SO_4 seems plausible enough. The following reactions show how NH_4 + NO_3 are mineralized from urea:

(1) $(NH_2)_2CO + 2\ H_2O \longrightarrow (NH_4)_2CO_3$

(2) $2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + H_2O + 4H^+$

(3) $2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2NO_3^-$

And sulphate is oxidized from elemental sulphur as shown in the following equation:

(1) $S + \frac{3}{2}O_2 + H_2O \xrightarrow{\text{Thiobacillus}} H_2SO_4$

In this study an effort was made to determine the significance of soil temperature and moisture stress on not only S-urea breakdown in the soil but concurrently its effect on ryegrass growth and nutrient status.

Shoot Dry Matter Yield

Since the aerial environment of the plants in all treatments was the same, it can be assumed that soil moisture, root temperature and plant nutrients were dominant factors influencing plant growth. The optimum root temperature and soil moisture for ryegrass (Lolium multiflorum) growth subsequent to the application of S-urea varied. Generally, the rate of nitrogen release from S-urea was greatest at a high soil moisture content (0.10 bar) and a high soil temperature (90° F) as shown in Table 7 and Figure 13. Besides the effect of soil temperature and moisture on the plant physiological activity, the amount of available nitrogen in soil also had a great influence on plant growth. At the second harvest (23 day old seedlings) soil water suction between 0.10 and 2.50 bars appeared to have little influence on ryegrass yield at any of the three root temperatures used in this study. However, there was a significant increase in shoot yield as root temperature was increased. Raising root temperature from 60 to 75° F resulted in greater ryegrass shoot yield at each soil moisture suction. These results would suggest 75° F as a near optimum root temperature for ryegrass. It is of interest that Davidson (1969) has reported 75° F as near optimum for ryegrass. Furthermore, plants grown at 90° F root temperature yielded more than those subjected to 60° F. It is possible that reduced growth at low soil temperature is associated with lower plant metabolic activity including lower water and nutrient translocation as well as low rates of photosynthesis (Beevers and Cooper I, 1964).

In both 8 day and 12 day cuttings (27 and 31 day old seedlings) plant yields were increased as temperature was raised until highest yields were obtained at 90° F. This increase in yield with soil temperature occurred whether roots were subjected to 0.10 bar or 2.50 bars suction.

Optimum soil temperature and moisture conditions for ryegrass grown in S-urea treated soil apparently vary according to the age of plant (Table 1). Moreover, unlike the soil temperature effect, changes in soil moisture between 0.10 and 2.50 bars, with plants less than 27 days old had no effect on shoot yield. However, after the second cutting the older plants were sensitive to changes in soil water suction at any of the three root temperatures included in the study.

Plant Nitrogen Status

The data presented in Tables 3 and 4 shows that the percent plant nitrogen and nitrogen content were affected by soil moisture, root temperature and stage of plant development. The percent nitrogen in ryegrass shoots decreased as the plant matured (Appendix Table 8). While root temperature and soil moisture profoundly influenced the percent nitrogen in the 31 day old ryegrass seedlings, no significant soil moisture-temperature interaction was observed. Percent nitrogen decreased with increase in soil temperature and soil moisture. Similar results were observed by Beevers and Cooper II (1964) and Bathurst and Mitchell (1958). It is probable that in a cool temperature regime the plant leaves mature more slowly. Less rapid hydrolysis of protein and a slower translocation rate of nitrogen from the leaves may account for the higher percentage of nitrogen observed in plants grown at the cooler root temperature (Hamid et al., 1966; Stewart and Whitfield, 1964). Moreover, in warm root temperature regimes, production of other cell constituents likely imposed a dilution effect on nitrogenous compounds. While root temperature appeared to have more effect on the percent plant nitrogen than soil moisture, the 31 day old seedlings at 60° F root temperature increased in percent nitrogen as the soil water suction was raised from 0.10 to 2.50 bars.

Total nitrogen content of ryegrass in contrast to percent nitrogen proved to be highest in 31 day old seedlings where root temperature was maintained at 75° F and at a moisture stress of 0.35 bar. This optimum condition for total nitrogen content coincided with optimum ryegrass yield.

Regardless of soil moisture suction, mean nitrogen content was higher in plants subjected to a root temperature of 75° F compared with other temperatures. However, at this temperature there was a marked drop in plant nitrogen associated with increase in soil water suction from 0.10 to 2.50 bars. Indeed, there appeared to be a significant soil temperature-moisture interaction as reflected in plant nitrogen content where root temperature was increased while lower soil moisture suctions were necessary for greatest plant nitrogen uptake.

