Effect of surface soil temperature on early growth, nutrient uptake, and nutrient translocation by spring wheat (Triticum aestivum)
by Glennis Owen Boatwright

Abstract:

Spring wheat was grown under growth chamber conditions to study the effect of surface soil temperature on early plant growth, nutrient uptake, and nutrient translocation.

Surface soil temperatures below optimum significantly decreased top growth but not root growth. Total nutrients accumulated in the tops increased with increases in surface soil temperature. Roots appeared to accumulate both Cu and Zn under cold surface soil conditions.

Translocation of 86Rb from the roots to the tops was significantly greater when the surface soil was warm than when it was cold. Translocation of nutrients from the roots to the tops may be restricted by the cold soil surface zone. Good nutrient status of the soil appears to modify the detrimental effect of cold surface soils. However, fertility did not completely alleviate the detrimental effect of cold surface soils.

The crown (transition region) of the plants appears to be the sensitive part to cold soil temperatures. Location of the crown above the cold zone resulted in near equal dry weights at both cold and warm surface soil temperatures.

The location of the shoot meristematic region did not influence the effect that surface soil temperature had on plant growth and. development.

A discussion of the theoretical significance of the transition region is presented in the results and. discussion section.

EFFECT OF SURFACE SOIL TEMPERATURE ON EARLY GROWTH, NUTRIENT UPTAKE, AND NUTRIENT TRANSLOCATION BY SPRING WHEAT (*Triticum aestivum*)

by

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ABSTRACT

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The location of the shoot meristematic region did not influence the effect that surface soil temperature had on plant growth and development.

A discussion of the theoretical significance of the transition region is presented in the results and discussion section.

INTRODUCTION

During the normal process of plant growth, a plant in the field is subject to continually changing conditions of environment. When these conditions lie outside the optimal range, a degree of stress is exerted on the organism. The effect of a given stress may differ with the condition of the plant at the time of stress (26, 49). Sensitivity and degree of response are known to vary with stage of development (9, 19, 50). Critical periods of high sensitivity prevail during early seedling growth and again near the flowering stage.

Soil temperature is recognized as one of the important factors in the production of plants. Soil temperature within a given geographic location varies with soil depth, amount and type of vegetative cover, color of the soil, amount of soil water, and type of cultivation.

Recent investigations (16, 54, 64) have demonstrated that stubble mulch cultivation often results in decreased yields of many crops. Initially, the yield reductions were attributed to decreased availability of nutrients. However, with additional fertilization, yields are usually lower than when no stubble is involved (36, 54, 64). Thus, a stubble mulch must change other growth factors such as soil temperature. Research has demonstrated (2, 43, 54, 64) that the surface soil temperature is considerably lower in the fall and early spring when stubble mulching is practiced than when no stubble is used. Soil temperature appears to exert a profound influence on plant growth and nutrition. The direct physiological effect of soil temperature on plant growth cannot easily be separated from the indirect effects of soil temperature upon nutrient availability and subsequent growth. The direct effects of soil temperature may result from the activation of temperature-sensitive endogenous mechanisms of the plant, which are determined by the genetic character of the plant.

Previous soil temperature studies have usually involved the entire root zone. Since stubble mulching exerts maximum influence on surface soil temperature and since this is the area for crown development, temperature studies of this zone seems important. The present research data are based on early growth and development of spring wheat and the uptake and translocation of nutrients as influenced by surface soil temperature when subsoils were maintained at optimum temperatures.

The objectives of this study were: (1) To determine the effect of surface soil temperature on plant growth and development, nutrient uptake, and nutrient translocation; and (2) To evaluate the importance of the crown (transition region) and meristematic components of wheat with respect to soil temperature effects. Fulfillment of these objectives will partially test the hypothesis that low temperatures at the transition region hinders normal development and functioning of the vascular structures therein.

LITERATURE REVIEW

Mulch And Its Influence On Soil Temperature And Plant Growth

At Lincoln, Nebraska, McCalla and Army (43) reported that 8 tons of straw mulch per acre decreased soil temperature at the 1-inch depth by as much as 17.7 C. Mulch rates of 2 to 3 tons per acre lowered soil temperatures 3 to 6 C at the 1-inch depth. Shubeck and Holmes (54) measured soil temperatures at 2-inch depths and found that 1.5 tons per acre of straw mulch lowered the temperature 15 F when compared to bare soil. Light colored mulch in Kansas (2) resulted in soil temperatures 2.8 C lower than bare soil, while partially decomposed mulch had still less influence on soil temperatures. Allmaras, et al (1) used straw mulch to vary soil temperatures from 60 to 83 F. At Sidney, Montana, Black[1] measured soil temperatures at 2-inch depths and found temperatures 18 F lower with 1.5 tons per acre of straw than when no residue was used. Boatwright and Ferguson[2] found soil temperatures at 1-inch depths as much as 28 F colder under 3 tons of mulch per acre than when no mulch was used.

Burrows and Larson (16) postulated that lower soil temperatures under mulch was a primary causative factor in reducing corn growth in

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[1] Black, A. L. 1965. Effect of residue level on moisture conservation and winter wheat survival in the Northern Great Plains (unpublished data).

[2] Boatwright, G. O. and H. Ferguson. 1965. Root Distribution of Winter Wheat as Influenced by Residues (unpublished data).

the North Central states. Plant height and dry matter production decreased progressively with increasing mulch rates. In cooler areas of the country, lower soil temperatures during the spring growing season, under mulch, frequently have an inhibiting effect on growth of crops such as corn (2).

Research presented by van Wijk et al (64) on uniform mulching experiments in Iowa, Minnesota, Ohio and South Carolina indicated that mulching caused a decrease in corn growth where soil temperatures were near the minimum for cron growth. However, when soil temperatures were above optimum for corn growth, the decreased soil temperature due to mulch was beneficial.

Brown (12) concluded that soil temperatures near the surface may exert a greater influence on growth of Kentucky bluegrass than air temperature or soil temperature at deeper depths.

Controlled Soil Temperature and Subsequent Plant Growth

Willis et al (69) used heating cables to control soil temperature under field conditions. They found that increases in soil temperature accelerated rate of emergence, rate of growth and promoted earliness in maturity of corn. Growth rates approximately followed the Van't Hoff law, the Q_{10} C of that law being from 2.0 to 2.8 for the average temperature range tested, 60 to 80 F.

In a study conducted by Walker (66), a soil chamber was constructed whereby precise soil temperature could be maintained. He showed that with each degree increase in soil temperature from 12 to 26 C, total maize seedling dry weights were an average of 20% greater than weights at previous soil temperatures. At soil temperatures above 26 C average seedling weights were 12% smaller with each degree increase in temperature.

In greenhouse experiments using sand cultures and nutrient solutions, Knoll et al (36) found that 15 C root zone temperatures severly restricted growth of young corn plants. High P levels never fully counteracted this harmful effect. In a similar experiments by Beauchamp and Lathwell (3), the time interval required by corn to reach specific stages of development increased substantially with decreasing temperatures from 25 C to 15 C. In 1967, Beauchamp and Lathwell (4) continued this work to define stages of shoot development as influenced by root zone temperatures. The rate of morphological development of corn plants increased substantially with increasing temperatures. Absolute growth rates of both shoots and roots tended to be greatest at 20 C and lowest at 25 C. The optimum root zone temperature decreased for shoot growth but increased for root growth during the 2 to 6-leaf growth stage interval.

