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.

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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 <u>Medicago</u> 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.

<u>Influence on Root Growth</u>. 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.

According to Davidson and Birch (1978) grain yield reductions from moisture and heat stress were due mainly to reductions in grain size whereas Luxmoore, et. al. (1973) associated yield reduction with a smaller mean grain weight.

Summary Comments. A soil temperature decrease of 1.0C below optimum reduced reproductive development (Smika, 1974). For most crops the favorable soil temperature range for emergence was between 15C and 25C with an upper limit near 35C (Singh and Dhaliwal, 1972). The optimum soil temperature for top growth in spring wheat was 19C (Boatwright, et. al., 1976). Nutrient uptake was affected by soil temperature (Whitfield and Smika, 1971). Plant roots were able to absorb more phosphorus from unfrozen than from frozen soils at a given level of available phosphorus (Phung, 1969). The crown node was the seedling part most sensitive to soil temperature (Boatwright, et. al., 1976). Final head formation was closely related to soil temperature in the initial growth stages (Brengle and Whitfield, 1969). Increase in the surface soil temperature significantly increased dry matter weight in spring wheat (Boatwright, et. al., 1976). The drought-resistant wheat cultivar maintained a larger difference between leaf and air temperature at various root temperatures than the drought-sensitive variety (Kirkham and Ahring, 1978).

Air temperature after grain anthesis greatly affected grain weight, high temperature resulting in smaller grains and a reduced number of the more distal grains in the ear (Warrington, et. al., 1977). The same study concluded that air temperature effects were most substantial during the ear development phase of wheat. Azzi (1956) found that day length and air temperature interacted to influence the time of earing in wheat.

When soil temperature-moisture treatments were initiated at a later stage of development (boot stage) versus at an earlier stage (after seeding), the yield reduction from low moisture and high soil temperature was not as great (Mack, 1973). Another study (Baker, et. al., 1970) concluded that soil temperature effects on emergence were greater than moisture effects.

Both lower soil temperature and lower soil oxygen levels (caused by flooding) can reduce root respiration (Luxmoore, et. al., 1973 and Sojka, et. al., 1975) although not completely since oxygen diffusion from the atmosphere through the intercellular spaces can supply oxygen to root cells (Luxmoore, et. al., 1973). Plants absorb less water at colder than at warmer root temperatures. Low soil temperature around the crown node influenced a metabolically-regulated translocation process (Boatwright, et. al., 1976). Higher root temperatures induced water stress even though adequate water was present (Kirkham and Ahring, 1978). For root temperatures both cooler than and warmer than the leaf, less water was taken up by winter wheat (Kirkham and Ahring, 1978).

Stoy (1965) found the optimum temperature for apparent photosynthesis in spring wheat leaves to be as high as 25C to 30C, which may easily exceed, especially at the early growth stages, the mean day temperature of the environment. He also found that apparent photosynthesis reached its highest values in ears at 20C. The rate of true photosynthesis in both ears and leaves reached its highest value at about 30C whereas respiration rates in both organs continued to increase up to at least 35C (Stoy, 1965).

General Summary

High soil temperature can result in different patterns of emergence in the field depending on the time of day seeds are sown (Gray, 1977). For example, sowing early in the day could cause imbibition to take place at high soil temperatures thus delaying germination and possibly reducing emergence of seedlings if the temperature in the profile remains high for several days. Sowing late in the day allows imbibition to occur initially at a lower soil temperature, but the next day if the stage of cell extension coincides with the rise in soil temperature, the result could also be a delay in germination. Exposure of the seed to low temperatures of 10C to 15C during initial imbibition can injure the embryo axis thus producing abnormal seedlings (Hartmann and Kester, 1975) although seeds are not affected by up to four hours of high soil temperature (Gray, 1977).

The following is a brief list of upper and lower threshold temperatures and optimum temperature for germination (Mayer and Poljakoff-Mayber, 1963):

Zea mays:	8-10C(min), 32-35C(opt), 40-44C(max);
Triticum sativum:	3-5C(min), 15-31C(opt), 30-43C(max);
Hordeum vulgare:	3-5C(min), 19-27C(opt), 30-40C(max).

Dubetz, et. al. (1962) found that the percentage emergence of beans, corn, sugar beets and sunflower was significantly lower at a 6C soil temperature than at any of the higher soil temperatures (13C, 18C and 24C) whereas the percentage emergence of spring wheat, barley, bromegrass, crested wheatgrass, oats, mustard, peas and wild oats was not significantly affected by soil temperature. Singh and Dhaliwal (1972) stated the emergence range of cotton, sorghum, rice and maize to be 15C to 40C (with a significant time lag at a soil temperature of 15C) and 5C to 40C for wheat.

Increased plant growth with increasing root temperature may be ascribed to increased ion absorption (DeMur, et. al., 1973 and Mederski and Jones, 1963) as well as an increase in diffusion rates, reaction velocities, solubility, synthesis and translocation (Mederski and Jones, 1963). At higher soil temperatures maize matured faster and had a larger and more finely divided root system (Watts, 1973). Bulbs held continuously at high temperature (30-32C +) or at temperatures near freezing had inhibited or retarded floral development (Hartmann and Kester, 1975). The number of heads per plant of winter wheat increased with increasing soil temperature near the crown up to 13-14C and thereafter an increase in temperature decreased the number of heads per plant (Smika, 1974). Warrington, et. al. (1977) found low grain numbers in wheat at high air temperatures and when the duration of the anthesis-to-maturity growth stage was extended by low air temperatures, the result was an increase in grain weight.

Protein content of grain is, in general, inversely related to grain yield (Mack, 1973). The level of available water affects the protein content of grain: a) Protein content is higher at lower moisture levels (Tisdale and Nelson, 1966); b) under high moisture conditions protein content increases with higher soil temperature (Mack, 1973); c) at high temperatures protein content is relatively constant with moisture level changes (Mack, 1973); and d) at low soil temperatures protein content becomes very sensitive to soil moisture levels (Mack, 1973). Archer (1977) found that soil temperature did not significantly affect the crude protein content of fescue and orchardgrass herbage, but there was a tendency for higher temperature levels (32C) to lower the In Vitro Dry Matter Digestibility (IVDMD) values (that is, its suitability for animal feed).

Typical plant growth curves (Rate of Growth Versus Temperature) are generally asymmetric and bell-shaped, gradually rising across the lower temperatures and sharply declining above optimum temperature. Growth curves are thought to be the resultant of two opposing influences (Sutcliffe, 1977): 1) the increased activation energy of reacting molecules with increasing temperature tends to favor growth, and 2) the inactivation of enzymes with rising temperature which depresses growth. With each degree increase in soil temperature from 12C to 26C total corn seedling dry weight was an average 20 percent greater than the weight at each previous temperature and an average of 12 percent smaller with each degree of soil temperature increase from 26C to 35C (Pulgar and Laude, 1974). Weber and Miller (1972) found that, as soil temperature increased, the rate of plant development increased, that is, the time required to reach various growth stages decreased. As the age of a plant progresses 'maximum growth' occurs at a lower optimum soil temperature (Willis and Power, 1975). Water use efficiency increases in a curvilinear response to increasing stress (Davidson and Birch, 1978). Given sufficient time, and within certain limits, the yield of some crops at low soil temperatures can be the same as, or better than, the yield at higher temperatures, if other factors are equal (Carson, 1974).

Chapter 3

PROCEDURES

The research plots were located on the Montana State University Agricultural Experiment Station approximately six miles west of Bozeman, Montana, along U.S. Highway 191. A description of the soil properties, plot layout, irrigation system and instrumentation is essential for placing the results of the off-season irrigation project in their proper perspective.

