The effect of off-season irrigation practices on crop growth
by Bruce Alan Ekholt

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agricultural Engineering
Montana State University

Abstract:
Research was initiated in 1977 at the Montana State University-Agricultural Experiment Station to investigate the effects of off-season irrigation practices on crop growth. Crops used in the study were alfalfa and spring wheat. Two spring wheat harvests and five alfalfa cuttings were removed from each plot for analysis. For alfalfa, annual irrigation treatments varied from a single fall irrigation to four water applications. Similarly, timing of irrigation in spring wheat treatments varied from once per year to numerous applications according to stage of growth. An irrigation was defined as the filling of the soil profile to field capacity.

In addition to the climatological data recorded at the Bozeman 6W meteorological station, soil moisture throughout the active root zone and soil temperatures at the 5 cm and 20 cm depths were also monitored. Yields among certain of the spring wheat treatments were found to differ significantly during the 1978 season but the yield data could not be related to treatment since the timing of the irrigations were in question. Of the five alfalfa harvests, only the second cutting in 1979 had yield differences with statistical significance at the 95 percent level of confidence. The single Fall irrigation treatment resulted in yields that were considerably less than the treatments with the more frequent water applications only during this summed: 1979 period indicating that a single annual water application might be adequate during certain years for production of alfalfa on the deep soils of the Agronomy Farm. Alfalfa yields were further processed through a stepwise multiple linear regression analysis to determine which of the selected variables best correlated with treatment yields. Soil moisture levels, as expressed in moisture-days, and degree-days of average air temperature (above a base of 4.44C) accounted for 97 percent of the alfalfa yield variation. Soil temperature, as expressed in degree-days (above 44.4C), and degree-days of average air temperature were found similarly to account for 96 percent of the yield variation. Suggestions were made for further research into the implications from this study.

STATEMENT OF PERMISSION TO COPY

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Montana State University, I agree that the Library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature Bruce A. Ekholt

Date 9/5/80

THE EFFECT OF OFF-SEASON IRRIGATION PRACTICES ON CROP GROWTH

by

BRUCE ALAN EKHOLT

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

of

MASTER OF SCIENCE

in

Agricultural Engineering

Approved:

Thomas L. Hanson
Chairperson, Graduate Committee

W. E. Larsen
Head, Major Department

[signature]
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

September, 1980

ACKNOWLEDGMENT

I wish to express my heartfelt gratitude to my wife for her constant support, patience and understanding during this process. I also wish to thank Dr. William E. Larsen, department chairman, and Dr. Thomas L. Hanson, major advisor, for their generous help and guidance, without which these degrees would not have been possible. I would like to further thank Dr. Charles M. Milne and Dr. Richard L. Brustkern for being the fine teachers that they are.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Research was initiated in 1977 at the Montana State University Agricultural Experiment Station to investigate the effects of off-season irrigation practices on crop growth. Crops used in the study were alfalfa and spring wheat. Two spring wheat harvests and five alfalfa cuttings were removed from each plot for analysis. For alfalfa, annual irrigation treatments varied from a single fall irrigation to four water applications. Similarly, timing of irrigation in spring wheat treatments varied from once per year to numerous applications according to stage of growth. An irrigation was defined as the filling of the soil profile to field capacity. In addition to the climatological data recorded at the Bozeman 6W meteorological station, soil moisture throughout the active root zone and soil temperatures at the 5 cm and 20 cm depths were also monitored. Yields among certain of the spring wheat treatments were found to differ significantly during the 1978 season but the yield data could not be related to treatment since the timing of the irrigations were in question. Of the five alfalfa harvests, only the second cutting in 1979 had yield differences with statistical significance at the 95 percent level of confidence. The single Fall irrigation treatment resulted in yields that were considerably less than the treatments with the more frequent water applications only during this summer 1979 period indicating that a single annual water application might be adequate during certain years for production of alfalfa on the deep soils of the Agronomy Farm. Alfalfa yields were further processed through a stepwise multiple linear regression analysis to determine which of the selected variables best correlated with treatment yields. Soil moisture levels, as expressed in moisture-days, and degree-days of average air temperature (above a base of 4.44C) accounted for 97 percent of the alfalfa yield variation. Soil temperature, as expressed in degree-days (above 44.4C), and degree-days of average air temperature were found similarly to account for 96 percent of the yield variation. Suggestions were made for further research into the implications from this study.

Chapter 1

INTRODUCTION

The recent exponential increases in energy costs make it imperative that all energy-dependent irrigation schemes become as efficient as possible. The maximization of irrigation efficiency must not only include improvements to the physical system but also must consider the timing and amount of water application. With this in mind, research was initiated in 1977 at the land-grant universities in Kansas, Montana and South Dakota to investigate the extent to which 'off-season' irrigation practices affect crop growth.

Statement of the Problem

The problem is to evaluate the effects of 'off-season' irrigation practices on annual soil temperature patterns, over-winter soil moisture retention and crop yield.

Soil Temperature Effects. Is the adage "A wet soil is a cold soil" applicable to fall and spring irrigated soil profiles? To what extent, if any, does a wet soil delay the onset of crop growth and eventually affect yield? If crop growth becomes adversely affected by pre-season water application (through its effect on the soil temperature profile), then subsequent yield reductions decrease the profit margin.