Root development of corn was also studied by Beauchamp and Lathwell (4). They showed that root growth was slower at 15 than 20 or 25 C. At 20 C, the root diameter was smaller, but the vascular cylinder diameter was greater at 15 and 25 C. Maturation of the protophloem elements occurred closer to the root apex at high temperatures, indicating that lower temperatures delayed maturation of the roots. They also suggested that cell division may take precedence over cell elongation at high temperatures, while at low temperatures cell elongation takes precedence. Walker (66) found that root weights increased linearly with an increase in soil temperature from 12 to 26 C. From 26 C to 35 C root weights decreased.

Shoot growth of young tomato plants increased as root zone temperature increased from 10 to 25 C (40). When roots were subjected to a 10 C temperature, growth rate of shoots approached zero, even though the shoots were exposed to normal greenhouse temperatures.

Davis and Lingle (20) grew tomato plants in distilled water and measured significant promotion of shoot growth in response to increased root temperature. They concluded that the effect of root temperature on shoot growth did not reside primarily in rates of mineral supply to the shoot, indicating a possible endogenous mechanism. Root temperatures may induce differential production of root-produced substances having root regulatory activity. Went and Bonner (68) presented such evidence for tomato plants.

Mack et al (42), found that as soil temperature increased from 54 to 78 F dry weight of snap beans increased. The largest increment of increase in dry weight occurred when soil temperature was increased from 54 to 62 F.

Diurnal temperature studies by Stanfield et al (58) indicate that rate of development by peas increased steadily as the average temperature increased from 7 C day - 4 C night to 32 C night. Rate of stem elongation was most rapid at 21/13 C; and the plant height was greatest at 16/10 C. On a dry weight basis, vine growth decreased at temperatures above and below a optimum which shifted from 21/16 to 16/10 C in the course of plant development. Tillering was most prolific at the lower temperatures and was absent at 32 C day temperatures. Pea yield decreased as temperature increased above 16/10 C, due mainly to a reduced number of pods per plant.

Growth of alfalfa was greatly affected by root zone temperature (31). More forage was produced at 27 C and the most root and nodular tissue at 12 C. The shape and color of nodular tissue was affected by soil temperatures. Beinhart (8) found that day soil temperatures markedly affected growth of white clover. Maximum dry weight occurred at 17 and 23 C, significantly less at 30 C and least at 10 C. Night time temperatures had less influence on growth of white clover.

Nelson (45) grew cotton seedlings in nutrient solutions at 3 growth chamber temperatures for 4 days with an additional 7.5 day period at 27 C. Little or no growth occurred at 12 C during the 4 day treatment period, but growth resumed after returning the temperature to 27 C and the rate was the same as the 27 C treatment. The detrimental effect of a short period of low root temperature was apparently caused by a reduction in water uptake which in turn decreased leaf expansion.

Finn and Mack (24) measured increased vegetative yields of orchardgrass as soil temperatures were increased from 10 to 20 C. According to Nielsen and Cunningham (47) maximum growth of ryegrass occurred when soil temperature was at 19.5 C with minimum growth at 11 C. Beevers and Cooper (6) found that perennial ryegrass yields decreased under a continuous soil temperature of 12 C when compared to 25 C. However, fluctuating temperatures (25 C day, 12 C night) resulted in maximum yields. Total leaf area per plant and leaf area index was also greatest when temperatures were fluctuated. Lowest values were measured at 12 C. Tiller numbers were also lowest at 12 C and 25 C.

Cohen and Tadmor (18) studied the elongation of seedling roots of various grasses and measured two- to three-fold increases over a temperature range of 10 to 20 C. They stated that optimum temperature for root elongation near the soil surface was generally higher than at deeper depths. Root elongation was positively correlated to seed weight. They speculated that increasing the soil temperature may increase enzymatic activity for the mobilization of seed reserves and thus enhance root elongation in the pre-emergence stage. In contrast, research by Finn and Mack (24) indicate that root yields of orchardgrass increased when soil temperatures were decreased from 20 to 10 C. Results by Nielsen and Cunningham (47) also showed that maximum ryegrass root yields occurred at 11 C. They speculated that greater respiration losses may occur at higher temperatures. Using birdsfoot trefoil, Qualls and Cooper (50) found that respiration rates varied with temperature and with age. Maximum respiration occurred at 15.6 C when plants were 4 to 8 days old and at 21.1 and 26.7 when only 2 to 4 days old.

In a greenhouse study with oats, Case et al (17) found that height response to added P was greatest at 15 C and least at 25 C. The effects of temperature on height were greatest when no P was applied. There was a marked response in forage yields to increasing soil temperature. However, root yields were greatest at 15 C and lowest at 25 C. Theron (63) found that yields of oats harvested just after heading were higher at a soil temperature of 25 C than at 15 or 20 C, when N was limiting, whereas yields were much higher at 15 or 20 C than at 25 C with adequate N. Nielsen et al (46) found that as oats grown at soil temperatures of 5, 12.2, 19.5 and 26.7 C approached maturity, shoot yields were highest at 19.5 C and lowest at 26.7 C. In contrast, root yields were usually lowest at highest temperatures.

Maximum barley yields (41) were achieved when soil temperatures were maintained at 18 C. Lowest yields occurred at 27 C. Intermediate yields of barley were obtained at 9 C. Growth chamber studies by

Power et al (49) indicate that soils warmer than 15 C were best for initial plant growth. After tillering, barley developed best at soil temperatures near 15 C. Fertilization with P partially offset the adverse effects of non-optimal soil temperatures. At sub-optimal temperatures, growth was less sensitive to changes in P fertilization. They suggested that factors limiting growth at low soil temperatures may be quite different from those active at high temperatures. Langridge (37) suggested that such differential responses may be explained by effects of temperature on the efficiency of enzyme systems within the plant.

Stewart and Whitfield (61) studied the influence of temperature on wheat yields and found that as temperatures were increased from 55 to 65 F, yields were significantly increased. Although fertilization increased yields, the effect of soil temperature was not completely modified.

Dry matter yield of winter wheat tops was considerably less when grown at soil temperatures maintained at 50 F than at 65 F (27). Phosphorus fertilization influenced dry matter very little when soil temperatures were maintained at 50 F regardless of available soil phosphorus. At 65 and 80 F, P fertilization doubled the yield of dry matter on low P soils.

Wooley (70) found that osmotic pressure and N treatment had only a small effect on dry matter production of wheat, whereas increasing root temperatures from 45 to 80 F significantly increased dry matter production of shoots and roots.

Burleigh, et al (13) found that 60 F temperature was optimum for coleoptile elongation of 8 varieties of winter wheat. At temperatures greater than 60 F coleoptile lengths decreased with increasing temperature. In a nutrient solution study using wheat, Burstrom (15) found that as soil temperature increased, cell length decreased, wall elasticity decreased, and cell wall plasticity disappeared at 30 C.

Soil Temperature Effect On Uptake And Translocation

Walker (66) found that total uptake of all elements except B, by corn, increased with increasing soil temperatures to a maximum value at temperatures between 26 and 34 C, depending upon the element. Allmaras et al (1) reported that yield of P and K in corn increased linearly with increases in soil temperature. At low temperature, (15 C) P uptake by corn, decreased and Knoll et al (36), suggested that the primary cause may be a result of depressed root growth.

Uptake of P and K by tomato plants (20) was significantly greater at 24 C than at 18 C. They also suggested that ion concentration in the xylem exudate may be temperature dependent. Potassium concentration declined from 534 ppm at 15 C to 457 ppm at 27 C. Nitrate N was not significantly affected. In an earlier study, Lingle and Davis (40) reported increased concentrations of P, Ca and Mg with increasing soil temperatures. In the case of tomatoes, they proposed that reduced rates of mineral transport may be responsible for reduced shoot growth at low temperatures.