Plant Sulphur Status

Not only was there a significant effect from both root temperature and soil moisture on the percent plant sulphur in 31 day old ryegrass seedlings but a soil moisture-temperature interaction was also observed (Appendix Table 10). At 60° F root temperature the percent sulphur varied directly with soil moisture and the rate of S-urea mineralization shown in Figure 15. It is interesting to note that the percent plant nitrogen at 60° F root temperature was increased with decreasing soil moisture content but this was not the case for percent sulphur. Since there is a close relationship between sulphur and nitrogen, these two elements might be considered to behave similarly. Theoretically the N:S ratio in normal plant is 14:1 (Cowling and Jones, 1970). In this case since the plant N:S ratio of 9:1 was narrow, luxury consumption of sulphur might be assumed to occur when subjected to 60° F root temperature and soil moisture stress of 0.10 bar. At 75° F root temperature, percent plant sulphur like percent nitrogen had a tendency to increase with a decrease in soil moisture content. At both 0.10 and 0.35 bar soil water suctions variation in percent sulphur due to different root temperatures followed the same pattern as did percent nitrogen which decreased as the root temperature was raised from 60 to 75 and 90° F. The percent sulphur was lowest (0.288%) at 60° F root temperature. However, if one were to assume a 14:1 of N:S ratio as nutritionally adequate then likely 0.288% sulphur was adequate for normal plant growth.

High soil moisture contents resulted in marked increases in plant sulphur content except at 60° F. In this instance sulphur content like nitrogen was highest at 0.35 bar soil water suction. These results confirm the reported close relationship between nitrogen and sulphur. Soil moisture and root temperature interacted in such a way that at the high root temperature regime ample moisture was required for optimum growth. On the other hand, at low soil temperature a soil moisture of 0.35 bar likely provides optimum conditions for sulphate nutrition of ryegrass.

Nitrogen Mineralization from S-Urea

That soil temperature had such a marked influence on the percent of S-urea mineralized to $NH_4 + NO_3$ at any soil moisture content used in this experiment confirms observations reported by other workers (Ahmed et al., 1963; Allen et al., 1968). Allen et al., (1968) noted that dissolution of sulphur coated urea granules was both highly soil temperature and time dependent. However, in this study the optimum conditions for mineralization appeared to be not only related to soil temperatures but also to soil moisture content. Some 17 days after the application of S-urea approximately 63% of the fertilizer was mineralized at 90° F when soil moisture was maintained at 0.10 bar suction while at 2.50 bars only 40% had been mineralized. On the other hand, 13 days after S-urea was applied the highest level of $NH_4 + NO_3$ released in the 75° F treatment occurred at field capacity (0.35 bar).

Increasing in soil temperature likely increases soil microbial activity which results in higher rates of S-urea breakdown. Higher temperature also increases the surface area through which diffusion must take place (Brown, 1966).

It is interesting to note that after 17 days at 0.10 bar soil water suction and 90° F soil temperature no subsequent increase in percent of N-mineralization took place. Denitrification may explain why at 0.10 bar soil water suction no increase in $NH_4 + NO_3$ was noted in the last 8 days of the experiment. Certainly soil conditions were favorable for denitrifying microorganisms (Greenland, 1962, Reuss and Smith, 1965). Bremner and Shaw (1958) reported that the rate of denitrification increased with raising in both soil temperature and moisture with time. They further suggested that when soil temperature was increased to 25° C the increase in rate of denitrification was not significant thereafter.

Soil moisture status in the range considered appeared to have little influence on the rate of S-urea mineralization at 60° F. However, at the warmer soil temperatures there was a considerable decrease in percent S-urea converted to $NH_4 + NO_3$ when soil moisture content was lowered from 0.10 to 2.50 bar suction. Indeed, at 90° F the rate of S-urea transformation was notably reduced when the soil water suction was raised from 0.10 to 0.35 bar. Possibly this reduction was associated with the rate of oxidation of the sulphur coated fertilizer granules since Burns (1967) has noted greater sulphur oxidation under soil moisture conditions in excess of field capacity.

The actual percentages of nitrogen calculated as mineralized S-urea in this study possibly are high since the content of nitrogen mineralized from organic matter in the unfertilized soil during incubation might well be less than the amount of nitrogen released after soil was fertilized with a nitrogen fertilizer (Broadbent and Nakashima, 1971).