Soil Moisture Retention. What portion of fall-applied irrigation water is lost to either percolation or evaporation over the winter period? How much of a crop's water requirement can be stored in the profile during the pre-season? Future irrigation schemes may incorporate into their design this concept of using energy at times other than during peak demand periods.

Crop Yield. Does off-season applied water adversely affect crop yield? The extent to which crop production levels can be maintained while taking advantage of readily available water is a key question addressed in this thesis.

Is the concept of an 'off-season' irrigation more practical during certain climatological periods than others? Can these periods be identified or, better yet, predicted? When will an off-season water application benefit crop growth? An irrigation schedule based on answers to these questions would be an extremely important crop management tool.

Objectives

This thesis does not attempt to investigate the many facets of the problems outlined above. Rather, this paper concentrates on the following objectives:

1. A review of the literature for the effects of soil temperature on plant growth and also the factors which affect soil temperature variation.

2. The determination if the various irrigaton treatments resulted in yield differences at a statistically significant level.

3. The determination of which monitored variables best account for yield differences, if any, between treatments.

Chapter 2

LITERATURE REVIEW

Introduction

All factors that influence plant growth can be classified as genetic or environmental. The most important environmental factors affecting plant growth are temperature, moisture supply, radiant energy, composition of the atmosphere, gas content of the soil, soil reaction and such biotic factors as supply of mineral nutrients (Tisdale and Nelson, 1966). Temperature influences plant growth indirectly by its effects on the availability of nutrient elements in the soil, soil moisture relations and water uptake (van Schilfgaarde, 1974). Both the surface tension and viscosity of water are inversely related to temperature and the relative hydraulic conductivity of the soil increases as temperature increases (Willis and Power, 1975). Temperature directly affects the plant functions of photosynthesis, respiration, cell-wall permeability, absorption of water and nutrients, transpiration, enzyme activity and protein coagulation (Tisdale and Nelson, 1966). Temperature affects tissue growth rate by influencing the chemical reaction rate in tissue and the osmotic pressure and imbibition of cell colloids (Jeffs, 1925). (Note that water is required by plants for the manufacture of carbohydrate, to maintain the hydration of protoplasm and as a vehicle for the translocation of foods and mineral elements). The effects of temperature on the physiological processes of a plant are expected to be of larger magnitude than on such physical processes as diffusion and soil-water relations since the latter are less temperature dependent (van Schilfgaarde, 1974).

The energy flux for a grassland community (short dense vegetation) has been aptly described by Sutcliffe (1977): 75-80 percent of the incoming daily solar radiation is dissipated in the evaporation of water from leaf or soil surfaces, 5-10 percent is transferred to the air by conduction and convection, and not more than about 5 percent is utilized in photosynthesis. Dry soils need only a small amount of heat for raising soil temperature and the bulk of the energy reaching this soil surface is re-radiated to the atmosphere (van Schilfgaarde, 1974). Wet soils absorb more radiation heat, but due to their large heat capacity soil temperatures will rise only slowly; moreover, as evaporation is greater, more heat is used for evaporating water from wet than from dry soils (van Schilfgaarde, 1974).

During the annual course of soil temperature fluctuation there usually occurs one maximum in July or August and one minimum in January or February. The average depth of penetration of annual soil temperature fluctuations varies from eight to twenty-five meters (Shul'gin, 1965). Below these depths no annual or diurnal soil temperature variations occur. Fluctuations in the soil temperature regime arise as a consequence of soil surface temperature variation, the basic pattern of which is imposed by insolation and in the way in which the net radiation at the soil surface is partitioned (Russel and Greacen, 1977). Soil heat exchange is large during the day, small at night and practically nil at sunrise and sunset (Shul'gin, 1965). Annual variation in heat exchange reaches its maximum positive value in spring and the first half of summer; maximum negative heat exchange (i.e., loss) occurs in early winter (Shul'gin, 1965). The simplest energy balance equation takes the form

$$Rn = LE + G + H$$

where Rn is the net radiation at the soil surface, E is the evaporation rate from the surface, L is the latent heat of evaporation for the soil surface temperature, G is the flux of heat into the soil and H is the energy loss from the surface by convective exchange with the air (Russell and Greacen, 1977). Soil heat exchange is a function of the height, character and amount of vegetative cover as well as the degree of turbulence surrounding the plant canopy (Shul'gin, 1965).

Soil temperature usually rises more rapidly than it falls with the cycle being approximately sinusoidal (Griffin, 1972). Because the wave length is inversely proportional to the square root of the frequency (365 days), in a homogeneous soil the annual soil temperature wave will penetrate about 19 times as far as the diurnal wave (Russell and Greacen, 1977). The damping of diurnal soil temperature oscillations occurs at a depth between 35 and 100 cm (Shul'gin, 1965), and are essentially damped out beyond 60 cm of depth (Sheikh, 1966). The marked variation in the temperature of surface soils in the field is manifest to a depth of about 20 cm, which encompasses the volume of soil containing most of the plant roots (Carson, 1974). The amplitude of oscillations at the surface of a bare soil remains approximately the same and decreases with depth (Shul'gin, 1965). Leonard, et. al. (1971) found that at the 300 cm depth maximum and minimum temperatures were reached two to three months later than the near surface soil temperature and the range of temperature extremes was about 7C, one-third that at the 5 cm depth.