The soil is an Amsterdam silty clay loam and is classified as a Typic Cryoboroll. Soil properties are described in detail in Table 1. The site is nearly level with at most a two percent slope to the north.

The off-season irrigation treatments were applied to alfalfa (Medicago sativa L. cv. Ladak 65) and spring wheat (Triticum aestivum L. cv. Norana). The Ladak 65 cultivar was developed at the MSU Experiment Station. Norana spring wheat is a semi-dwarf variety.

Three irrigation treatments were applied to the alfalfa and five to the spring wheat. Table 2 summarizes these irrigation treatments. Irrigation treatments on the alfalfa were: (1) fall irrigation (once per year); (2) irrigation after each cutting (twice per year); and, (3) fall + spring + after each cutting (four times per year). The spring wheat plots received irrigation under the following

Table 1. Classification and Physical Properties of the Soil at the Research Site.

CLASSIFICATION: Amsterdam series; Typic Cryoboroll (mollisol); fine-silty, mixed; well-drained; Stoniness: Class 0

LOCATION: Montana Agricultural Experiment Station west of Bozeman, Montana; Gallatin County; Sec. 7 T2S R5E

ELEVATION: Approximately 1460 m

Horizon depth (cm)	Particle size distribution (percent)			Bulk density (g/cc)		pH 1:1 water	Water content (percent)		
	Total sand	Total silt	Total clay	1/3 bar	Oven dry		1/10 bar	1/3 bar	15 bar
0- 16	10.3	62.4	27.3	1.40	1.54	6.6	24.6	22.0	13.2
16- 27	10.7	61.8	27.5	1.30	1.46	6.4	28.7	26.4	12.6
27- 41	10.7	60.6	28.7	1.31	1.54	6.9	23.4	21.4	13.4
41- 53	11.6	64.6	23.8	1.36	1.52	7.4	26.1	23.5	11.3
53- 62	12.6	67.0	20.4	1.35		8.0			10.9
62- 80	12.2	66.9	20.9	1.37	1.46	8.0	30.7	27.8	9.6
80- 98	12.5	68.5	19.0	1.31	1.38	8.0	36.3	29.2	8.8
98-135	14.5	68.5	17.0	1.29	1.39	8.2	38.9	34.5	8.5
135-180	15.7	68.7	15.6	1.25	1.30	8.3	36.9	24.4	8.2

Table 2. Description of Irrigation Treatments

Treatment No.	Plot No.	Irrigation Treatment
CROP: Alfalfa		
I	2A, 4A, 7A	Fall
II	3A, 6A, 8A	After each cutting
III	1A, 5A, 9A	Fall + spring preseason + after each cutting
CROP: Spring Wheat		
I	1, 10, 11	Fall
II	2, 7, 15	Fall + boot stage
III	4, 8, 13	Boot stage
IV	3, 6, 12	Joint stage + boot stage
V	5, 9, 14	Fall + joint stage + boot stage

five treatment schemes: (1) fall; (2) fall + boot stage; (3) boot stage; (4) joint stage + boot stage; and, (5) fall + joint stage + boot stage. A single irrigation, as defined in this thesis, refers to the filling of the soil profile to field capacity. In certain instances, more than one water application was required to constitute a 'single' irrigation.

Figure 1 shows the physical layout of the plots at the Agronomy Farm. Each treatment consisted of three replications resulting in a total of nine alfalfa plots and fifteen spring wheat plots. Individual plots were sized ten meters by ten meters separated with two-meter pathways. A four meter strip separated the spring wheat from the alfalfa treatments. An aluminum access tube for the neutron moisture meter was placed in the center of each plot.

In order to better account for any differences in soil type, prevailing wind direction or snow accumulation patterns, a randomized block concept was utilized for assigning treatment locations, with the exception of Treatment I of the spring wheat. Problems with equipment availability at the onset of the project necessitated that spring wheat Treatment I be derandomized and placed in a row near the instrument shed.

The irrigation system design incorporated the capability of individualized plot water application. Rainbird 25PJDA sprinkler heads with a single 3.175 mm (1/8 inch) diameter nozzle were

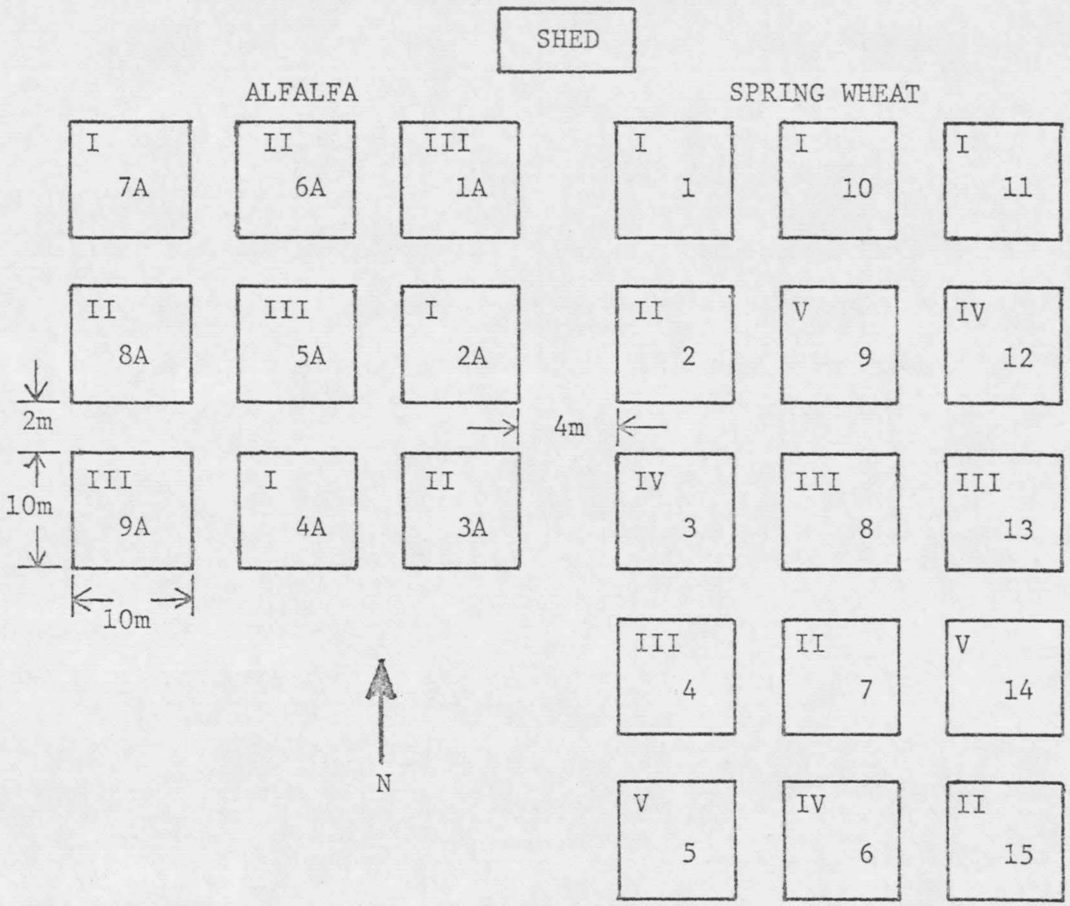


Figure 1. Schema of Research Plots at the Agronomy Farm with Treatment (Roman Numeral) and Plot Number.

located at each corner of the plot. Each plot was thus irrigated by four quarter-circle sprinklers rated at 2.81 kg/cm^2 (40 psi) for an application rate of 11.35 liters per minute (3 gpm). The design of the irrigation system was the primary topic of the Oellermann Thesis (1978) and additional details on the system design are described there.