Sulphur Mineralization from S-Urea

While sulphur is actually used as a coating for the slow release of nitrogen from urea its potential source of available sulphate in sulphur deficient soils cannot be under estimated. Generally, increasing the soil temperature increases biological oxidation of sulphur (Ahmed *et al.*, 1963; Brown *et al.*, 1966). Rate of sulphur oxidation has been reported higher at moisture contents greater than field capacity (Burns, 1967) and lower in flooded condition (Giordano and Mortvedt, 1970). Percent sulphate released under the conditions incurred in the present investigation support the previous reports cited above. Only 40% sulphate from S-urea was determined under the optimum conditions of 0.35 bar suction and a soil temperature of 90° F. This actually represents a significant amount of available sulphate. As with the release of $NH_4 + NO_3$, soil temperature had a greater effect on the rate of S-mineralization than did soil moisture content. No significant difference was noted between soil water suctions of 0.10 and 0.35 bar at each soil temperature. However, the rate of sulphur release increased sharply with increase in soil temperature at each soil moisture level.

The highest rate of S-mineralization from S-urea occurred 5 to 9 days after S-urea application and drastically decreased thereafter, suggesting possibly that sulphate ion saturation decreased the rate of sulphur release from S-urea. Biological and possibly chemical oxidation of sulphur initially hasten sulphur mineralization, then ion diffusion may exert some control on subsequent rate of sulphur oxidation to sulphate. Certainly more nitrate and sulphate were found in the carbowax solution from treatments subjected to high soil moisture and temperature (Appendix Tables 14 and 21) at the termination of the experiment.

Under optimum conditions (soil temperature of 90° F and soil water suction of 0.10 bar) for S-urea mineralization reported in this study as much as 183 kgs N/hec. and 70 kgs S/hec. could be expected to be mineralized from S-urea applied at a rate of 300 kgs N/hec. and 178 kgs S/hec. within 17 days.

SUMMARY AND CONCLUSIONS

This investigation was conducted to examine both the rate of mineralization of S-urea and the effect of S-urea on Lolium multiflorum as influenced by soil temperature and moisture stress. Ryegrass seedlings and S-urea fertilizer were placed in a cell containing Steiwer soil enclosed in a membrane which in turn was held in a temperature controlled osmotic chamber. Soil temperature and moisture stress effects on the rate of S-urea mineralization, ryegrass shoot yield and both nitrogen and sulphur plant uptake were studied. The pellets of S-urea were applied to soil containing 14 day old seedlings. Some 5 days after S-urea application, the unit cells containing plants grown in S-urea treated soil were immersed in osmotic chambers to control soil temperatures of 60, 75, and 90° F and soil water suctions of 0.10, 0.35, and 2.50 bars. Shoot dry matter yields were recorded at 4 day harvest intervals beginning with 19 day old seedlings.

Plant nitrogen and sulphur were determined at each harvest. Available soil nitrogen (NH_4 +NO_3) and SO_4-S were also determined at each harvest. Root-shoot ratios were used as a basis for calculating root nitrogen and root sulphur content. Amount of available nitrogen and sulphur mineralized from unfertilized soil during 32 day incubation was also determined. The data so obtained was used to compute the extent of S-urea transformation in Steiwer soil subjected to varying soil temperature and moisture content over a 17 day period.

The optimum root temperature and soil moisture content for ryegrass growth subsequent to the application of S-urea varied. Increasing the root temperature from 75 to 90° F changed the optimum soil water suction for ryegrass growth from 0.35 to 0.10 bar.

Raising root temperature and soil moisture content decreased the percent of plant nitrogen in the 31 day old seedlings. The content of nitrogen proved to be highest in the 31 day old ryegrass seedlings maintained at 0.35 bar suction and a root temperature of 75° F.

Any factor which affected percent plant nitrogen and plant nitrogen content similarly influenced plant sulphur content. However, at low soil temperature and high soil moisture content luxury consumption of sulphate by ryegrass likely occurred.

The soil moisture and temperature had a profound influence on the rate of nitrogen and sulphur mineralized from S-urea. The rate of nitrogen so mineralized varied due to the interaction of soil temperature with soil moisture status. The amount of nitrogen mineralized was directly related to plant growth. On the other hand, SO_4-S mineralized from S-urea while influenced by soil temperature and soil moisture did not provide a temperature-moisture interaction as did nitrogen.

Under optimum conditions (soil temperature of 90° F and soil water suction of 0.10 bar) for S-urea mineralization reported in this study as much as 183 kgs N/hec. and 70 kgs S/hec. could be expected to be mineralized from S-urea applied at a rate of 300 kgs N/hec. and 178 kgs S/hec. within 17 days.