Minimum, maximum and optimum are the three cardinal points of activity which are used to describe the effect of temperature on plant growth (van Schilfgaarde, 1974). For example, the definition of "optimal temperature for germination" would be the temperature that gives the highest percent emergence in the shortest time (Singh and Dhaliwal, 1972). The optimal temperature for growth varies between species and strains (Willis and Power, 1975), between different organs on the same plant (even between two sides of the same organ), and also changes as the plant ages (Sutcliffe, 1977). Results of an exploratory study by Brengle and Whitfield (1969) indicated that there was no closer relationship of plant response to soil temperature at a given depth than to the average soil temperature, and the temperature at the 5 cm depth most nearly approximated the average. Black (1970), however, found that the mean maximum soil temperature at -5 cm on moist soil days was a better measure of the soil temperature differential among his residue treatments than the mean soil temperature.

As the diurnal soil temperature wave lags behind the wave of evaporative demand and a favorable plant-water status during high evaporation rates is maintained, soil temperature during the day becomes more important for plant growth than nighttime soil temperature (van Schilfgaarde, 1974). Cooper and Law (1977) concluded that temperature and moisture conditions during the first five weeks of maize growth were critical in determining potential grain yield and adverse conditions thereafter modified this potential, but "poor early growth conditions can not be compensated for by good conditions later." Adams (1970) stated that environmental conditions other than soil temperature become the dominant factors affecting sorghum and corn growth and development four to six weeks after planting. In the field, growth delay caused by low soil temperatures could result in exposure to frost, drought, insects, hail and disease (Power, et. al., 1970). Follet and Reichmann (1972) hypothesized that the maintenance of root weight increases the plant's ability to survive a period of drought, allowing for a renewal of vegetative and/or reproductive growth if growing conditions again become favorable. They concluded that if root weight and/or numbers of root buds are assumed to be measures of the capability of the root system to supply water and nutrients for plant needs, then a soil temperature of 22C would be detrimental to the barley plant. Luxmoore, et. al. (1973) suggested that reduced root respiration due to low soil temperatures would subsequently allow more photosynthylate movement to the grain, therefore resulting in higher yields.

In general, the threshold of high temperature stress for higher land plants is from 45C to 65C, with a generally lower threshold for growing than for resting plants (Levitt, 1972). Yield reduction due to late planting has been generally associated with the result of late summer drought (Benoit, et. al., 1965). Metabolic changes in a forage species during the development of cold or heat resistance 1) decreased the total water and free water content and increased the bound water content of tissues, 2) increased the water-holding colloids, 3) increased tissue sugar content, 4) converted starch to sugars, and 5) slowed down metabolic activity (Heath, et. al., 1973). Munns, et. al. (1977) remarked that any legume planted in bare soil during hot weather would be heat sensitive (especially the clover and annual Medicago legumes which have shallow rooting habits) until deep nodulation or ground cover becomes established. Their greenhouse experiment demonstrated the irreversible effects of soil temperatures on nitrogen fixation.

Factors Affecting Soil Temperature

Field soil temperatures are directly or indirectly dependent upon the air temperature, the intensity, quality and duration of radiant energy, the precipitation and evaporative potential of the air, the color and thermal conductivity of the soil, and the surface cover (Carson, 1974). All agricultural crops involve a certain amount of soil manipulation during seeding and subsequent harvesting which results in a rearrangement of the soil matrix and deposition of plant residue on or near the soil surface (Voorhees, 1975). The optimum soil temperature for plant growth depends on the soil water content, the supply of available nutrients and their placement within the soil root zone (Carson, 1974).

Vegetative cover and irrigation both result in cooler temperatures within the soil profile (Sheikh, 1966). Wadsworth (1939) noticed that when cold soils were warmed, heat was absorbed without a corresponding temperature increase thus suggesting to him that the simple cooling of a soil generates heat. Vegetation affects soil temperature profiles by decreasing heat influx, by preventing nighttime reradiation, by dessicating the soil, by using heat energy for the creation of plant tissue and lastly, by hindering the turbulent mixing of air in the microclimate (Shul'gin, 1965). Hay, et. al. (1978) noted that from 40 days after planting onward the major factor controlling soil temperature under a barley crop was the interception of incoming radiation by the crop canopy resulting in soil shading, although this had little effect on the minimum daytime soil temperature.

There are some differences between the effects of natural vegetation and cultivated plants on soil temperature (Shul'gin, 1965). Spring soil temperatures under sod are always cooler than soil temperatures under cultivated crops (Carson, 1974). Maximum and minimum soil temperatures at the 10 cm depth and diurnal amplitudes depend on the density of the grass stand and on the type of plant; vegetative cover having lots of green bulk produced the least amplitude (Shul'gin, 1965).

Changes of soil temperature in time and depth are determined by the soil's thermal conductivity. Clayey soils with their greater heat capacity when at a limited moisture content will warm up less in daylight than sandy soils and cool off less at night (Shul'gin, 1965). In deep soil layers the soil temperature requires more time to increase and decrease (Shul'gin, 1965).