Riekels and Lingle (51) showed that both uptake and translocation of Fe by tomato plants was enhanced by increases in root temperature. At 30 C, radioactive Fe^{59} measured in the leaves was 14 times greater than at 12 C. Radioactivity in the roots was nearly twice as great at 30 C as at 12 C.

Webb (67) studied the effect of localized temperature treatment on translocation of sugars by Cucurbita melopepo. He showed that both basipetal and acropetal movement of C^{14}-labeled compounds in the phloem was almost completely inhibited at o C, but at 10 C a partial inhibition occurred. At temperatures between 15 and 35 C, translocation of C^{14} was not significantly affected. At 45 C, partial inhibition occurred and at 55 C almost complete cessation was observed. Translocated compounds unable to pass a temperature inhibited zone were diverted toward other importing regions of the plant. Because of the similarity of the translocation response to temperature change in the various organs of the plant, he suggested that a uniform mechanism may control movement of compounds through the plant.

Isolated cells from the green tissue of tobacco leaves were suspended and incubated in aqueous solutions to study Rb and P uptake by

Jyung et al (35). They found that both Rb and P uptake were temperature dependent. The Q_{10} was slightly less than 2 for Rb and greater than 2 for phosphate absorption. A Q_{10} of 2 or more has been a traditional criterion for active uptake.

Beevers et al (7) showed that the induction of nitrate reductase in excised radish cotyledons was temperature dependent, with an optimum temperature at 31 C. Nitrate uptake was also temperature dependent over the entire temperature range tested, and closely paralled enzyme induction until the temperature reached a lethal point (37 C).

Hartt (29) grew sugarcane under 2 air and 2 soil temperature regimes and fed $^{14}CO_2$ to the leaves to study translocation. At 17 C root temperature, the translocation rate was less (1.3 cm/m) than the translocation rate at 22 C (1.8 cm/m). Root temperature influenced translocation more than air temperature. Very little ^{14}C was found in the roots, possibly due to their slow rate of metabolism and growth.

Uptake of Ca^{45} by tobacco increased significantly with an increase in root temperature from 20 to 30 C (44). A further temperature increase to 30 C resulted in a non-significant difference in Ca^{45} uptake. The increase in uptake was not related to increases in root growth during the absorption period.

A study of water movement in plants by Taylor and Jensen (62) indicated that low temperatures decreased both absorption and movement.

The results depict a straight line relationship over the temperature range 10 to 40 C. Activation energies were higher for water moving through roots than through stems or leaves and they were greater for leaves than stems. Apparently, molecular mechanisms of water movement through these three tissues are different.

Nielsen and Cunningham (47) found that soil temperature affected the concentration of Cl, Ca and Mg in Italian ryegrass, but had little influence on the uptake of N, P, S, Na and K except when it altered yields. As soil temperature increased an increase in the uptake of divalent cations occurred. Beevers and Cooper (6) working with Irish perennial ryegrass and Italian ryegress, reported that total N content was affected by temperature and stage of plant development. They concluded that both temperature and age influence N metabolism. Nitrogen content was greatest in cool regimes. According to Steward and Sutcliffe (60), nitrate content decreases with decreasing temperatures and may in part be attributed to the depressing effect of low temperatures on salt absorption and ion accumulation.

Numerous inventigators have shown that uptake of P by oat plants increased with increasing soil temperatures (17), (11), (71), (46). Brady, et al (11), however, showed that at high soil temperatures, P uptake may decrease.

Uptake of N, P and K by barley plants increased with increasing soil temperatures (41). Sosulski et al (57) found that protein content of wheat was influenced more by varying moisture than by varying N except under low temperature conditions. Wooley (70) found that as root zone temperature increased from 45 to 80 F, P in wheat shoots increased 38% where as shoot N increased only 17%. Temperature influenced P in the roots similarly to the effect on shoot P. However, percentage N in the roots was highest at lower temperatures.

Temperature and Its Influence On Other Growth Factors

Duncan and Hesketh (21) studied the effect of soil temperature on rate of photosynthesis by corn. Net photosynthesis was lowest (48% of maximum) at 15 C and highest at 30 C. Leaf area growth rate increased linearly as temperatures increased from 15 to 30 C. Jolliffe and Tregunna (34) working with detached wheat leaves showed no significant difference between apparent rates of photosynthesis at 21% and 3% O_2 below 13 C. Above this temperature, the rate was always less in the 21% O_2 chamber. The temperature optimum was also different. In 21% O_2, photosynthesis was most rapid between 20 and 26 C, while in 3% O_2, 30 to 36 C was optimum.

Schmidt and Blaser (53) found that carbohydrate reserves in Bermudagrass were usually higher, and N contents lower when soils are warm as compared to cold soil conditions. Carbohydrates accumulated at high temperatures, although net photosynthesis was low because of the high leaf-root ratio. When bermudagrass was switched from cold to warm temperatures, N percentage increased and top growth was stimulated with corresponding reduction in carbohydrates.

Total root RNA was lower at 60 F than at 70 or 80 F (48). Content of DNA in the entire root increased significantly with each increase in temperature. Both RNA and DNA in the lower root section (10 mm) decreased at all temperatures and increased in the upper root section at 70 and 80 F, but not at 60 F.

Hodgson (32) studied the effect of temperature on endosperm utilization by orchardgrass. Complete endosperm utilization occurred between 14 and 16 days at 15 and 22 C. At 10 C complete endosperm utilization did not occur until the 24th day. Although temperature affected the rate of endosperm utilization, the amount of endosperm utilization was not influenced.

The response of prairie bromegrass to gibberellic acid at various temperatures was evaluated by Laubscher and Laude (38). Without gibberellic acid, maximum rate of early growth occurred at 70 F. At the later stages of growth, optimum temperature was 55 F. Plants sprayed with gibberellic acid produced maximum dry weight at 70 F irrespective of growth stage. These data suggest that temperature may influence growth hormones and could be a factor in reduced yields at temperatures below or above optimum.

MATERIALS AND METHODS

This research project was conducted in controlled environmental plant chambers to study the effect of surface soil temperature on plant growth, nutrient uptake and nutrient translocation by *Triticum aestivum* (Thatcher).

Soil temperatures, both surface and subsurface, were controlled by circulating water of different temperatures through specially constructed containers, Figure 1. Plexiglass[1] cylinders, 13 cm in diameter with a wall thickness of 6 mm, were used for the outside section of the water jacket. The inside section of the water jacket was a Plexiglass cylinder, 8 cm in diameter with a wall thickness of 3 mm. Stainless steel metal conductors, 4 cm long and 3 mm in diameter, were spaced 3 cm apart with one end extending into the water jacket and the other end extending into the soil chamber. Soil temperatures were controlled within ± 1.5 C. Air temperature was controlled by plant growth chambers and was maintained at 18 C ± 2 C.

Refrigerated water baths were used to control water temperatures for circulation purposes. The baths were custom built and were 1.51 meters long, 1.07 meters wide and 0.44 meters deep. Wall contruction included 7.6 cm styrofoam encased with stainless steel sheeting. Water

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement of preferential treatment by the author.

circulation was obtained with a Goode Pump[1] (model GV30, Little Giant Pump Co.); which delivers 260 gallons per hour. Water temperature in each bath was controlled by a Barber Coleman[1] thermostat and a penn pressure switch suspended in the bath. The refrigeration compressor was a 3/4 H.P. Copeland,[1] (model KAG-2-0075-1AB)[1] and was controlled by a high and low pressure Penn[1] cutout. The heating element provided 1500 watts to heating cables woven across the bottom of the baths. Aluminum racks used to support pots permitted water circulation throughout the bath. Desired water temperatures were maintained within ± 1 C.