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APPENDIX

Appendix Table 1. Shoot dry matter yield (mg/chamber) of 19-day old ryegrass seedlings as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	398	370	384	428	410	419	410	432	421
0.10	9	438	492	465	536	574	555	503	501	502
	13	639	668	654	830	815	822	908	983	946
	17	853	882	869	1104	1043	1074	1182	1173	1177
0.35	9	399	443	421	507	539	523	501	520	510
	13	624	592	608	767	772	770	832	845	839
	17	1047	1111	1079	1206	1293	1249	954	1036	995
2.50	9	439	398	418	517	511	514	537	514	526
	13	556	579	568	649	640	644	757	785	771
	17	649	712	680	937	909	923	963	901	932

*check, pre-osmotic treatment

Appendix Table 2. Ryegrass dry matter yield (4 day interval harvest) as influenced by different root temperatures and soil water suctions.

Source of variation	df	SS	MS	F	
Rep.	1	1440.00	1440.00	1.91	NS
Treatment	35	4562015.00	130343.28	173.48	**
suction (A)	2	123428.00	61714.00	82.13	**
temperature (B)	2	245422.70	122711.35	163.36	**
time (C)	3	3801828.10	1267276.03	1686.69	**
AB	4	29716.80	7429.20	9.88	**
AC	6	165785.90	27630.98	36.77	**
BC	6	106011.80	17835.30	23.73	**
ABC	12	88821.70	7401.80	9.85	**
Error	35	26297.00	751.34		
Total	71	4589752.00			

Appendix Table 3. Ryegrass accumulative dry matter yield as influenced by different root temperatures and soil water suctions.

Source of variation	df	SS	MS	F	
Rep.	1	5760.00	5760.00	2.15	NS
Treatment	8	1594270.00	199283.75	74.42	**
suction	2	493712.30	246856.15	92.19	**
temperature	2	981691.00	490845.50	183.31	**
suction x temp.	4	118866.70	29716.68	11.10	**
Error	8	21422.00	2677.75		
Total	17	1621452.00			

**significant at the 0.01 level of probability

Appendix Table 4. Percent plant nitrogen in 19-day old ryegrass shoots as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	5.02	5.15	5.09	5.14	5.05	5.10	5.01	5.17	5.08
0.10	9	5.20	5.19	5.20	5.60	5.66	5.63	4.90	4.99	4.95
	13	4.69	4.68	4.69	4.91	4.92	4.92	3.74	3.69	3.72
	17	3.56	3.47	3.51	3.26	3.05	3.16	3.05	3.22	3.14
0.35	9	5.01	5.32	5.16	5.90	5.78	5.48	4.55	4.89	4.72
	13	4.89	4.83	4.86	5.19	5.01	5.10	3.54	3.71	3.62
	17	3.75	3.65	3.70	3.26	3.49	3.38	3.11	3.47	3.29
2.50	9	5.27	5.16	5.22	6.79	5.35	6.07	4.60	4.69	4.65
	13	4.33	4.34	4.34	4.85	5.52	5.19	3.79	3.91	3.85
	17	4.27	4.27	4.27	3.33	3.46	3.39	3.24	3.42	3.33

*check, pre-osmotic treatment

Appendix Table 5. Nitrogen content (mg/chamber) of 19-day old ryegrass shoots as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	19.9	19.1	10.5	22.0	20.7	21.4	20.5	22.3	21.4
0.10	9	22.8	25.5	24.2	30.0	32.5	31.2	24.6	25.0	24.8
	13	30.0	31.2	30.6	36.0	31.9	33.9	34.0	36.3	35.1
	17	30.4	30.6	30.5	40.7	40.1	40.4	36.1	37.7	36.9
0.35	9	20.0	23.6	21.8	29.9	31.2	30.5	22.8	25.4	24.1
	13	30.5	28.6	29.6	39.8	38.6	39.2	29.4	31.3	30.4
	17	39.3	40.5	39.9	39.4	45.1	42.2	29.7	35.9	32.8
2.50	9	23.2	20.5	21.8	25.9	27.3	26.2	24.7	24.1	24.4
	13	24.1	25.1	24.6	31.5	35.3	33.4	28.7	30.7	29.7
	17	27.7	30.4	29.0	31.2	31.4	31.3	31.2	30.8	31.0