The season affects the soil temperature profile. In summer, soil temperature decreases with depth; in winter temperature increases with depth; in the autumn there exists a layer at a certain depth where the soil temperature is maximum and in the spring there is a coolest layer sandwiched between upper and lower layers which are warmer (Shul'gin, 1965). In the spring clayey soils are usually colder than sandy soils but are warmer in the autumn (Shul'gin, 1965).

Wind influences soil temperatures by its evaporative effect at the soil surface, thus decreasing soil temperatures. Cloudiness reduces the daily amplitude of soil temperature (Shul'gin, 1965). Sheikh (1966) reported soil surface temperatures on non-irrigated, non-vegetated dryland plots as high as 49C during a period in mid-July. The highest soil temperatures occur in soils which are not quite bare, that is, on surfaces with sparse burned-out grassy vegetation (Shul'gin, 1965).

Shul'gin (1965) also expressed the relationship between soil temperature and air temperature as follows: Mean annual soil temperature is greater than mean annual air temperature, and annual average soil temperatures to the 3 m depth differ from one another only by a few tenths of a degree whereas annual average air temperatures vary from a few tenths to five degrees Celsius. Archer and Decker (1977) reported that soil temperature fluctuations at the 5 cm depth are closely associated with air temperature changes. Similarly, Motes and Greig (1969) noted that soil temperature at -10 cm followed the trend of air temperature. Tong (1965) found that the mean soil temperature at each depth (from 2.5 to 20 cm) changed only gradually with mean air temperature. Nighttime soil surface temperatures in cloudy weather are greater than the ambient air temperature and are less than air temperature in clear weather (Shul'gin, 1965).

Weignad and Swanson (1973) studied the soil temperature response of a bare, dry soil to surface shading. They found that the bare soil approached within 0.5C of equilibrium ten minutes after the initiated insolation change. In comparison, thermal equilibrium for a single leaf and for the complete canopy was reached between 40 and 60 seconds after the radiation change. Furthermore, they found that one-third to one-half of the temperature differential occurred within ten seconds.

Another factor, besides soil structure, soil composition and plant cover, that influences the differential between air and soil temperature is relative humidity. The volumetric heat capacity of the soil increases with humidity, and the greater the soil porosity the greater this increase (i.e., a higher content of air in the soil pores reduces the soil's heat capacity) (Shul'gin, 1965).

Moisture also affects soil temperature. Precipitation tends to equalize soil temperature at the various depths by reducing the amplitude of temperature oscillation in the soil and increasing its pore space humidity; for example, diurnal oscillations of soil temperature in a moist soil are less than in a dry soil (Shul'gin, 1965). A cold soil holds more water than a warm soil (Willis and Power, 1975) and moist soil warms and cools more slowly than a dry soil (Shul'gin, 1965). Precipitation causes an increase in soil temperature on a sandy soil but a decrease in clay (Shul'gin, 1965).

The effects of irrigation water temperature on soil temperature depend on the water holding capacity of the soil and the actual water and soil temperatures (Carson, 1974). Irrigation water temperature effects on soil temperature are small and of short duration (Brockwell and Gault, 1976 and Wierenga, et. al., 1971) and periodic irrigation with either warm or cold water would not appreciably change soil temperature more than with water of moderate temperature (Wierenga, et. al., 1971). Brockwell and Gault (1976) noted that even though there was an immediate effect on surface soil temperature following irrigation, equilibrium at -2.5 cm occurred quickly, was complete within two hours and the effect of irrigation water temperature on soil temperature lessened with depth into the profile. Wierenga, et. al. (1971) found that differences in soil temperature caused by 14C and 27C irrigation water lasted less than 24 hours at the 5 and 10 cm depths, and for 60 hours at 30 cm. Leonard, et. al. (1971) reported that their irrigation treatment modified soil temperatures below the 20 cm depth by extending the period of higher temperature. At the 300 cm depth the irrigated plots had added sufficient heat so that maximum soil temperatures occurred a month to one-and-a-half months earlier and then cooled to the temperature of the dryland plot one to three weeks later. They also found that the warming of the subsoil due to the irrigation treatment resulted in prolonged periods of relatively higher soil temperature, which provided a more favorable environment for biological activity. Kohl (1973) noticed that the cooling from irrigation reduced both the daily high and low soil temperatures; the maximum cooling attributed to daily irrigation amounted to only 2.5C at the 10 cm depth. Kohl also extrapolated that an irrigation frequency of five to seven days might reduce soil temperature one to two degrees centigrade under full plant cover and maybe 4C on bare soil. If lower soil temperatures are needed, irrigate frequently (Kohl, 1973 and Sheikh, 1966); if higher soil temperatures are desired, use less frequent irrigations (Kohl, 1973).

In summary, field soil temperature depends upon the net amount of heat the soil absorbs, the heat energy required to bring about a given change in the temperature of a soil and the energy required for changes, especially evaporation, which are constantly occurring at or near the soil surface.

Influence of Soil Temperature on Plant Growth

Light, temperature and moisture are the three cardinal environmental factors influencing the vegetative development and maturation of a forage species (Heath, et. al., 1973). For hot conditions plants tend to be shorter and bloom earlier (Heath, et. al., 1973), whereas as the soil temperature decreases the total time needed for growth increases (McElgunn and Heinrichs, 1975). Recovery from cold stress tends to be significantly higher for plants grown on soils at or near field capacity than for those same soils at or near saturation (Calder, et. al., 1965).