The water was pumped through garden hose leading into and out of the water jacket and back into the water baths. To obtain a soil temperature of 7.22 C, the circulating water temperature had to be o.56 C. At higher soil temperatures, the difference between soil temperature and water temperature was not so great.

Amsterdam silt loam soil, characterized in Table 1, was used in all experiments. Soil pH was measured potentiometrically with a glass-calomel electrode pair in the sediment of a 1 to 2 soil-water ratio mixture after ½ hour was allowed for sedimentation. Conductivity was determined in the supernatant of the pH sample with a Wheatstone bridge. Readings were converted to a saturated paste equivalent by the following equation, $y = 4x + .7$. The method of Smith et al (56) was used for P determinations. Calcium, Mg and Na was analyzed using the Perkin-Elmer 290 B atomic absorption spectrophotometer. The cations

Table 1. Selected chemical properties of, Amsterdam silt loam, the soil used for all experiments.

Analysis	Values
Soil pH	8.20
Organic Matter %	3.55
Phosphorus, ppm	54.00
Potassium, ppm	780.00
Calcium, meq/100g	12.00
Magnesium, meq/100g	3.16
Sodium, meq/100g	0.52
E.C.e, mmhos/cm	0.60
Zinc, ppm	4.00
Iron, ppm	2.30
Copper, ppm	1.30
Manganese, ppm	9.70

were extracted from the soil with neutral normal NH_4OAC using a 1:20 soil to solution ratio. The minor elements, Zn, Cu, Fe and Mn were extracted according to the procedure of Lindsay (39).

The extracts were analyzed with the Perkin-Elmer 290 B spectrophotometer. The air dry soil (1175 g) was uniformly packed in the soil containers, Figure 1, after aluminum foil had been used to cover the outside of the containers. Foil was used to reflect light, thus permitting better control of the water temperature inside the water jacket. The soil was watered and 15 kernels of Thatcher wheat seeded 1.25 cm below the soil surface. After germination the stand was thinned to 10 plants. During the early stages of plant growth all plants were permitted to grow at growth chamber temperatures of 19 C. At specified time intervals, sterile cotton was placed on the soil surface to modify heat effect from the light and temperature treatments imposed. Soil temperatures were monitored during the remainder of the experiment using soil thermocouples placed at 1, 5 and 10 cm depths. A Honeywell stripchart recorder was used and soil temperatures measured at 4 hour intervals (0600, 1000, 1400, 1800 and 2200 hrs).

In most experiments the soil temperature variable applies only to the surface 2.54 cm of soil. Both air and subsurface soil temperatures were maintained at 19 C.

During the temperature treatment period, plant growth and development were monitored by plant height measurements, growing point move-

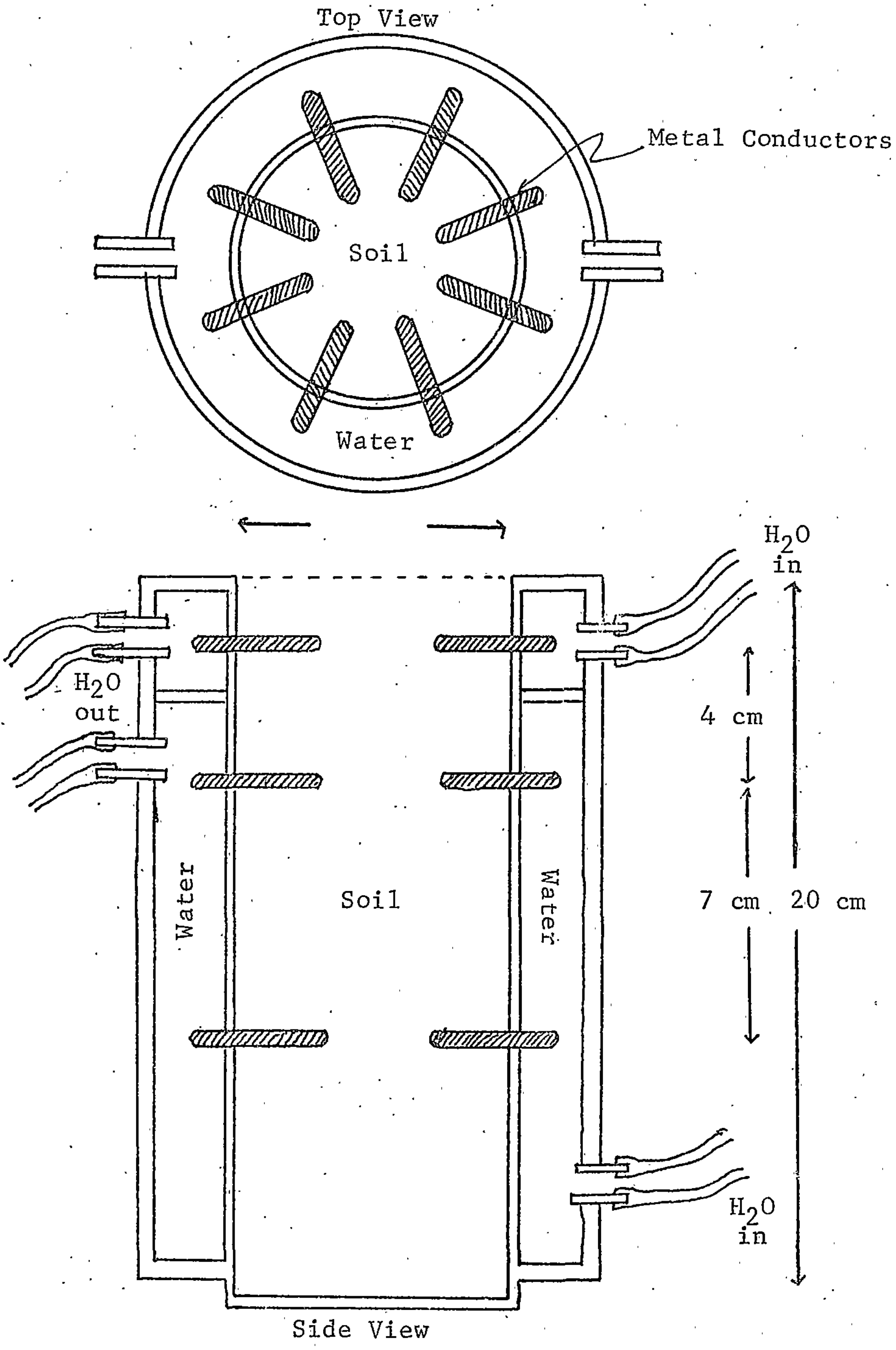

Figure 1. Diagram showing top and side view of one soil chamber used to control soil temperatures.

ment, and leaf numbers and lengths. At the end of the temperature treatment period, plant tops and roots were harvested for dry matter yield and in some cases, the material was ground and analyzed for P, K, Ca, Mg, Na, Mn, Fe, Zn and Cu. Roots were washed from the soil with a fine spray using water from the tap. Heavy material such as small gravel was hand picked from the root samples prior to weighing. Plant material was dry ashed for analysis by modifying the procedure outlined by Jackson (33, method 12-32). The modification involved a 525 C ignition temperature and the omitting of an alcoholic solution of Mg $(NO_3)_2$ or Mg $(OAC)_2$. After ashing, the samples were prepared according to the procedure outlined by Haby (28) and all elements except P were determined with a Perkin-Elmer 290 B atomic absorption spectrophotometer. Samples for P determinations were analyzed using the vanadomolybdophosphoric yellow color procedure described by Jackson (33, method 7-61).