Soil moisture was monitored throughout the year by a neutron moisture meter with a Troxler 2651 Scaler-Rate Meter and a 104A probe with Am/Be source. Aluminum access tubes were centrally placed to a depth of 210 cm in each alfalfa plot and 180 cm in each spring wheat plot. According to Pair, et. al. (1975) nearly 100 percent of the water required for growth of small grains and alfalfa is extracted from the upper 120 and 180 cm of the root zone, respectively. Thus, the zone of active water extraction for both crops was adequately monitored. Moisture readings were measured at depths of 22.5, 45, 75, 105, 135 and 165 cm in the spring wheat and, additionally, at 195 cm in each alfalfa plot. Readings were taken on all plots approximately every month during the off season and at more regular intervals during the growing season including immediately prior to and after each application of irrigation water. The required amount of irrigation water on each plot was determined from the neutron probe readings. The numerical count from each probe reading was processed into soil moisture content on a volume basis and then compared to soil values for wilting point and field capacity. The required amount of irrigation water thus was defined as the deficit, in cm of water, below field capacity. Accuracy of the neutron probe readings was checked by gravimetric samples taken over the spectrum of soil moisture levels and at various depths.

Soil temperatures were monitored at the 5 cm and 20 cm depths by copper-constantan thermocouples attached to a Leeds and Northrup Speedomax 24-point recorder. Thermocouples were placed in at least one replication of each of the irrigation treatments. Limitations on equipment did not permit the monitoring of every individual plot. Daily temperatures at both soil depths were registered during four 15-minute duration recordings, one near sunrise, one in mid-morning, another in mid-afternoon and the final recording in early evening. This recording scheme monitored the maximum and minimum soil temperatures at each depth. Checks on the reliability of the timer settings to record the daily maximum and minimum temperatures were taken every few months. Timer settings were adjusted with the change in seasons.

The Bozeman 6W Weather Station (Index No. 1047) located approximately one kilometer to the west of the research site supplied the climatological data. Daily meteorological variables monitored included maximum and minimum air temperatures, precipitation, incoming solar radiation, wind run and pan evaporation. The latter three were only monitored during the growing season.

Yields in the spring wheat plots both years were obtained by a small plot combine with a four-foot (1.22 m) header. After each full pass through a plot, the grain sample was removed to a labelled bag, after which each sample was cleaned and oven dried. Measurement of the swath length and actual ground swath width permitted the yield for each plot to be computed for any given seed moisture content. No protein analysis was made.

No alfalfa yield measurements were taken during the stand establishment season of 1977. The following seasons' yields were sampled with a special Mott flail plot harvester. Two gross samples were flailed from each plot, placed in labelled plastic garbage bags, weighed and then a smaller sample from each bag was oven dried. Two harvests were taken each season during 1978 and 1979, one in early July and another in late August. The final harvest was removed in June 1980. Measurement of path length and swath width, 0.61 m (2 ft), enabled yield extrapolation for any given herbage moisture content to a tons-per-hectare reference basis.

Chapter 4

RESULTS AND DISCUSSION

Before discussing results of the yield analyses, certain climatological variables are presented so that the influence of natural climatological variability on crop yields might be assessed. The climatological variables of air temperature and monthly precipitation are presented in Tables 3-5 and Figure 2, respectively. Tables 3, 4 and 5 show the deviation in degrees Celsius of the monthly maximum, minimum and mean air temperatures from their respective values for the 1958-70 base period. No general trends were obvious with the possible exception of a warm trend for minimum air temperature during the last quarter of 1978 and early 1979. Examination of the yearly mean air temperatures shows that their deviation during the three-year duration of the project did not exceed seven tenths of a degree Celsius. The bar graphs of Figure 2 contrast the monthly precipitation received at the Bozeman 6W Station for 1977-79 with the average values for the 1958-70 base period. The following differences in precipitation are notable: (1) April of 1977 and 1978 were drier than average, both years being followed by slight increases in precipitation amounts during May, but amounts decreased again during June of those years; (2) above normal precipitation was recorded in July 1978, below normal in August

Table 3. Deviations of the Mean Monthly Maximum Air Temperatures Observed at the Bozeman 6W Station for the Project Duration from the 1958-70 Base Period (Degrees Celsius)

Months	Average Maximum 1958-70	Deviation from Average Maximum 1977	1978	1979
January	0.28	-1.6	-1.4	-8.5
February	3.2	+3.4	-1.8	-1.7
March	5.4	-0.6	+3.7	+0.5
April	11.7	+4.7	+1.5	+0.1
May	18.5	-1.5	-2.3	0
June	22.3	+2.4	+0.7	+1.5
July	27.9	-0.9	-1.6	-0.2
August	27.1	-1.2	-0.3	-0.3
September	20.5	+0.3	+1.2	+5.8
October	15.2	-0.1	+1.5	+1.3
November	6.6	-1.6	-5.1	-3.7
December	1.5	+0.2	-4.6	+4.6
Yearly Mean	13.3	+0.3	-0.7	0

Table 4. Deviations of the Mean Monthly Minimum Air Temperatures Observed at the Bozeman 6W Station for the Project Duration from the 1958-70 Base Period (Degrees Celsius)

Months	Average Minimum 1958-70	Deviation from Average Minimum 1977	1978	1979
January	-12.4	-0.7	+0.6	-9.5
February	- 9.2	+3.6	-0.8	-1.8
March	- 7.8	+0.2	+3.9	+2.3
April	- 2.2	+2.2	+2.3	+1.2
May	2.6	0	+0.3	+0.4
June	6.5	+1.8	-0.7	+0.8
July	8.8	-0.1	+0.4	+0.7
August	8.1	+0.2	-0.8	+1.0
September	3.6	+0.8	+1.2	+1.8
October	- 0.61	+1.2	+0.6	+1.3
November	- 6.5	+0.4	-4.3	-2.1
December	-10.6	-0.3	-4.6	+3.8
Yearly Mean	- 1.6	+0.7	-0.2	-0.1

Table 5. Deviations of the Mean Monthly Average Air Temperatures Observed at the Bozeman 6W Station for the Project Duration from the 1958-70 Base Period (Degrees Celsius)

Months	Average 1958-70	Deviation from Average 1977	1978	1979
January	- 6.1	-1.1	-0.4	-9.0
February	- 3.0	+3.5	-1.3	-1.8
March	- 1.2	-0.1	+3.8	+1.4
April	4.8	+3.4	+1.9	+0.6
May	10.6	-0.8	-1.1	+0.1
June	14.4	+2.1	0	+1.2
July	18.3	-0.5	-0.6	+0.3
August	17.6	-0.5	-0.6	+0.3
September	12.0	+0.6	+1.2	+3.8
October	7.3	+0.5	+1.0	+1.3
November	0.06	-0.6	-4.8	-2.9
December	- 4.6	0	-4.5	+4.2
Yearly Mean	5.9	+0.5	-0.5	-0.1