*check, pre-osmotic treatment

Appendix Table 6. Percent nitrogen in 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F								
	60			75			90		
	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
0.10	3.56	3.47	3.51	3.26	3.05	3.16	3.05	3.22	3.14
0.35	3.75	3.65	3.70	3.26	3.49	3.38	3.11	3.47	3.29
2.50	4.27	4.26	4.27	3.33	3.46	3.39	3.24	3.42	3.33
	Angle = Arcsin $\sqrt{\text{Percentage}}$								
0.10	10.90	10.80	10.85	10.50	10.10	10.30	10.10	10.30	10.20
0.35	11.20	10.90	11.05	10.50	10.80	10.65	10.10	10.80	10.45
2.50	12.00	12.00	12.00	10.50	10.90	10.70	10.30	10.60	10.45

Analysis of variance in angles

Source of variation	df	SS	MS	F	
Rep.	1	0.06	0.06	1.00	NS
Treatment	8	4.72	0.59	9.83	**
suction	2	1.08	0.54	9.00	**
temperature	2	2.93	1.47	24.50	**
suction x temp.	4	0.71	0.18	3.00	NS
Error	8	0.50	0.06		
Total	17	5.28			

$LSD_{0.01} = 0.17$

$LSD_{0.05} = 0.12$

CV = 1.58%

Appendix Table 7. Nitrogen content (mg/chamber) in 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Source of variation	df	SS	MS	F	
Rep.	1	16.07	16.07	4.95	NS
Treatment	8	399.82	49.98	15.40	**
suction	2	195.91	97.95	30.18	**
temperature	2	86.24	43.12	13.28	**
suction temp.	4	117.67	29.42	9.07	**
Error	8	25.97	3.25		
Total	17	441.85			

**significant at the 0.01 level of probability

Appendix Table 8. Percent plant sulphur in 19-day old ryegrass shoots as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature ^oF								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	0.37	0.31	0.34	0.39	0.37	0.38	0.31	0.29	0.30
0.10	9	0.51	0.49	0.50	0.58	0.54	0.56	0.38	0.37	0.37
	13	0.43	0.28	0.35	0.53	0.52	0.53	0.37	0.37	0.37
	17	0.37	0.37	0.37	0.29	0.29	0.29	0.30	0.30	0.30
0.35	9	0.48	0.43	0.46	0.63	0.65	0.64	0.34	0.39	0.37
	13	0.37	0.40	0.39	0.50	0.47	0.49	0.28	0.33	0.30
	17	0.35	0.34	0.35	0.29	0.29	0.29	0.27	0.26	0.26
2.50	9	0.52	0.52	0.52	0.39	0.49	0.44	0.31	0.34	0.32
	13	0.41	0.41	0.41	0.43	0.42	0.43	0.31	0.29	0.30
	17	0.28	0.30	0.29	0.33	0.33	0.33	0.31	0.29	0.30

*check, pre-osmotic treatment

Appendix Table 9. Sulphur content (mg/chamber) of 19-day old ryegrass shoots as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	1.46	1.16	1.31	1.67	1.50	1.58	1.28	1.24	1.26
0.10	9	2.21	2.40	2.31	3.12	3.12	3.12	1.89	1.85	1.87
	13	2.76	1.84	2.30	3.24	2.99	3.11	3.33	3.60	3.46
	17	3.19	3.29	3.24	4.42	4.23	4.33	3.54	3.52	3.53
0.35	9	1.92	1.91	1.92	3.21	3.48	3.34	1.72	2.05	1.88
	13	2.29	2.39	2.34	3.83	3.75	3.79	2.16	2.81	2.49
	17	3.70	3.77	3.74	3.53	3.70	3.62	2.54	2.69	2.62
2.50	9	1.60	1.70	1.65	2.04	2.52	2.28	1.62	1.74	1.69
	13	1.78	2.14	1.96	2.81	2.68	2.75	2.24	2.31	2.28
	17	2.28	2.06	2.17	3.12	2.94	3.03	2.95	2.65	2.80

*check, pre-osmotic treatment

Appendix Table 10. Percent sulphur in 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Soil water suction (Bar)	Root temperature °F								
	60			75			90		
	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
0.10	0.37	0.37	0.37	0.29	0.29	0.29	0.30	0.30	0.30
0.35	0.35	0.34	0.35	0.29	0.39	0.29	0.27	0.26	0.26
2.50	0.28	0.30	0.29	0.33	0.33	0.33	0.31	0.29	0.30

Angle = Arcsin $\sqrt{\text{Percentage}}$

0.10	3.50	3.50	3.50	3.10	3.00	3.05	3.10	3.10	3.10
0.35	3.40	3.30	3.35	3.10	3.00	3.05	2.90	2.90	2.90
2.50	3.00	3.10	3.05	3.30	3.30	3.30	3.20	3.10	3.15

Analysis of variance in angles

Source of variation	df	SS	MS	F	
Rep.	1	0.005	0.005	2.000	NS
Treatment	8	0.558	0.070	28.000	**
suction	2	0.041	0.020	8.000	**
temperature	2	0.195	0.098	39.200	**
Suction x temp.	4	0.322	0.080	32.000	**
Error	8	0.020	0.0025		
Total	17	0.583			

$LSD_{0.01} = 0.17$

$LSD_{0.05} = 0.12$

CV = 1.58%

Appendix Table 11. Sulphur content (mg/chamber) of 31-day old ryegrass shoots as influenced by different root temperatures and soil water suctions.