Constable (1976) reported that for a wet soil higher soil temperatures resulted in a substantial increase in both the rate and percentage of emergence, whereas for a dry soil cotton emergence was slow with soil temperature having very little effect. Low available water and high soil temperature resulted in a decrease in the number of root buds per tiller bud for barley and high available water conditions coupled with low soil temperature produced the greatest number of root buds, soil temperature alone having no effect on the number of tiller buds formed (Follet and Reichmann, 1972). Barlow, et. al., (1976) reported that at low soil moisture potentials corn root growth decreased with increasing soil temperature and remained the same at high moisture potentials. Similarly, Cannell, et. al. (1963) found larger and more extensive roots at 0.2 bar suction than at 0.8 bar for a given soil temperature. Lal (1974) reported that the effect of high soil moisture was more severe at high root temperatures. Kramer (1942) found that collards absorbed 75 percent as much water at soil temperatures of 10C than at 25C. Benoit, et. al. (1965) noticed that lower air temperatures produced less plant water stress.

Udol'skaja demonstrated the negative influence of controlled water stress during meiosis on wheat grain yield (Davidson and Birch, 1978). Soil temperatures over the range of 10C to 18C influenced grain yield only slightly at low soil moisture levels according to Mack (1973). Follet and Reichmann (1972) found that higher levels of available water tended to increase the top weight of barley at all temperature and fertility treatments. Similarly, Cannell, et. al. (1963) in their research indicated that dry matter yields of tomato were significantly increased at all soil temperature regimes by decreasing the soil moisture suction.

Davidson and Birch (1978) reported that the main shoots of wheat are very tolerant to water stress. The minor shoots, however, were temperature sensitive under conditions of plentiful water and became temperature insensitive with decreasing water supply, at which time their contribution to total grain yield was small.

Influence of Soil Temperature on the Growth of Alfalfa (*Medicago* L.)

General Remarks. When temperature exceeds the optimum range for alfalfa growth, stress is imposed on the plant. The severity of a heat stress is a function of the magnitude and duration of the temperature and the stage of plant development (Heath, et. al., 1973). Pulgar and Laude (1974) in their heat stress studies reported that longer exposure to "lower" (46C) temperature can induce a plant response similar to that of a shorter exposure to a higher temperature (52C) and the period of depressed growth was extended as the intensity of stress increased. They also reported a significant reduction in both the number and length of shoots in the after-cutting regrowth within seven days of the heat stress. Furthermore, following a stress which produced no visible evidence of tissue mortality the measurable reduction in shoot number and size persisted up to six weeks.

The optimum temperature for vegetative growth is usually lower than that for either flowering or fruiting and is lower for root than for top growth (Heath, et. al., 1973). McElgunn and Heinrichs (1975) reported an increase in water use (per unit of production) with increases in soil temperature, with most genotypes using twice as much water at 15C than at 10C soil temperatures. And as soil temperatures increased from 15C to 20C water use for most genotypes did not increase. They also reported that water use (per gram of herbage) was highest at 20C.

Most studies of legumes and grasses show that increases in temperature not only hasten maturity but decrease both the nonstructural carbohydrate percentage and the digestibility of the herbage and, in general, tend to increase protein and mineral percentages (Heath, et. al., 1973). Significant differences of the percentages of nitrogen and phosphorus in herbage were recorded for soil temperatures above 5C in the Heinrichs and Nielsen (1966) study.

Optimal relationships of temperature with respiration, cell division and cell enlargement vary with species and genotype (Heath, et. al., 1973, Heinrichs and Nielsen, 1966 and McElgunn and Heinrichs, 1975). The metabolic energy required for translocation of photosynthates (from the chloroplasts to the growing points) is catalyzed by enzymes which are extremely temperature dependent (Heath, et. al., 1973). A lowering of temperature below threshold levels results in increasing damage to the translocation system and starch accumulation in the chloroplasts quickly (the following day) reduces the rate of photosynthesis (Heath, et. al., 1973). Rates of respiration and cell expansion increase with temperature but high temperatures result in such metabolic disorders as enzyme inactivation, imbalance of reaction rates and reduced metabolic synthesis (Heath, et. al., 1973). Barta (1978) reported that high air temperatures reduce the assimilate available for transport to the root by reducing net photosynthetic activity. Ku and Hunt (1977) noted that temperature increases up to 30C resulted in an increased stomatal opening, a lower net carbon dioxide exchange rate (as compared to the rate at lower air temperatures) and a higher rate of oxygen inhibition.

Influence on Germination. Since the duration of the mitotic cycle is temperature dependent then it follows that the rate of cell division is closely related to the temperature at the meristem (Heath, et. al., 1973). Indeed, McElgunn's studies (1973) on the effects upon germination of constant soil temperature versus alternating soil temperature led him to conclude that an alternating cold temperature reduced both the speed of germination and total germination whereas a constant cold soil temperature retarded the germination rate but had no effect on total germination percent. Up to day five in his experiment, the constant soil temperature regimes also had greater germination rates than corresponding alternating temperature regimes.