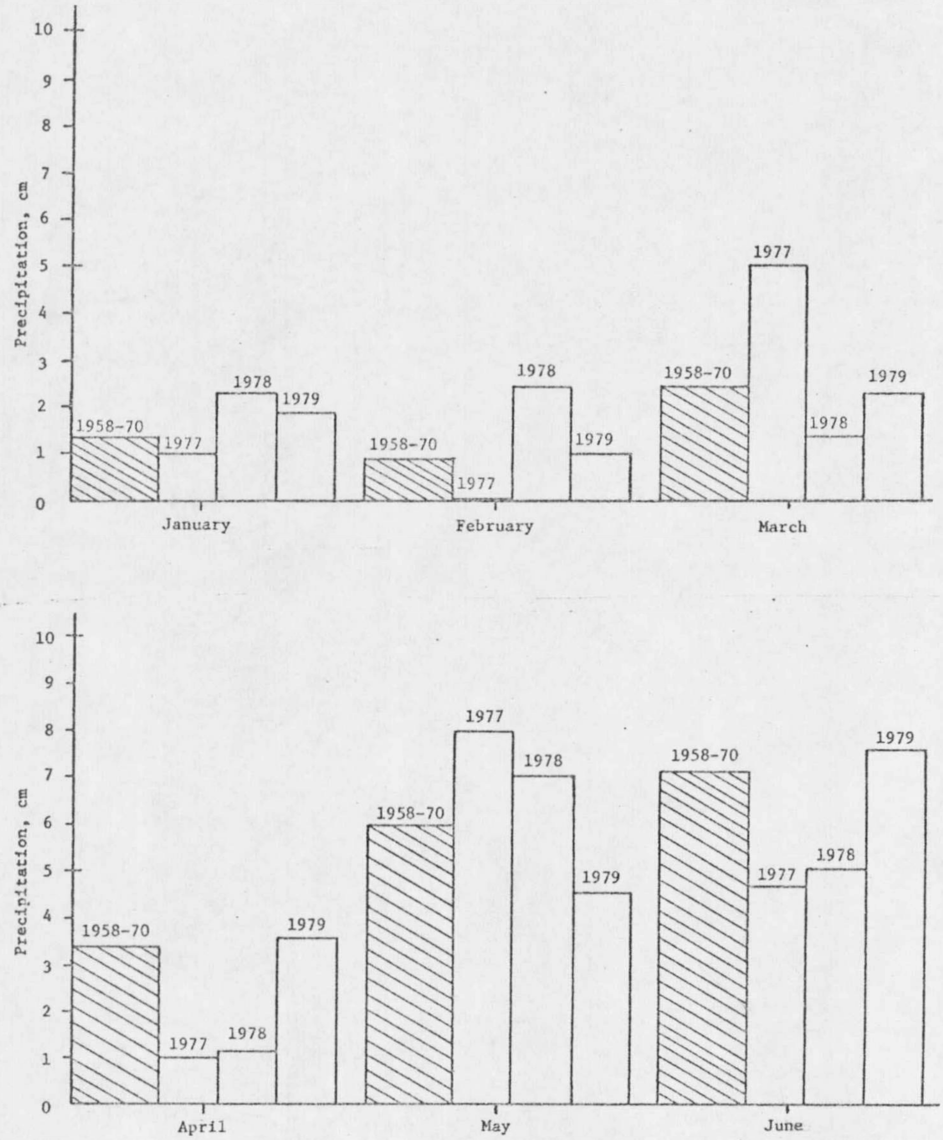
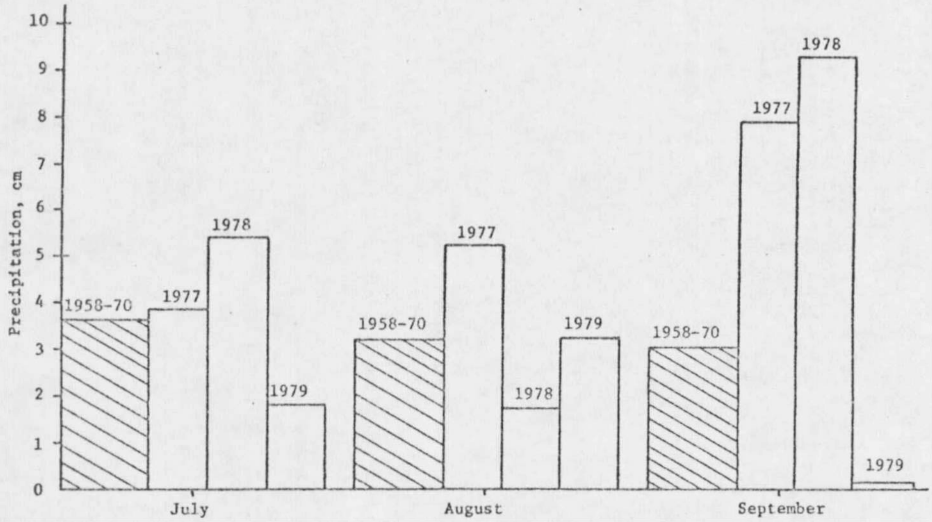


Figure 2. Comparison of Precipitation Recorded at the Bozeman 6W Station for the Base Period (1958-70) and the Years of Project Duration (in centimeters)



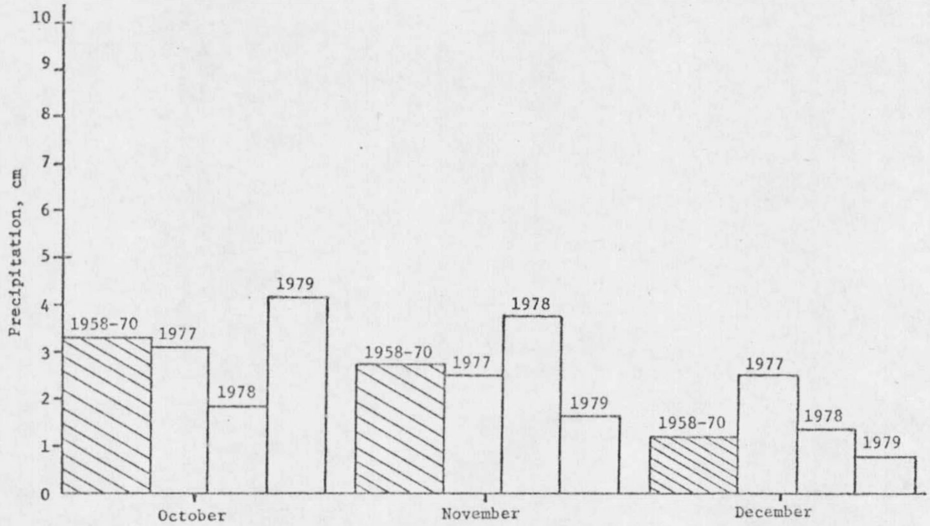


Figure 2 Continued

1978; (3) July 1979 was drier than the normal average for the base period as was September of 1979; and (4) substantial amounts above the average were received in September of both 1977 and 1978. The extent to which these precipitation and air temperature differences affected crop growth among the treatments was impossible to assess.

The cultural practices applied to both the spring wheat and alfalfa plots are indicated in Tables 6 and 7, respectively. Irrigations noted as being "partial" refer to the profile not having been filled to field capacity and consequently a second water application was required. It should be noted that the seeding rate for the spring wheat was 10 kg/ha less in 1977 than in 1978 so that yield comparisons between the years may not be valid.

Tables 8 and 9 detail the amounts of irrigation water applied to the various spring wheat and alfalfa treatments, respectively. It should be noted that an accurate flow measurement device was not installed until June of 1978 so that prior values must be considered only as approximate.

Table 10 chronicles the dates of spring wheat soil moisture readings taken with the neutron probe while Table 11 does the same for alfalfa.