Since this project involved a sequence of experiments that varied in treatment numbers and design, the results and discussion section will contain some aspects of materials and methods.

RESULTS AND DISCUSSION

Experiment I

This experiment was initiated to evaluate the influence of 4 surface soil temperatures, imposed at different stages of plant growth, on dry matter production of plant tops and roots. The experimental design was a complete randomized block with two replications. The four temperature treatments (8, 12, 19 and 26 C) were imposed at three stages of plant growth (2, 7 and 14 days after emergence). The temperature variable period was 11 days, after which tops and roots were harvested for dry matter yields. Statistical analyses included an analysis of variance and Duncan's new multiple range test.

The control of soil temperature within specific soil zones is very difficult. The heat conductance of soils is quite high, thus warmer subsoil tends to conduct heat to the cooler surface soil. Further radiation tends to warm the soil from the surface downward. To modify the effect of light on surface soil temperature, sterile cotton was placed on the soil surface. In this study there was not a distinct boundary between the surface 2.5 cm soil temperature and the subsurface soil temperature. For example, there was a linear gradient (8 to 19 C) from 2.5 cm depth to the 5.0 cm depth.

Surface soil temperature fluctuations during the temperature subjection period are shown in Figure 2. These data demonstrate that soil temperature control was acceptable. Desired temperatures were maintained within ± 1.5 C. The low value shown in the 26 C temperature

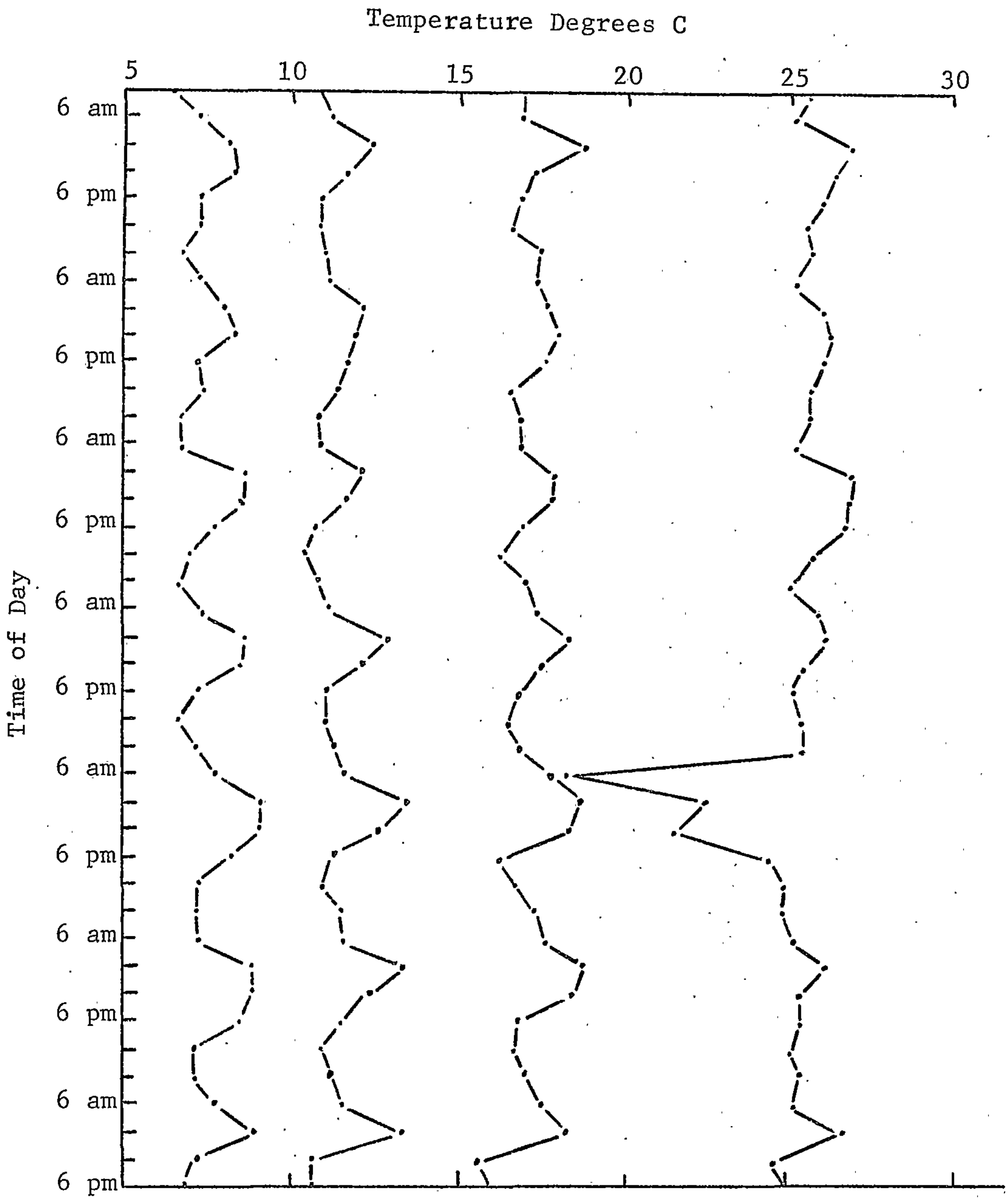

Figure 2. Soil temperature fluctuation at 1.5 cm below the soil surface for the 4 temperature variables (8, 12, 19, and 26 C).

treatment was due to a water pump failure, an indication of the problems common to experiments of this type. Soil temperatures were monitored during all experiments with temperature control similar to that shown in Figure 2.

The effect of surface soil temperature on plant growth is illustrated in Figure 3. Plant height was fairly uniform prior to initiation of the temperature variables. Plant growth during the 11 day temperature subjection period was drastically reduced when surface soils were maintained at 8 C compared to 19 C. Stage of plant growth, prior to the temperature treatment period, did not drastically alter the effect of surface soil temperatures. When surface soil temperature was at 8 C, plant height increased only about 2 cm during the 11 day temperature period. At a soil temperature of 12 C, the increase in plant height was from 3 to 4 cm. Greatest increase occurred when plants were youngest prior to imposing the temperature treatments. When the surface soil was maintained at 19 C, plant height increased as much as 13 cm during the 11 day temperature period. Greatest increase in plant height occurred with the youngest plants followed by lesser increases as the plant increased in age prior to the temperature treatment period. Plant height was less when surface soils were maintained at 26 C than at 19 C irrespective of growth stage.

These data indicate that low surface soil temperatures hinder early growth of spring wheat even though subsoil temperatures are near