Source of variation	df	SS	MS	F	
Rep.	1	0.01	0.01	0.67	NS
Treatment	8	6.84	0.86	57.00	**
suction	2	3.28	1.64	109.20	**
temperature	2	1.67	0.83	55.60	**
suction temp.	4	1.90	0.47	31.60	**
Error	8	0.123	0.015		
Total	17	6.97			

**Significant at the 0.01 level of probability

Appendix Table 12. Available nitrogen (NH_4-N + NO_3-N) content in ppm mineralized from unfertilized soil during 32 day incubation.

Time (Day)	NH_4-N	NO_3-N	available-N
0	14.8	5.5	20.3
2	17.9	4.1	21.0
4	29.6	4.4	34.0
8	26.8	4.2	31.0
16	34.5	4.1	38.6
24	34.0	4.1	38.1
32	43.7	5.7	49.4

Appendix Table 13. Available nitrogen content (mg/chamber) in fertilized soil as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	26.7	28.1	27.4	24.1	24.9	24.5	22.9	24.8	23.8
0.10	9	20.3	18.0	19.2	18.6	18.8	18.7	47.1	49.6	48.3
	13	15.5	15.9	15.7	18.6	17.9	18.3	40.3	45.5	42.9
	17	11.1	10.4	10.7	17.5	19.8	18.7	34.4	33.5	34.0
0.35	9	22.5	21.6	22.0	18.3	17.8	18.1	31.2	28.3	29.8
	13	17.5	17.3	17.4	17.3	19.6	18.4	30.8	31.8	31.3
	17	13.7	15.1	14.4	20.8	20.5	20.7	36.1	30.3	30.2
2.50	9	19.7	21.5	20.6	25.9	24.4	25.1	27.8	27.1	27.4
	13	21.6	21.6	21.6	22.7	22.7	22.7	31.4	31.5	31.4
	17	21.9	21.1	21.5	25.7	26.9	26.3	39.0	31.9	35.5

*check, pre-osmotic treatment

Appendix Table 14. Available nitrogen (NH_4-N + NO_3-N) content (mg/chamber) in carbowax solution as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
0.10	9	8.6	8.4	8.5	8.4	8.8	8.6	10.8	9.7	9.9
	13	10.5	8.8	9.7	11.8	10.7	11.2	13.2	11.8	12.0
	17	12.2	12.0	12.1	12.6	12.8	12.7	13.2	14.3	13.8
0.35	9	7.8	6.7	7.2	8.0	8.4	8.2	9.4	9.9	9.7
	13	9.2	9.7	9.4	11.8	10.5	11.1	12.2	10.7	11.4
	17	10.3	10.5	12.2	12.0	12.0	12.1	11.6	12.8	12.2
2.50	9	6.9	6.5	6.7	8.2	7.6	7.9	8.7	8.7	8.7
	13	7.4	7.6	7.5	8.8	8.2	8.5	10.5	10.1	10.3
	17	9.0	8.0	7.5	10.3	9.6	9.9	10.1	10.7	10.4

Appendix Table 15. Shoot and root dry weights and proportion (percent) of nitrogen and sulphur present in the shoots and roots of ryegrass grown in soil temperature of 75° F and soil water suction of 0.35 and 2.50 bars.

	Soil water suction (Bar)	Dry weight (mg)	% dry wt.	% N	% S
shoot	0.35	5.55	69.88	54.40	36.92
root	0.35	2.39	30.12	45.60	63.08
shoot	2.50	4.73	71.23	58.94	36.87
root	2.50	1.91	28.77	41.06	63.13