Table 12 presents the spring wheat yield data by treatment and by plot for the 1978 season. Yield data for the 1977 season can be found in Table 8, page 33, of the Oellerman (1978) thesis. Tables

Table 6. Cultural Practices on the Spring Wheat Plots For the Years of Project Duration

Gregorian Date	Practice
4/25/77	Plots were seeded with 56 kg/ha of Norana semi-dwarf spring wheat, no fertilizer
6/29-6/30/77	Treatments IV & V were partially irrigated
7/5-7/6/77	Treatments II-V were irrigated
9/9/77	Yield samples were taken from all plots
11/8/77	Treatments I, II & V were irrigated
4/24/78	Plots were seeded with 67 kg/ha of Norana semi-dwarf spring wheat, no fertilizer
6/28/78	Treatments IV & V were irrigated
7/8/78	Irrigation on Treatments II-V was completed
7/16/78	Hail storm severely damaged the spring wheat
8/8/78	Weeds were removed from the plots
8/30/78	Yield samples taken from all plots
10/6/78	Treatments I, II & V were partially irrigated
10/11/78	Irrigation of Treatment I was completed
6/8/79	Treatments were terminated

Table 7. Cultural Practices on the Alfalfa Plots For the Years of Project Duration

Gregorian Date	Practice
4/19/77	All plots were top-dressed with 224 kg/ha of 0-45-0 fertilizer
5/2/77	Plots were seeded with approximately 15 kg/ha of Ladak 65 alfalfa
6/28/77	Weeds were removed from plots
7/7/77	All plots were irrigated
8/9/77	All plots were harvested. No yield data was recorded
11/9/77	Treatments I & III were irrigated
6/2/78	Treatment III was irrigated
7/6/78	Plots were infested with "alfalfa loopers"
7/11/78	Yield samples were taken from all plots
7/19/78	All plots were irrigated with approximately 3 cm water; Treatment I should not have been irrigated
7/26/78	Irrigation of Treatments II & III was completed
8/31/78	Yield samples were taken from all plots
10/6/78	Treatments I & III were irrigated
10/11/78	Irrigation of Treatment I was completed
5/25/79	Treatment III was mistakenly irrigated (no irrigation was necessary) with approximately 9 cm of water

Table 7 Continued

Gregorian Date	Practice
7/2/79	Yield samples were taken from all plots
7/14/79	Treatments II & III were partially irrigated
7/18/79	Irrigation of Treatments II & III was completed
8/20/79	Yield samples were taken from all plots
8/23/79	Treatments II & III were irrigated
9/30/79	Treatments I & III were irrigated
6/25/80	Yield samples were removed; Treatments were terminated

Table 8. Amount of Water Applied to Spring Wheat (in centimeters)

Gregorian Date	Treatment	Plot No.	Applied water, cm.
6/29-6/30/77	IV	3	5
		6	5
		12	5
	V	5	5
		9	5
		14	5
7/5-7/6/77	II	2	9.7
		7	11.6
		15	7.3
	III	4	15.2
		8	17.2
		13	18.9
	IV	3	8.3
		6	5.0
		12	4.9
	V	5	3.4
		9	2.3
		14	10.9
11/8/77	I	1	3
		10	3
		11	3
	II	2	3
		7	3
		15	3
	V	5	3
		9	3
		14	3
6/28/78	IV	3	5.5
		6	5.5
		12	5.5
	V	5	5.5
		9	5.5
		14	5.5

Table 8 Continued

Gregorian Date	Treatment	Plot No.	Applied water, cm.
7/8/78	II	2	6.6
		7	6.6
		15	6.6
	III	4	6.6
		8	6.6
		13	6.6
	IV	3	2.2
		6	2.2
		12	2.2
	V	5	2.2
		9	2.2
		14	2.2
10/6/78	I	1	7.2
		10	7.2
		11	8.4
	II	2	2.9
		7	0.9
		15	4.7
	V	5	1.8
		9	2.0
		14	0
10/11/78	I	1	0
		10	0
		11	2.9

Table 9. Amount of Water Applied to Alfalfa (in centimeters)

Gregorian Date	Treatment	Plot No.	Applied water, cm.
7/7/77	All	All	unknown (no flow-meter)
11/9/77	I	2A	3
		4A	3
		7A	3
	III	1A	3
		5A	3
		9A	3
6/2/78	III	1A	3.3
		5A	5.6
		9A	5.6
7/19/78	All	All	2.9
7/26/78	II	3A	2.9
		6A	10.7
		8A	4.9
	III	1A	1.0
		5A	0
		9A	0
10/6/78	I	2A	11.0
		4A	11.0
		7A	11.0
	III	1A	9.4
		5A	7.3
		9A	6.4
10/11/78	I	2A	2.0
		4A	0
		7A	0
5/25/79	III	1A	9.0
		5A	9.0
		9A	9.0

Table 9 Continued

Gregorian Date	Treatment	Plot No.	Applied water, cm.
7/14/79	II	3A	13.5
		6A	14.4
		8A	14.4
	III	1A	7.2
		5A	9.6
		9A	8.2
7/18/79	II	3A	2.8
		6A	7.2
		8A	7.2
	III	1A	2.8
		5A	2.8
		9A	4.1
8/23/79	II	3A	16.4
		6A	17.2
		8A	17.1
	III	1A	14.5
		5A	16.4
		9A	12.6
9/30/79	I	2A	20.0
		4A	20.0
		7A	20.0
	III	1A	12.3
		5A	12.3
		9A	12.3

Table 10. Log of Soil Moisture Readings On Spring Wheat

Gregorian Date	Event
6/21/77	Initial reading
7/1/77	Post-irrigation
7/5/77	Pre-irrigation
7/7/77	Post-irrigation
7/8/77	Post-irrigation
8/2/77	Monthly check
10/20/77	Pre-irrigation
11/14/77	Post-irrigation
12/29/77	Monthly check
1/23/78	Monthly check
2/22/78	Monthly check
3/30/78	Monthly check
5/26/78	Monthly check
6/28/78	Pre-irrigation
6/30/78	Post-irrigation
7/7/78	Pre-irrigation
7/10/78	Post-irrigation
8/11/78	Monthly check
8/30/78	Monthly check
10/2/78	Pre-irrigation
10/9/78	Post-irrigation
10/13/78	Post-irrigation
11/24/78	Monthly check
1/2/79	Monthly check
2/21/79	Monthly check
3/16/79	Monthly check
5/9/79	Monthly check
6/8/79	Final reading

Table 11. Log of Soil Moisture Readings On Alfalfa

Gregorian Date	Event
7/7/77	Initial reading & post-irrigation
8/2/77	Monthly check
10/28/77	Pre-irrigation
11/14/77	Post-irrigation
12/29/77	Monthly check
1/23/78	Monthly check
2/22/78	Monthly check
3/30/78	Monthly check
5/10/78	Monthly check
5/15/78	Pre-irrigation
5/22/78	Post-irrigation
5/26/78	Monthly check
5/30/78	Pre-irrigation
6/1/78	Pre-irrigation
6/4/78	Post-irrigation
6/28/78	Pre-irrigation
6/30/78	Post-irrigation
7/7/78	Pre-irrigation
7/19/78	Pre-irrigation
7/21/78	Post-irrigation
7/26/78	Pre-irrigation
7/28/78	Post-irrigation
8/10/78	Monthly check
8/30/78	Monthly check
9/15/78	Pre-irrigation
10/2/78	Pre-irrigation
10/9/78	Post-irrigation
10/13/78	Post-irrigation
11/25/78	Monthly check
1/5/79	Monthly check
2/21/79	Monthly check
3/16/79	Monthly check
5/9/79	Monthly check
5/25/79	Pre-irrigation
6/8/79	Post-irrigation