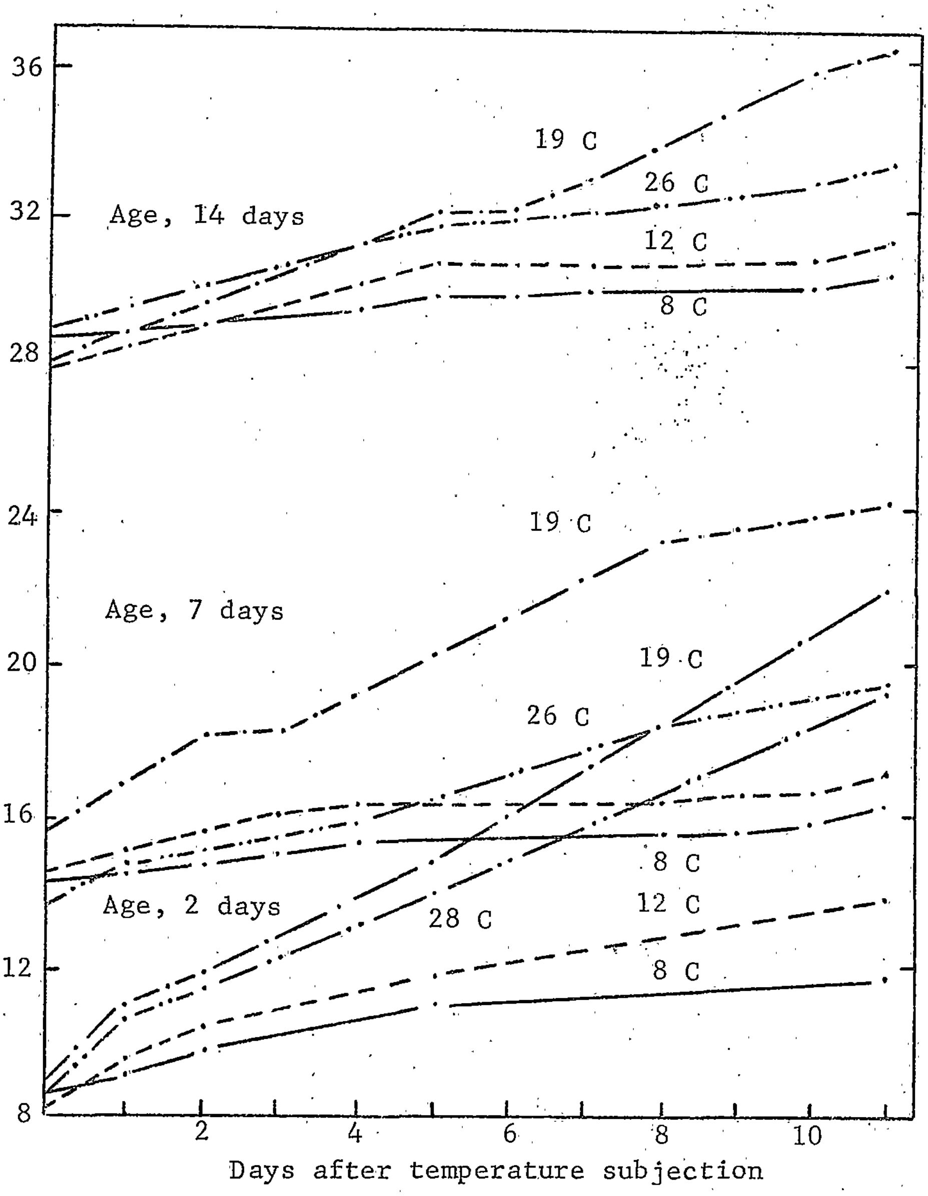

Figure 3. Effect of surface soil temperature on height of spring wheat at various stages of growth.

optimum. Of the temperatures studied, 19 C appears to be optimum whereas 26 C is too high for maximum growth.

Dry matter yield of tops and roots and the length of individual leaves as influenced by surface soil temperature from 2 to 13 days after plants emerged are shown in Figure 4. Statistical analysis, appendix Table 10 indicate that dry matter yield of the tops was significantly greater when surface soil temperatures were 19 and 26 C than when 8 and 12 C. Greatest differences in yield occurred when the surface soil temperature was increased from 12 to 19 C. Dry matter yield of roots was not significantly altered due to the surface soil ? temperature variable.

Leaf growth was most rapid when surface soil temperature was maintained at 19 C, Figure 4. The data showing growth pattern was very similar to that of dry matter yield. After 13 days of growth, plants grown in the soil with a surface temperature of 8 and 12 C had not developed the second leaf. In contrast, when the surface soil was 19 or 26 C, the second leaf had extended to about 10 cm in length.

When soil temperature treatments were delayed until 7 days after plant emergence, the 11 day temperature treatment period resulted in significant changes in plant growth and development, Figure 5. With increasing surface soil temperatures (8, 12 and 19 C) dry weight of tops significantly increased, appendix Table 11. However, soil tem-

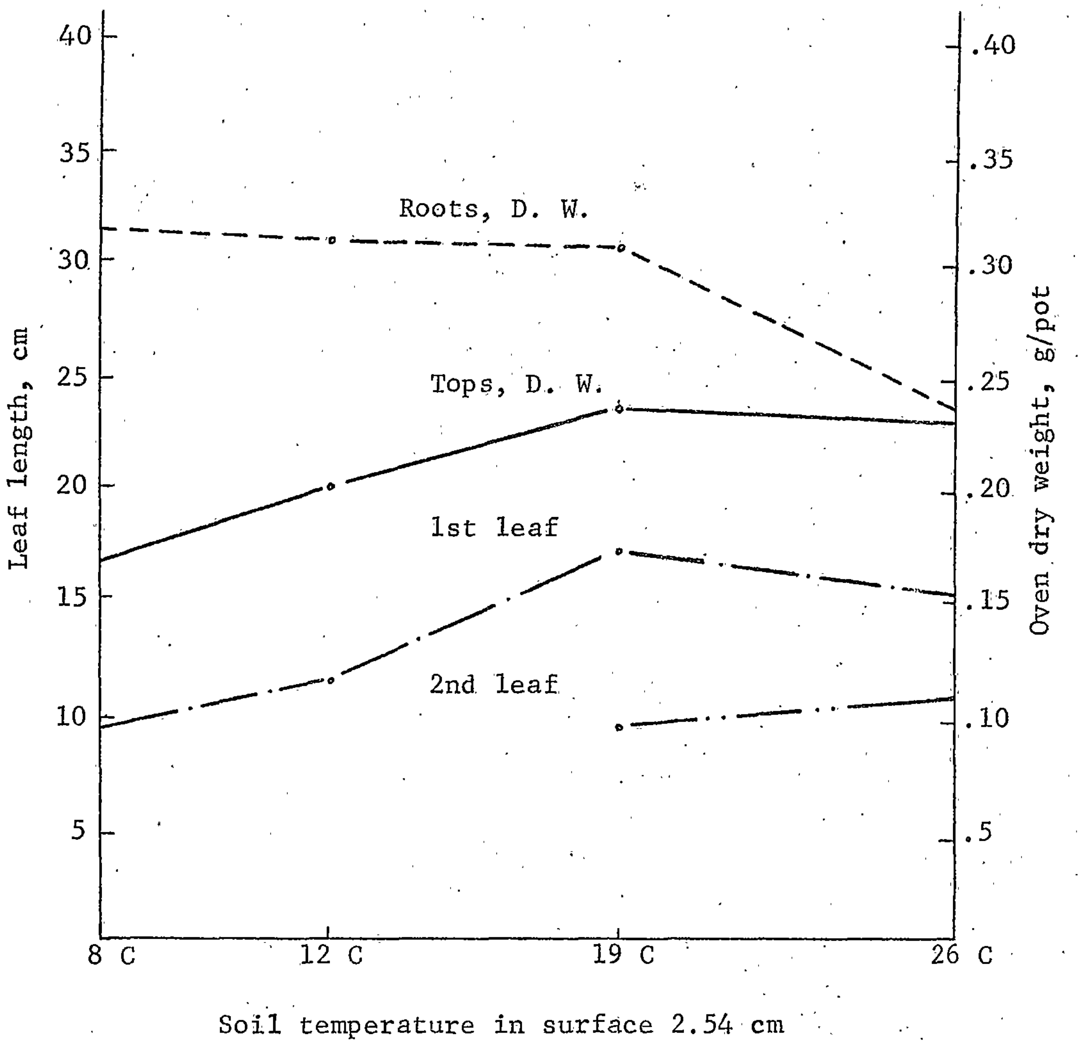

Figure 4. Effect of surface soil temperature (from 2-13 days after wheat emergence) on dry matter yield of roots and tops and on leaf growth.