Appendix Table 16. Root dry matter yield (mg/chamber) of 19-day old ryegrass seedlings as influenced by time, moisture status and soil temperature.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F: 60 Rep. I	60 Rep. II	60 Average	75 Rep. I	75 Rep. II	75 Average	90 Rep. I	90 Rep. II	90 Average
	5*	119.4	111.0	115.2	128.4	123.0	125.7	123.0	129.6	126.3
0.10	9	131.4	147.6	139.5	160.8	172.2	166.5	150.9	150.3	150.6
	13	191.7	200.4	196.0	249.0	244.5	246.7	272.4	294.9	283.6
	17	255.9	264.6	260.2	331.2	312.9	322.0	354.6	351.9	353.2
0.35	9	119.7	132.9	126.3	152.1	161.7	156.9	150.3	156.0	153.1
	13	187.2	177.6	182.4	230.1	231.6	230.8	249.6	253.5	251.5
	17	314.1	333.3	323.7	361.8	387.9	374.8	386.2	310.8	298.5
2.50	9	131.7	119.4	125.5	155.1	153.3	154.2	161.1	154.2	157.6
	13	166.8	173.7	170.2	194.7	192.0	193.3	227.1	235.5	231.3
	17	194.7	213.6	204.1	281.1	272.7	276.9	288.9	270.3	279.6

*check, pre-osmotic treatment

Appendix Table 17. Root nitrogen content (mg/chamber) of ryegrass seedlings as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Root temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
	5*	7.17	6.85	7.01	7.90	7.43	7.67	7.37	8.01	7.69
0.10	9	8.18	9.17	8.68	10.77	11.65	11.21	8.84	8.98	8.91
	13	10.77	11.22	10.99	12.91	11.43	12.17	12.20	13.30	12.75
	17	10.93	10.98	10.95	14.63	14.40	14.51	12.96	13.55	13.25
0.35	9	7.17	8.46	7.81	10.74	11.18	10.96	8.18	9.12	8.65
	13	10.96	10.26	10.61	14.30	13.83	14.06	10.56	11.24	10.90
	17	14.09	14.55	14.32	14.13	16.00	15.07	10.65	12.89	11.77
2.50	9	8.32	7.37	7.84	8.24	11.21	9.73	8.88	8.66	8.77
	13	8.65	9.02	8.83	11.31	11.99	11.65	10.30	11.03	10.66
	17	9.95	10.90	10.42	11.19	11.23	11.21	11.18	11.07	11.13

*check, pre-osmotic treatment

Appendix Table 18a. Average amount of nitrogen (mg/chamber) mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F		
		60	75	90
	5*	26.6	26.2	25.6
0.10	9	33.1	42.4	64.6
	13	36.7	45.0	63.0
	17	30.0	51.8	63.3
0.35	9	31.5	40.4	44.8
	13	36.8	52.6	53.7
	17	44.4	55.5	55.4
2.50	9	30.3	41.6	42.0
	13	33.2	46.1	51.9
	17	34.2	44.7	55.2

*check, pre-osmotic treatment

$LSD_{0.01}$ = 4.5 mg N per chamber

$LSD_{0.05}$ = 3.4 mg N per chamber

CV = 4.1%

Appendix Table 18b. Amount of nitrogen (mg/chamber) mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Source of variation	df	SS	MS	F	
Replication	1	67.57	73.27	18.67	**
Treatment	35	10615.01	302.96	111.10	**
Suction (A)	2	230.26	115.13	42.22	**
temperature (B)	2	2794.12	1397.06	512.31	**
time (C)	3	5600.85	1866.06	684.62	**
AB	4	426.22	106.55	39.07	**
BC	6	968.38	161.40	59.18	**
ABC	12	399.57	33.30	9.20	**
Error	35	126.71	3.62		
Total	71	10772.19			

**significant at the 0.01 level of probability

Appendix Table 19. Available sulphur (SO_4-S) content in ppm mineralized from unfertilized during 32-day incubation.

Time (Day)	Available sulphur (ppm)		
	Rep. I	Rep. II	Average
0	4.65	4.60	4.62
2	1.60	1.50	1.55
4	3.40	3.00	3.20
8	4.15	3.55	3.85
16	4.25	3.20	3.72
24	3.35	2.52	2.94
32	6.00	6.00	6.00

Appendix Table 20. Available sulphur content (mg/chamber) mineralized from fertilized soil as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F								
		60			75			95		
		Rep. I	Rep. II	Average	Rep. I	Rep. **	Average	Rep. I	Rep. II	Average
	5*	3.42	3.24	3.33	3.49	3.38	3.44	3.35	3.35	3.35
0.10	9	1.55	1.33	1.44	2.56	2.05	2.30	4.30	4.50	4.40
	13	1.08	0.86	0.97	2.66	2.38	2.52	4.72	4.72	4.72
	17	1.19	1.19	1.19	1.91	2.02	1.96	4.93	5.00	4.96
0.35	9	2.41	1.98	2.20	2.59	2.63	2.61	3.46	3.35	3.40
	13	0.94	0.86	0.90	2.92	2.92	2.92	3.56	3.67	3.62
	17	1.62	1.44	1.53	2.16	2.09	2.12	3.60	3.92	3.76
2.50	9	2.99	2.41	2.70	2.23	2.23	2.23	4.21	4.03	4.12
	13	2.77	2.05	2.41	3.46	1.91	2.68	3.71	3.46	3.85
	17	2.70	1.87	2.29	2.29	2.74	2.51	2.99	2.77	2.88