Influence of Emergence. The Dubetz, et. al. report (1962) for nineteen native and cultivated crop species highlighted the following aspects of soil temperature effects on emergence: 1) the emergence rate of all species increased as soil temperature increased from 6C to 18C; 2) the five forage species tested had best emergence at moderate soil temperatures, with alfalfa showing one of the largest percentages of emergence; 3) alfalfa emergence percentage was significantly greater at a soil temperature of 18C than for either 6C or 24C temperature regimes; and 4) emergence rates increased as soil temperature increased from 18C to 24C for all species except alfalfa, flax, orchard grass and both fescue species examined.

Influence on Root Growth. Experiments by Heinrichs and Nielsen (1966) indicated the following succession of increase in root numbers for almost all varieties examined: 5C, 27C, 19C and 12C (least to most); also, root yield was highest for a root temperature of 15C and crown yield was highest between 15C and 20C. Barta (1978) suggested that low root temperatures may retard the mobilization and translocation of root reserves, thus imposing limits on shoot growth.

Influence on Vegetative Growth. McElguun and Heinrichs (1975) observed that total herbage production increased from 10C to 15C but did not change significantly with soil temperature increases from 15C to 20C. Greatest herbage production in most of their varieties occurred at a soil temperature of 27C and least at 5C, herbage production at the latter being one-fifth of that at 27C. Higher root temperatures resulted in greater nitrogen and phosphorus content in alfalfa herbage, with a greater phosphorus than nitrogen accumulation in the tissues (Heinrichs and Nielsen, 1966). In a comparable study of alfalfa hay quality Brosz (1960) found that crude protein was significantly greater (1.0 to 1.5 percent) under irrigation treatments than dryland. As the increment of phosphorus fertilizer increased the percent protein of the irrigated alfalfa hay increased. Calder, et. al. (1965) reported total available carbohydrate content and etiolated regrowth higher for plants grown at field capacity. Barta (1978) noted that during the latter period of regrowth, when dry matter production is at a maximum, alfalfa is sensitive to high root temperature.

Influence on the Reproductive Phase. Heinrichs and Nielsen in their 1966 study reported no relation between soil temperature and the time for alfalfa to reach flowering stage, suggesting to them that reproductive growth is not regulated by root temperature but rather by foliage temperature. However, McElgunn and Heinrichs reported in 1975 significant effects of soil temperature on time to flower in alfalfa. Barta (1978) found that high root temperatures had a significant effect on both the total plant weight and the root dry weight at flowering. Heat stress can even induce flower sterility (Heath, et. al., 1973).

Influence on Yield. Total dry matter production increased as soil temperature increased from 10C to 15C and then decreased as soil temperature raised above 15C to 20C, due to the reduction in root weight at 20C (McElgunn and Heinrichs, 1975). Herbage and total plant production per day did not differ at 15C and 20C, but were significantly lower at the 10C soil temperature regime according to the same study. The shoot:root (S:R) ratio was also reduced by low root temperatures in studies by Barta (1978) suggesting to him that, as concerns dry matter production, the shoot is primary in regulating the carbohydrate supply for the plant and therefore S:R ratios may decrease independent of soil temperature.

Summary Comments. The cyclic pattern of use and storage of carbohydrates in alfalfa is influenced by light, temperature and moisture. The time to plant maturity proceeds rapidly under conditions of warm temperature, limited moisture and abundant sunshine and is prolonged for cool temperature, abundance of moisture and cloudy weather conditions (Heath, et. al., 1973 and Heinrichs and Nielsen, 1966). In general, the higher the soil temperature the greater the herbage production (Heinrichs and Nielsen, 1966), with water use per day increasing from 15C to 20C temperatures (McElgunn and Heinrichs, 1975). High temperature stress frequently occurs concurrent with moisture stress thus making it difficult to separate the two effects (Heath, et. al., 1973). The late summer decline in alfalfa productivity can be attributed to the effects of high soil temperature on root reserves, shoot numbers, and net rates of photosynthesis, as well as the impairment of symbiotic nitrogen fixation (Munns, et. al., 1977).

Influence of Soil Temperature on the Growth of Wheat (Triticum ___ L.)

General Remarks. Warrington, et. al. (1977) noted that temperature conditions at any stage of plant development can influence both the final grain yield (of the main ear) and the time taken by the plant to reach successive growth stages. Experiments by Wort (1940) on the response of spring wheat to soil temperatures ranging from 22C to 44C indicated 1) that the top:root ratio was maximum at a soil temperature of 30C to 40C (decreasing thereafter as temperature increased), 2) the greatest dry weight of tops and roots and total dry weight at harvest occurred at 22C, and 3) plant height, root length and tiller number decreased with soil temperature increases from 22C to 42C. Warrington, et. al. (1977) also found that low temperatures from germination through anthesis resulted in higher growth rates in the stage from anthesis to wheat maturity.