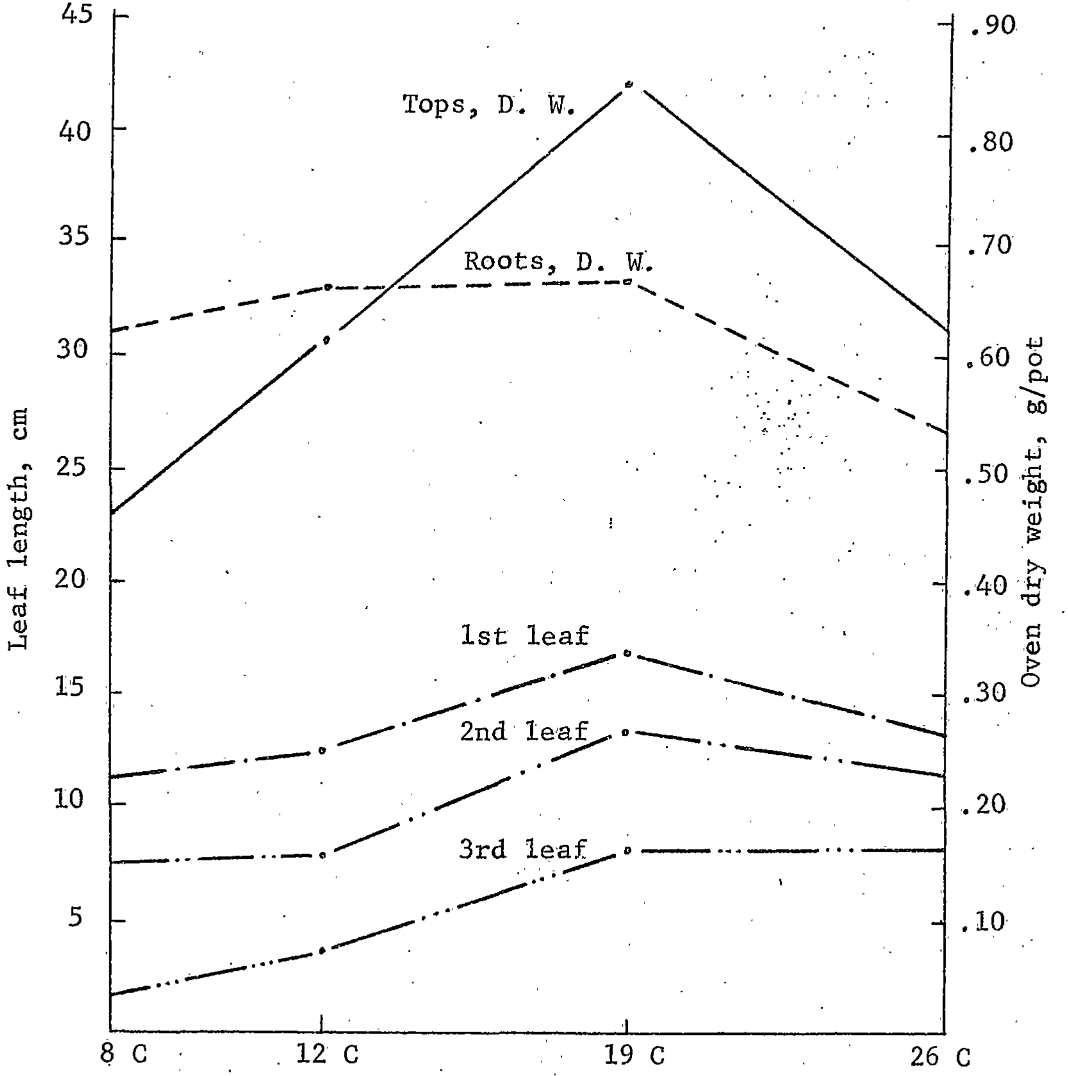

Figure 5. Effect of surface soil temperature (from 7-18 days after wheat emergence) on dry matter yield of roots and tops (oven dry weight and on leaf growth).

peratures at 26 C significantly decreased dry matter production when compared to yields from the 19 C treatment. Perhaps the differential between soil and air temperature influenced growth to some degree when the soil surface temperature was 26 C. Dry weight of roots was not significantly altered by the surface soil temperature treatments. Previous research (5, 58) indicates that as root temperature increased up to about 25 C, root yields increased. At higher temperatures, Finn (24) measured less growth by orchardgrass roots and speculated that greater respiration losses may account for the decreased root growth. Perhaps dry weights of roots were not influenced in this study because most of the roots were located in a subsoil of 19 C.

Length of individual leaves increased as surface soil temperatures increased up to 19 C. At the lower surface soil temperatures leaf length decreased.

When surface soil temperature treatments were delayed until 14 days after plant emergence, the 11 day temperature subjection period significantly influenced dry matter yield of the tops, appendix Table 12. Top yields shown in Figure 6 were about equal when surface soil temperatures were maintained at 8 and 12 C. However, increasing the temperature from 12 C to 19 C resulted in a 60% increase in dry weight of tops.

Maximum length of individual leaves occurred at a surface soil temperature of 19 C. In general, temperatures at 26 C resulted in