*check, pre-osmotic treatment

Appendix Table 21. Sulphate sulphur content (mg/chamber) in carbowax solution as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F								
		60			75			90		
		Rep. I	Rep. II	Average	Rep. I	Rep. II	Average	Rep. I	Rep. II	Average
0.10	9	5.80	6.60	6.20	7.40	8.50	7.95	8.90	10.60	9.75
	13	6.60	7.60	7.10	9.50	10.40	9.95	14.40	14.20	14.30
	17	7.35	8.40	7.87	10.80	12.30	11.55	15.60	18.60	17.10
0.35	9	5.60	6.20	5.90	8.30	7.50	7.90	8.20	9.60	8.90
	13	7.20	7.20	7.20	9.50	10.80	10.12	15.90	14.40	15.15
	17	6.60	8.10	7.35	11.10	12.30	11.70	18.90	21.90	20.40
2.50	9	4.80	4.10	4.45	5.55	6.10	5.80	6.60	8.20	7.40
	13	4.90	4.30	4.60	11.00	6.50	10.80	8.65	10.80	9.72
	17	4.80	5.70	5.25	10.50	12.30	11.40	13.20	11.40	12.30

Appendix Table 22. Root sulphur content (mg/chamber) of 19-day old ryegrass seedlings as influenced by time, different root temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F: 60 Rep. I	60 Rep. II	60 Average	75 Rep. I	75 Rep. II	75 Average	90 Rep. I	90 Rep. II	90 Average
	5*	1.06	0.84	0.95	1.22	1.10	1.16	0.93	0.91	0.92
0.10	9	1.62	1.75	1.68	2.27	2.28	2.28	1.38	1.35	1.36
	13	2.01	1.34	1.68	2.36	2.18	2.27	2.43	2.63	2.53
	17	2.33	2.40	2.37	3.23	3.09	3.16	2.59	2.57	2.58
0.35	9	1.40	1.39	1.40	2.34	2.54	2.44	1.26	1.49	1.38
	13	1.67	1.74	1.71	2.80	2.74	2.77	1.57	2.05	1.81
	17	2.70	2.75	2.73	2.58	2.70	2.64	1.86	1.96	1.91
2.50	9	1.17	1.24	1.21	1.49	1.84	1.66	1.20	1.27	1.23
	13	1.30	1.56	1.43	2.05	1.96	2.01	1.72	1.68	1.70
	17	1.66	1.51	1.58	2.28	2.15	2.21	2.15	1.93	2.04

*check, pre-osmotic treatment

Appendix Table 23a. Average amount of sulphur (mg/chamber) mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Soil water suction (Bar)	No. of days after S-urea applied	Soil temperature °F		
		60	75	90
	5*	2.99	3.60	2.93
0.10	9	9.33	13.31	15.08
	13	9.09	14.90	22.06
	17	10.67	17.02	24.17
0.35	9	9.11	14.00	13.26
	13	9.20	16.32	20.12
	17	11.34	16.44	24.69
2.50	9	7.21	9.68	13.14
	13	7.45	13.23	14.39
	17	7.29	15.15	16.02

*check, pre-osmotic treatment

$LSD_{0.01}$ = 3.36 mg S per chamber

$LSD_{0.05}$ = 2.50 mg S per chamber

CV = 10.95%

Appendix Table 23b. Amount of sulphur (mg/chamber) mineralized from S-urea as influenced by time, different soil temperatures and soil water suctions.

Source of variation	df	SS	Ms	F	
Replication	1	2.53	2.53	1.69	NS
Treatment	35	2766.40	79.04	52.83	**
suction (A)	2	110.53	55.27	39.94	**
temperature (B)	2	572.53	286.27	191.35	**
time (C)	3	1705.78	568.59	380.08	**
AB	4	18.85	4.71	3.15	NS
AC	6	47.20	7.87	5.26	**
BC	6	262.24	43.71	29.22	**
ABC	12	49.27	4.10	2.74	NS
Error	35	52.37	1.50		
Total	71				

**significant at the 0.01 level of probability