Table 11 Continued

Gregorian Date	Event
7/12/79	Pre-irrigation
7/17/79	Post-irrigation
7/20/79	Post-irrigation
8/22/79	Pre-irrigation
8/25/79	Post-irrigation
9/28/79	Pre-irrigation
10/2/79	Post-irrigation
10/24/79	Monthly check
12/13/79	Monthly check

Table 12. Yield from Spring Wheat Plots for 1978 Season (metric tons per hectare at 12% moisture content, wet basis)

Treatment	Plot No.	Yield on 8/30/78, tons/ha
I	1	2.20
	10	2.21
	11	2.44
	Average	2.28
II	2	1.95
	7	2.11
	15	2.33
	Average	2.13
III	4	1.74
	8	1.88
	13	2.04
	Average	1.89
IV	3	1.66
	6	1.67
	12	1.94
	Average	1.76
V	5	1.88
	9	2.43
	14	1.93
	Average	2.08

13, 14 and 15 similarly show the yields from the alfalfa plots for the 1978 and 1979 seasons and for the final harvest on June 25, 1980.

The following statistical scheme was employed for the analysis of yield differences for both the alfalfa and spring wheat. First, plot yields were processed through an analysis of variance program in which treatment means were compared with the mean of all samples. The variance ratio, or F-value, was the preliminary test criterion for mean yield differences. An F-value near unity suggested that the treatments had the same population mean, whereas if the treatment means did differ substantially from one another (i.e., were not of the same population), then the F-value exceeded unity. If this analysis of variance for yield differences resulted in an F-value not statistically significant at the 95 percent confidence level, then no further statistical analysis was considered. However, if the F-value implied statistical significance between treatment yields at the 95 percent level or above then a multiple comparison of the treatment means was done to pinpoint which treatments had yields significantly different at the 95 percent level. This multiple comparison analysis used the t-statistic for mean separation. The final stage of the statistical framework used to handle the yield data was to process the treatment yield through a multiple linear regression program. The aim was two-fold:

Table 13. Yield from Alfalfa Plots for 1978 Season (metric tons per hectare at 12% moisture content, wet basis)

Treatment	Plot No.	Yield at dates harvested, tons/ha 7/11/78	8/31/78	Total 1978
I	2A	6.11	3.78	9.89
	4A	7.28	3.14	10.42
	7A	7.65	3.83	11.48
	Average	7.01	3.58	10.60
II	3A	6.67	3.69	10.36
	6A	7.23	4.15	11.38
	8A	6.98	4.13	11.11
	Average	6.96	3.99	10.95
III	1A	6.89	3.83	10.72
	5A	7.33	3.93	11.26
	9A	7.18	3.86	11.04
	Average	7.13	3.87	11.01

Table 14. Yield from Alfalfa Plots for 1979 Season (metric tons per hectare at 12% moisture content, wet basis)

Treatment	Plot No.	Yield at dates harvested, tons/ha 7/2/79	8/20/79	Total 1979
I	2A	5.55	2.68	8.23
	4A	6.46	2.69	9.15
	7A	5.48	2.41	7.89
	Average	5.83	2.59	8.42
II	3A	4.96	3.06	8.02
	6A	5.89	3.53	9.42
	8A	5.99	3.63	9.62
	Average	5.61	3.41	9.02
III	1A	5.45	3.15	8.60
	5A	6.34	3.77	10.11
	9A	5.44	3.09	8.53
	Average	5.74	3.34	9.08

Table 15. Yield from Alfalfa Plots for the June 1980 Harvest (metric tons per hectare at 12% moisture content, wet basis)

Treatment	Plot No.	6/25/80 Yield, tons/ha
I	2A	4.01
	4A	4.45
	7A	4.95
	Average	4.47
II	3A	4.78
	6A	4.46
	8A	4.25
	Average	4.50
III	1A	3.45
	5A	4.55
	9A	3.72
	Average	3.91

(1) To determine which of the selected independent variables best accounted for the differences between treatment yields and (2) to determine the "goodness of fit" (R-squared value) for the resultant regression equation. In this manner, a linear equation for the prediction of crop yield in terms of one or more independent variables was derived.

Analysis of the Spring Wheat Yield Data

Differences in the spring wheat yields for the 1977 season have not been analyzed statistically for the following reasons: (a) Irrigations were not done at the correct growth stages; (b) no seed moisture analysis of the harvest samples was done; and (c) the supporting data on soil moisture and soil temperature was largely incomplete.

Table 16 presents both the analysis of variance and the between-treatment mean comparisons for the 1978 spring wheat yields. The statistical analysis utilized the computerized Statistical Analysis Package developed by Dr. R.E. Lund (1978) of the Mathematics Department at Montana State University. The two-way analysis of variance indicated that differences in treatment yields were significant at the 95 percent level of confidence. The Multiple Comparison aspect of Table 16 indicated that that yield of Treatment IV was significantly different at the 95 percent level from

Table 16. Analysis of Variance and Comparison of Means[1]
For the Spring Wheat Yield Data
For the 1978 Season

Analysis of Variance (Two-Way)

Source of Variations	df	S.S.	M.S.	F-Value
Blocks	2	0.1643		
Treatments	4	0.5157	0.1289	4.565*
Error	8	0.2260	0.0282	
Total	14	0.9059		

Multiple Comparisons

Treatments	Mean (tons/ha)	Difference	T-Value
IV : IV	1.757		
III	1.887	0.1300	0.9474
V	2.080	0.3233	2.356*
II	2.130	0.3733	2.721*
I	2.283	0.5267	3.838**
III : III	1.887		
V	2.080	0.1933	1.409
II	2.130	0.2433	1.773
I	2.283	0.3967	2.891*
V : V	2.080		
II	2.130	0.5000	0.3644
I	2.283	0.2033	1.484
II : II	2.130		
I	2.283	0.1533	1.117

*denotes significance at 95 percent level
**denotes significance at 99 percent level

[1]Above values were obtained by the ANOV2 and COMPARE programs developed by R.E. Lund (1978).

Treatments II and V and differed significantly at the 99 percent level from Treatment I. Also, the yield of Treatment III differed significantly at the 95 percent level from Treatment I. Yields between the other treatments were not significantly different within 95 percent confidence limits. Thus the application of irrigation water at the joint stage + boot stage (Treatment IV) resulted in the least yield (1.76 tons/ha). This yield value was significantly different from all other treatments except the boot-stage irrigation (Treatment III) which had the next lowest yield (1.89 tons/ha). Treatment I, the fall irrigation, yielded the highest and was statistically different from the boot-stage irrigation treatment (III) and the joint + boot stage treatment (IV).

Since the irrigations during this 1978 season were not applied at the correct growth stages, no further analysis involving the supporting data was undertaken. Oellerman (1978) in his thesis rectified this condition by studying an aspect of the water use efficiency for each treatment. This author suggests that a similar analysis should be conducted on the 1978 spring wheat yield data but said analysis was beyond the scope of the thesis objectives established herein.