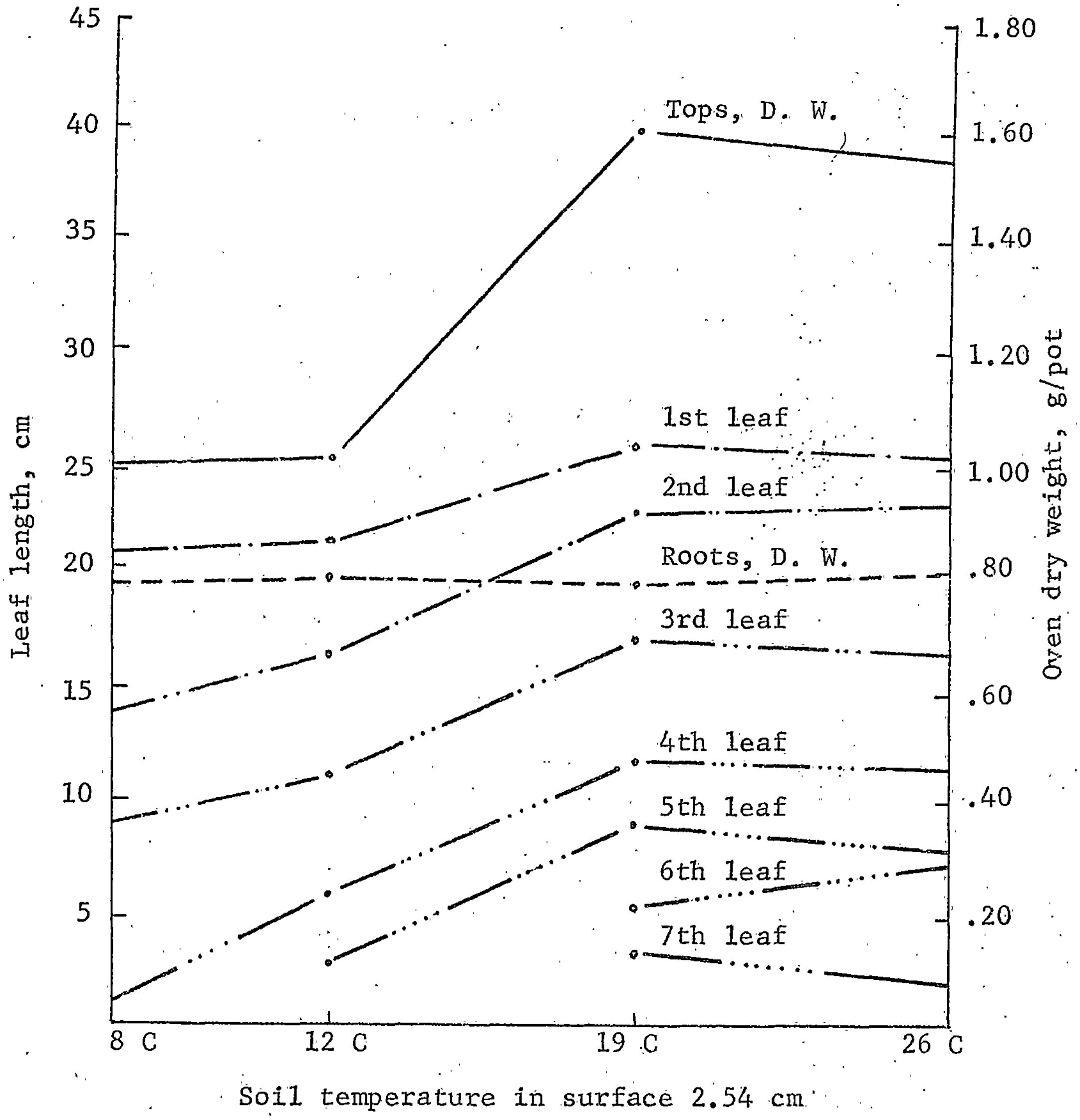

Figure 6. Effect of surface soil temperature (from 14-25 days after wheat emergence) on dry matter yield of roots and tops and on leaf growth.

slightly shorter leaves. The number of leaves present at harvest time (25 days after emergence) was also influenced by surface soil temperature. At 8 C, plants produced only 4 leaves. At 12 C, 5 leaves were present and at 19 and 26 C, plants produced 7 measurable leaves.

These data indicate that surface soil temperatures did not significantly alter root yields and that temperature effects may be slightly different as the plant increases in age. They also indicate that leaf development is delayed at lower surface soil temperatures. Considering the temperatures studied, 19 C appears to be near optimum, irrespective of growth stage. Speculation of reasons for decreased growth and development are discusses in a latter section.

Experiment II

This experiment was conducted to more closely evaluate optimum surface soil temperatures for maximum plant growth, and to determine the temperature effects on uptake of various elements by spring wheat. The experimental design was a complete randomized block involving 4 replications and 4 surface-soil temperature treatments (11, 14, 18 and 22 C). Subsurface soil temperatures were maintained at 22 C. Soil temperature subjection period was delayed until 7 days after plants emerged. The temperature treatment period was also 11 days. Plant material, tops and roots, were harvested at 18 days after plants emerged. The temperature treatment period was also 11 days. Plant material, tops and roots, were harvested at 18 days after plants emerged. Plant material was dried, weighed and ground for chemical analysis (P, K, Ca, Mg, Mn, Fe, Zn and Cu).

Soil temperature treatments were changed from those in experiment I to more closely evaluate optimum surface-soil temperatures for maximum spring wheat growth and nutrient uptake.

Data presented in appendix Table 14 shows the temperature control achieved for each soil temperature variable. It is noted that the 18 C temperature treatment was not achieved. This was due to a water bath failure after the experiment was initiated. Initially, the surface soil temperature for this treatment was 2 C colder than 18 C, followed by temperatures that were 3 C higher than 18 C. The remaining 3 temperature variables were maintained within ± 1 C of that desired.

Plant growth, measured in terms of plant height, increased with each increment increase in surface soil temperature, Figure 7. During the 11 day temperature treatment period, plants grew only about 6 cm at a soil temperature of 11 C. This compares with an increase of 11, 14 and 16 cm at soil temperatures of 14, 18 and 22 C respectively. This indicates that 22 C surface-soil temperatures may be closer to optimum than 19 C. However, the temperature problems encountered with the 18 C treatment makes it impossible to make a definite conclusion.

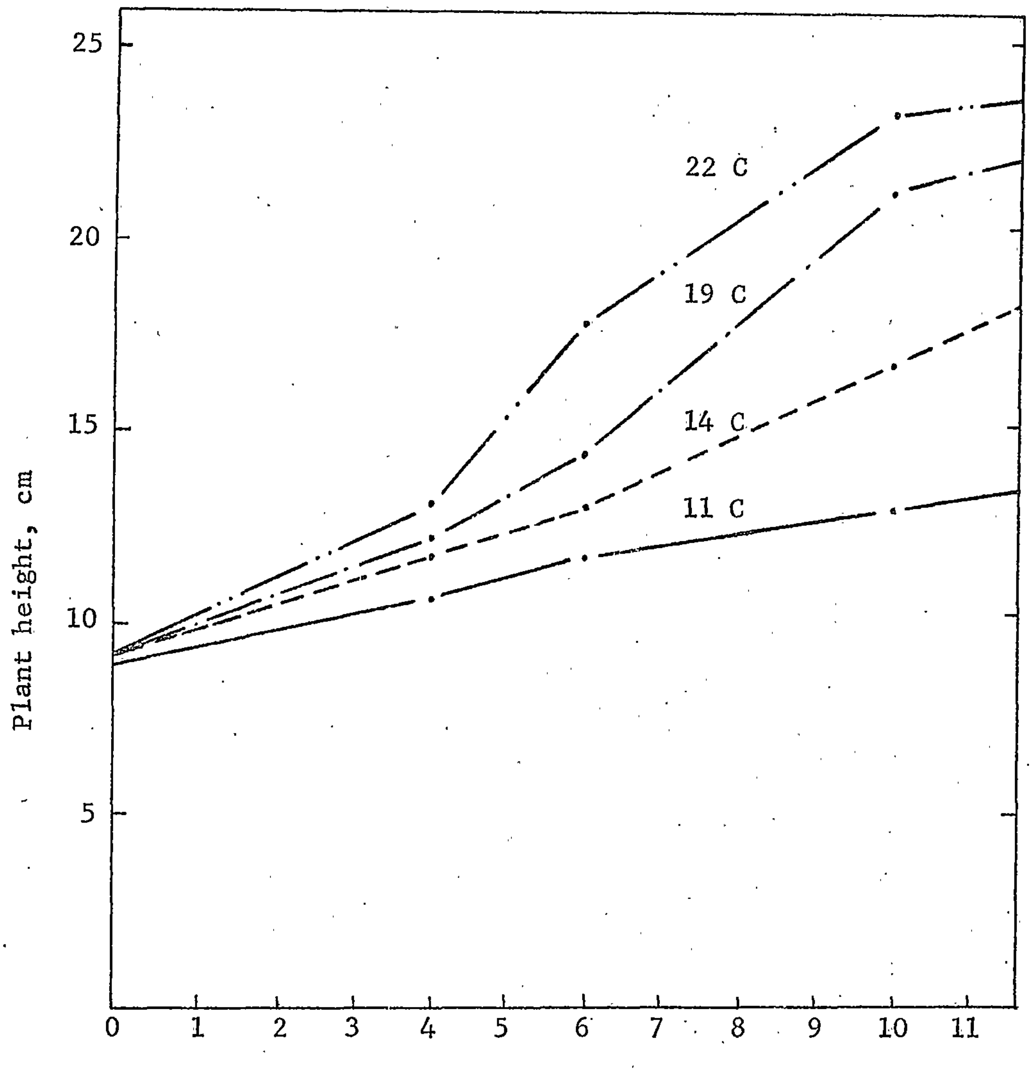

Figure 7. Effect of surface soil temperature variables on height of spring wheat during the temperature subjection period.