Phung (1969) stated that soils subjected to the freezing and thawing process generally produced less dry matter and a prolonged incubation of soils under either frozen or unfrozen conditions increased the yield of dry matter, but decreased phosphorus uptake. Gingrich (1965) also found that the total amount of phosphorus absorbed and metabolized was affected by soil temperature. Freezing of soils produced a greater phosphorus uptake than keeping soils at room temperature (Phung, 1969). Boatwright, et. al. (1976) found that a soil surface temperature of 11C reduced wheat yield by 60 percent (no fertilizer present) but only 24 percent on fertilized treatments. Since his results were similar when the whole soil system was subjected to low temperature treatments Boatwright (1970) decided that surface soil temperature will affect plant growth as much as the temperature of the whole plant system. An extensive study by Kirkham and Ahring (1978) on the effects of root temperature on leaf temperature and internal water relations of winter wheat brought to light the following information: 1) when root temperatures were either cooler or warmer than air temperature the stomatal conductance, leaf water potential, osmotic potential, and turgor potential were lower compared to plants with similar root and shoot temperatures; 2) as root temperature increased from 15.6C to 32C the difference between air and leaf temperature decreased, the leaves always remaining cooler than air temperature at all ranges of root temperature; 3) water and osmotic potentials were more negative at the warmest root temperatures than at the coolest; 4) water and osmotic potentials were least negative when root temperature and air temperature were equal; 5) osmotic potential was greatest (-42.3 bars) at highest root temperature regimes (32C); and 6) turgor potentials remained at approximately twelve bars over the root temperature range of 20C to 28.5C, dropped to ten bars suction at 15.6C but were lowest (-7.4 bars) at the highest root temperature.

The Davidson and Birch study (1978) on wheat response to temperature and water stress reported the following: 1) water use (per unit of grain produced) decreased as temperature increased and at all temperature levels water use decreased markedly with each increase in water stress, that is, water stress amplified the effects of temperature; 2) water use efficiency increased with increasing degrees of stress; and 3) water use efficiency was considerably less at low temperatures (day/night of 18/13C).

Influence on Germination. A drought-resistant wheat variety germinated faster at lower root temperature than a drought-sensitive variety (same moisture levels) and for both varieties no germination occurred at root temperatures of 37.3C according to the Kirkham and Ahring study (1978).

Influence on Emergence. Numerous studies (Baker, et. al., 1970, Dubetz, et. al., 1962, Singh and Dhaliwal, 1972 and Warrington, et. al., 1977) have documented the effect of soil temperature on emergence in wheat. Baker, et. al. (1970) found a reduction in emergence 1) as soil temperature increased from 15C to 25C, 2) as moisture tension increased from 1.0 to 3.0 bars, 3) greater on sandy soil than for medium-textured soil, and 4) that fertilizer treatment effects on seedling emergence were dependent upon soil temperature, moisture and soil texture. Singh and Dhaliwal (1972) observed a delay in onset of emergence for cooler soil temperatures and at warmer temperature ranges (above optimum) emergence generally started as if at optimum but its rate sharply dwindled within 48 hours. Dubetz, et. al. (1962) reported that the percentage emergence of spring wheat was not significantly affected by soil temperature whereas winter wheat percentage emergence was greater at 18C than for soil temperatures of 6C, 13C and 24C. He also showed that winter wheat was among the crops showing the largest percentage emergence at moderate soil temperatures. A soil temperature of 40C greatly reduced emergence and 45C completely inhibited wheat seedling emergence (Singh and Dhaliwal, 1972). Warrington, et. al. (1977) showed that air temperature had only a relatively small effect on emergence but high air temperatures did have a beneficial effect on the number of wheat ears which reached maturity. Shul'gin (1965) stated that the temperature of the upper soil layers was the principle factor influencing tillering rates in winter wheat and millet. A soil temperature range for wheat emergence of 5C to 40C with a probability of 90 percent-plus emergence within 150 hours for temperatures between 25C and 30C was expressed by Singh and Dhaliwal (1972). They also reported that soil temperature effects were more influential on the rate of emergence than on the final (total) count: At soil temperatures of 25C, 30C and 35C seedling emergence started between 72 and 84 hours after sowing and was completed within 108 hours, while at lower temperatures the time lag increased from 12 to 24 hours at 20C and at the 5C soil temperature regime emergence took 400 hours to be completed.

Influence on Root Growth. Whitfield and Smika (1971) found that root weight tended to increase with increasing soil temperatures and the uptake of nitrogen, potassium and copper in roots was proportional to root weight. Boatwright, et. al. (1976) from spring wheat experiments concluded the following: 1) a shallow surface soil temperature range of 8C to 26C had no effect on root yield; 2) copper and zinc accumulated in the roots (thus possibly restricting translocation) at soil temperatures below 14C; 3) when the crown node was located above the soil surface, soil temperature had no influence on the dry weight of wheat tops; 4) low surface soil temperatures affected the crown node and not the shoot growing point (meristem); and 5) the translocation of rubidium, which acts similar to potassium in plant systems, from roots to tops was three times greater for a soil temperature of 22C than for 11C.

In two other studies of soil temperature and wheat root growth (Gingrich, 1965 and Sojka, et. al., 1975, respectively) root dry weight was found to be significantly lower for temperatures of 18.5C and 27C than for 10C and decreases in soil temperature had a slight effect on decreasing root dry weight.