Analysis of the Alfalfa Yield Data

Tables 17, 18 and 19 analyze the alfalfa yields for both

Table 17. Analysis of Variance[1] (Two-Way) for the Alfalfa Yield Data for the 1978 Season

Source of Variations	df	S.S.	M.S.	F-Value
		7/11/78 Harvest		
Blocks	2	1.032		
Treatments	2	0.0473	0.0236	0.1827
Error	4	0.5178	0.1294	
Total	8	1.597		
		8/31/78 Harvest		
Blocks	2	0.0708		
Treatments	2	0.2631	0.1315	1.439
Error	4	0.3658	0.0914	
Total	8	0.6996		
		Combined 1978 Harvests		
Blocks	2	1.308		
Treatments	2	0.2962	0.1481	0.8350
Error	4	0.7093	0.1773	
Total	8	2.313		

* denotes significance at 95 percent level
** denotes significance at 99 percent level

[1]Above values were obtained by the ANOV2 program developed by R.E. Lund (1978).

Table 18. Analysis of Variance[1] (Two-Way) for the Alfalfa Yield Data for the 1979 Season

Source of Variations	df	S.S.	M.S.	F-Value
		7/2/79 Harvest		
Blocks	2	1.280		
Treatments	2	0.0713	0.0357	0.2873
Error	4	0.4967	0.1242	
Total	8	1.848		
		8/20/79 Harvest		
Blocks	2	0.2230		
Treatments	2	1.219	0.6095	8.232*
Error	4	0.2962	0.0740	
Total	8	1.738		
		Combined 1979 Harvests		
Blocks	2	2.562		
Treatments	2	0.7908	0.3954	1.128
Error	4	1.402	0.3505	
Total	8	4.755		

*denotes significance at 95 percent level
**denotes significance at 99 percent level

[1] Above values were obtained by the ANOV2 program developed by R.E. Lund (1978).

Table 19. Analysis of Variance[1] (Two-Way) for the June 1980 Alfalfa Yield Data

Source of Variations	df	S.S.	M.S.	F-Value
		6/25/80 Harvest		
Blocks	2	0.2492		
Treatments	2	0.6661	0.3331	1.342
Error	4	0.9930	0.2482	
Total	8	1.908		

*denotes significance at 95 percent level
**denotes significance at 99 percent level

[1]Above values were obtained by the ANOV2 program developed by R.E. Lund (1978).

individual and combined yearly harvests. Statistical significance at the 95 percent level between treatment yields occurred only for the second cutting of the 1979 season. Table 20 investigates this August 20, 1979 yield data. Multiple comparisons of the yield means resulted in statistical significance at the 95 percent confidence level between Treatments I and III and between I and II. No statistically significant differences occurred between Treatments II and III. Yields from the fall irrigation treatment lagged about 0.8 metric ton per hectare behind the yields from the plots receiving the more frequent irrigations.

In order to better explore these yield differences, three additional sets of variables were investigated. These were air temperature, soil moisture and soil temperature. These variables were processed over the time spans between harvests in order to provide an assessment of their relationship with the observed differences in treatment yields. This analysis was conducted by the multiple linear regression technique. Table 21 describes the time periods for which these variables were processed. These periods will hereafter be referred to by the reference abbreviations of that table; that is, Period 1 will be referred to as PA1, et. cetera, through PA9 (Period 9).

<u>Degree-Days for Air Temperature</u>. The average daily air temperatures for the Bozeman 6W station were processed into weekly

Table 20. Comparison of Means[1] for the August 20, 1979 Alfalfa Yield Data

Treatments	Mean (tons/ha)	Difference	T-Value
	Multiple Comparisons		
I : I	2.593		
III	3.337	0.7433	3.346 *
II	3.407	0.8133	3.661 *
III : III	3.337		
II	3.407	0.0700	0.3151

*denotes significance at the 95 percent level
**denotes significance at the 99 percent level

[1] Above values were obtained by the COMPARE program developed by R.E. Lund (1978)

Table 21. List of Time Periods Used for Analysis of the Air Temperature, Soil Temperature and Soil Moisture Variables

Period	Reference Abbreviation	Time Span Gregorian	Description
1	PA1	8/9/77-3/1/78	From the stand-establishment cutting 1977 to early season 1978
2	PA2	3/1/78-7/11/78	From early season to first cutting 1978
3	PA3	3/1/78-8/31/78	From early season to second cutting 1978
4	PA4	7/11/78-8/31/78	Between cuttings 1978
5	PA5	8/31/78-3/1/79	From second cutting 1978 to early season 1979
6	PA6	3/1/79-7/2/79	From early season to first cutting 1979
7	PA7	3/1/79-8/20/79	From early season to second cutting 1979
8	PA8	7/2/79-8/20/79	Between cuttings 1979
9	PA9	8/9/77-8/20/79	From stand establishment in 1977 to second cutting harvest 1979

means. These weekly mean temperature values were then multiplied by seven (days/week) in order to establish a Celsius degree-day for air temperature. The lower threshold air temperature used for the degree-day computations was 4.44C (40F). The lower threshold temperature (4.44C) for crop growth was suggested by both Caprio (1979) and Wiesner (1979). No upper threshold temperature was applied. Table 22 shows the summation of degree-days for the average air temperature regime for the time periods defined in Table 21. For example, from the stand establishment cutting on 8/9/77 through the second cutting of 1979 (i.e., PA9), a total of 3925 degree-days for average air temperature was calculated.

Degree-Days for Soil Temperature. A similar type of degree-day analysis was completed for the soil temperature recorded under the alfalfa plots. A lower threshold soil temperature of 4.44C (40F) was used and no upper threshold limit was considered. Computations were based on the weekly mean soil temperatures as determined by daily thermocouple recordings. This computation was done for both the 5 cm and 20 cm soil depths. Table 23 shows the soil temperature degree-day (Celsius) summations by treatment for both soil depths during the various time periods defined in Table 21. For example, for PA9 the average soil temperature at the 5 cm depth produced approximately 3860 degree-days for Treatment I as compared to 3560 and 3600 for Treatments II and III, respectively. Also,

Table 22. Degree-Day Summation[1] of Mean Air Temperature For Selected Time Periods (Celsius-Days)

Period[2]	Summation of Degree-Days for Average Air Temperature
PA1	614
PA2	827
PA3	1549
PA4	722
PA5	463
PA6	597
PA7	1299
PA8	702
PA9	3925

[1]Data from Bozeman 6W Station; computations based on weekly averages for the particular regime with a lower threshold temperature of 4.44C and no upper threshold.

[2]Time periods refer to those defined in Table 21.

Table 23. Soil Temperature Degree-Day Summation[1] For Selected Time Periods (Celsius-Days)

Period[2]	Treatment	Degree-Day Summation for Average Soil Temperature Regimes	
		5 cm depth	20 cm depth
PA1	I	673	568
	II	603	592
	III	561	598
PA2	I	678	525
	II	552	470
	III	600	461
PA3	I	1478	1247
	II	1318	1173
	III	1354	1131
PA4	I	800	722
	II	766	703
	III	754	670
PA5	I	357	350
	II	382	365
	III	389	356
PA6	I	552	459
	II	552	497
	III	582	497
PA7	I	1353	1188
	II	1257	1183
	III	1291	1169
PA8	I	801	729
	II	705	686
	III	709	672

Table 23 Continued

Period[2]	Treatment	Degree-Day Summation for Average Soil Temperature Regimes	
		5 cm depth	20 cm depth
PA9	I	3861	3353
	II	3560	3313
	III	3595	3254

[1]Data from thermocouples; computations based on weekly temperature averages with a lower threshold temperature of 4.44C and no upper threshold.

[2]Time periods refer to those defined in Table 21.

at the 20 cm depth for PA9, the soil temperature degree-days decreased from approximately 3350 for Treatment I to 3250 for Treatment III. Both these examples illustrate the decrease in soil temperature due to increased levels of irrigation water as well as the time lag in soil temperature with depth into the soil profile.