Influence on Vegetative Growth. The Boatwright, Ferguson and Sims (1976) experiment investigating root zone temperature influences on spring wheat growth noted that 1) leaf elongation was most rapid when soil temperature was kept at 19C; 2) leaf-length was poorest for temperatures of 8C; 3) after 25 days of growth only four leaves were produced at 8C, twelve leaves at 12C and seven leaves at 19C and 26C; 4) dry matter yield of tops was significantly greater at temperatures of 19C and 26C than for the 8C and 12C regimes; 5) the increase in dry yield of tops was greatest (60 percent increase) for soil temperature increases from 12C to 19C; 6) dry matter yield was about the same for soil temperatures of 8C and 12C; and 7) dry matter weight was significantly greater (most to least) at each of these soil temperatures: 22C, 19C, 14C, 11C.

Another study showed that growth of all wheat varieties tested was poorest at soil temperatures of 7C and best at 18C (Whitfield and Smika, 1971), lower temperatures being more detrimental than higher soil temperatures (Gingrich, 1965 and Sojka, et. al., 1975). In contrast, Kirkham and Ahring (1978) found high root temperature more detrimental to final growth for both varieties examined than low root temperature. Largest leaves occurred at 22C soil temperatures and became lighter in color as temperature increased above 32C (Wort, 1940). Air temperature after germination and up to anthesis affected the number of florets differentiated within each spikelet (i.e., the number of sites for grain development) (Warrington, et. al., 1977). Plant heights were maximum at conditions of equal air and root temperature, as was dry weight, and plant height decreased in the following order of root temperatures: 24.7C, 28.5C, 19.9C, 15.6C, 32.1C (Boatwright, et. al., 1976).

Greater activity in wheat tops occurred at a soil temperature of 21C than at 11C; the nutrient concentration in tops was higher (although only calcium and manganese were significantly higher) in plants grown at 11C than at soil temperatures of 14, 19 or 22C

(Boatwright, et. al., 1976). They also concluded that top growth was reduced by restricted potassium translocation to the plant tops in the colder soil zone. Whitfield and Smika (1971) reported that phosphorus, potassium, manganese and copper uptake in crowns was proportional to crown weight and Gingrich (1965) disclosed that phosphorus percentage in top growth was not affected by soil temperature.

Using higher stomatal conductance as an indicator of better plant growth, the Kirkham and Ahring (1978) experiment revealed that maximum stomatal conductance occurred at the warmest root temperature (32C) for the drought-sensitive variety and at the coolest root temperature (15.6C) for the drought-resistant wheat variety.

Influence on the Reproductive Phase. In contrast to the Whitfield and Smika (1971) research which reported that the number of heads per plant was fairly constant independent from soil temperature, Smika in 1974 reported that the number of heads per plant increased linearly with increased soil temperature at the crown node. Furthermore he reported that 1) optimum crown soil temperature for spikelet number per head was from 14.5 to 15C and decreased rapidly for soil temperatures other than optimum; 2) for winter wheat the leaf area per tiller was not significantly affected by temperatures at crown depth; 3) the number of tillers per plant in spring wheat increased with the rise in crown soil temperature to 15C, thereafter remaining constant for temperatures above 15C; and 4) for a maximum development of heads per plant the optimum soil temperature at crown depth should be above 18C. Wort (1940) reported that soil temperature increases from 22C to 34C accelerated heading by as much as eleven days while soil temperatures above 34C retarded or prevented earing in wheat. Luxmoore, et. al. (1973) showed that stem dry weight per tiller decreased about 25 percent with soil temperature increases from 5C to 25C. Low soil temperature and low soil oxygen both inhibited tillering (Sojka, et. al., 1975), while temperatures near 19-20C were more beneficial for both tillering and heading; cooler soil temperatures during the latter growth stages increased grain yield (Brengle and Whitfield, 1969).

Influence on Yield. Warrington, et. al. (1977) in their report on the affects of air temperature on wheat yield stated that 1) air temperature did not influence spikelet number although low temperatures prior to anthesis produced an increase in the number of sites for grain set within each spikelet; 2) the number of sites within each spikelet which produced harvestable grain was affected by air temperature after anthesis; and 3) a low air temperature after anthesis resulted in a long linear phase of grain growth preceded by a lag period and a high final grain yield, whereas a high air temperature after anthesis produced high grain growth rates of short duration which were not preceded by a lag period and terminated in low final grain yield.

Mack (1973) found highest spring wheat yield under relatively cool soil temperatures, with plant tolerance to soil temperature variations from 'cool' (10C) to 'seasonal' (18C), and a severe reduction in wheat yield at temperatures from 18 to 28C. Smika (1974) noted that the number of tillers per plant, heads per plant, spikelets per plant and weight per head on winter wheat were all positively correlated with crown depth soil temperature, the relation being curvilinear. Davidson and Birch (1978) found the highest grain yield at a 21/16C (day/night) soil temperature regime, a 30 percent yield reduction for a 3C rise in temperature with somewhat lower reductions for a 3C decrease below optimum. Black (1970) reported a high soil temperature correlation between the number of heads, number of head-producing tillers and grain yields to the number of adventitious roots; grain yield suffered as low soil temperature and low levels of soil moisture in the 0-7.6 cm soil layer restricted adventitious root formation and tillering. Brengle and Whitfield (1969) stated that although soil temperature did not affect grain weight per kernel it did affect the number of kernels per head, a soil temperature of 12.8C resulting in more kernels per head than higher temperatures. Sojka, et. al. (1975) reported maximum total dry weight to be at the low oxygen-15C root temperature treatment.