Moisture-Days for Soil Moisture Levels. The concept of a moisture-day follows that of the degree-day. The moisture-day summation is based on the centimeters of water present in the soil profile multiplied by the number of days the profile contained this amount. Such a summation may be done for any single level or combination of levels, one level being defined as 30 cm (one foot) of profile depth. Since neutron probe readings in the alfalfa plots were taken down to 210 cm (7 ft) it was possible to compute moisture-days for each or any of the seven levels. However, for the sake of brevity, moisture-days were calculated only for the top 90 cm (3 ft) and the lower 120 cm (4 ft) of the profile. These two values were then summed for the moisture-days of the total profile. Table 24 presents the results of this kind of computation for the various time periods defined in Table 21. For time intervals overlapping neutron probe reading dates the average moisture content between readings was used in the moisture-day computation. For example, for Treatment I, plot 2A, the moisture-days computed from the top three depth levels (D1-3)

Table 24. Alfalfa Moisture-Day Summation[1] for Selected Time Periods (Centimeter-Days)

Treatment	Period[2]	Moisture-Day Summation for Various Profile Depths								
		Plot No. 2A			Plot No. 4A			Plot No. 7A		
		D1-3	D4-7	D1-7	D1-3	D4-7	D1-7	D1-3	D4-7	D1-7
I	PA1	4386	5039	9428	4131	4976	9108	3842	4963	8804
	PA2	2890	3195	6081	2805	3185	5988	2642	3093	5729
	PA3	3903	4224	8125	3912	4179	8088	3678	4047	7716
	PA4	1013	1029	2044	1107	994	2100	1036	954	1987
	PA5	4605	4162	8767	4581	3958	8538	4478	4059	8542
	PA6	2894	3129	6020	2964	3234	6197	2852	3085	5933
	PA7	3683	3979	7658	3760	4126	7885	3592	3916	7501
	PA8	789	850	1638	796	892	1688	740	831	1568
	PA9	16577	17404	33978	16384	17239	33619	15590	16985	32563
		Plot No. 3A			Plot No. 6A			Plot No. 8A		
II	PA1	3932	5129	9060	3807	4523	8330	4001	4884	8884
	PA2	2737	3187	5918	2553	2813	5372	2710	3016	5723
	PA3	3740	4172	7908	3557	3688	7251	3809	3952	7760
	PA4	1003	985	1990	1004	875	1879	1099	936	2037
	PA5	4132	3282	7413	4001	3044	7045	4040	3037	7083
	PA6	2696	2509	5201	2662	2495	5157	2491	2410	4903
	PA7	3671	3406	7073	3624	3367	6993	3498	3286	6787
	PA8	975	897	1872	962	872	1836	1007	876	1884
	PA9	15475	15989	31454	14989	14622	29619	15348	15189	30514

Table 24 Continued

Treatment	Period[2]	Plot No. 1A D1-3	Plot No. 1A D4-7	Plot No. 1A D1-7	Plot No. 5A D1-3	Plot No. 5A D4-7	Plot No. 5A D1-7	Plot No. 9A D1-3	Plot No. 9A D4-7	Plot No. 9A D1-7
		Moisture-Day Summation for Various Profile Depths								
III	PA1	4411	4804	9215	4312	5043	9381	4034	4757	8795
	PA2	2917	3031	5947	2984	3181	6162	2890	3037	5930
	PA3	3997	4049	8045	4137	4303	8435	4155	4125	8281
	PA4	1080	1018	2098	1153	1122	2273	1265	1088	2351
	PA5	4708	4266	8977	4738	4135	8874	4578	3713	8298
	PA6	3031	3518	6549	3059	3239	6298	3062	3155	6220
	PA7	4066	4579	8646	4092	4266	8358	4128	4171	8303
	PA8	1035	1061	2097	1033	1027	2060	1066	1016	2083
	PA9	17182	17698	34883	17279	17777	35048	16895	16766	33677

[1]Data from neutron probe readings; computations based on conversion of probe readings to cm of water at each 30 cm depth; for periods between readings the average moisture content was used.

[2]Time periods refer to those defined in Table 21.

for PA9 was approximately 16,000 cm days. The moisture-day concept developed here does not consider the aspects of field capacity and wilting point. If moisture-days for plant-available water are desired, then summations must be done for the same time periods using the amount of profile water at field capacity and also at wilting point. Then a comparison can be made with the above values.

A preliminary analysis of variance for soil moisture levels between treatments was done prior to the multiple linear regression with all variables. This analysis was aimed at clarifying two general questions: (1) Did the various applications of irrigation water actually result in differences in the treatment soil moisture regimes? and (2) How well did any treatment differences in soil moisture levels correspond with the single, observed difference in alfalfa treatment yields? Question One served to determine whether the proposed irrigation scheme successfully produced significant differences in treatment soil moisture levels. The second question served as a guide for further analysis as to which variable best accounted for the variations in the alfalfa yield of the 8/20/79 harvest. Such an analysis of variance to determine the statistical significance between treatments for the moisture-day summations of the total profile (D1-7) was completed and appears in Tables 25 and 26. Table 25 evaluated Question Two. Statistical significance for moisture-day differences among treatments began to occur with PA5, the

Table 25. Results of the Two-Way Analysis of Variance[1] For the Moisture-Day Summation Between Periods For the Entire Soil Profile (D1-7)

Period[2]	F-Value
PA1	0.1317
PA2	1.962
PA3	2.870
PA4	5.473
PA5	68.80 **
PA6	106.5 **
PA7	96.01 **
PA8	72.70 **
PA9	29.04 **

*denotes significance at 95 percent level
**denotes significance at 99 percent level

[1] Values were obtained by the ANOV2 program developed by R.E. Lund (1978).

[2] Time periods refer to those defined in Table 21.

Table 26. Results of the Multiple Comparison Analysis[1] For the Moisture-Day Summations Between Selected Periods for the Entire Soil Profile (D1-7)

Period[2]	Treatments	T-Value
PA5	II : I	9.798 **
	II : III	10.49 **
	I : III	0.6872
PA6	II : I	10.61 **
	II : III	13.98 **
	I : III	3.369 *
PA7	II : I	6.816 **
	II : III	13.86 **
	I : III	7.040 **
PA8	I : II	6.252 **
	I : III	12.06 **
	II : III	5.804 **
PA9	II : I	5.278 **
	II : III	7.400 **
	I : III	2.123

*denotes significance at the 95 percent level
**denotes significance at the 99 percent level

[1]Values were obtained by the COMPARE program developed by R.E. Lund (1978).

[2]Time periods refer to those defined in Table 21.

period after the second cutting in 1978. This implied that another factor (or factors) was responsible for the alfalfa yield differences observed on August 20, 1979. (A similar analysis was done for the moisture-days of the upper (D1-3) and lower (D4-7) profile depths but since the results were similar they were not included.) Table 26 provided insight into the first question by investigating differences in the moisture-day summations among treatments with the Multiple Comparison test. This analysis showed that all treatments beginning with PA5 were significantly different at the 95 percent level with two exceptions: During PA5, Treatments I and III were not statistically significant at the 95 percent confidence level and neither were they over the entire yield time span (PA9). An important implication from this analysis was that another variable (or variables) besides soil moisture may better serve to explain the variation in alfalfa yield observed on the August 1979 harvest.

To summarize the results of the alfalfa yield analysis scheme so far: (1) Of the five alfalfa harvests only the second cutting of 1979 showed yield differences between treatments significant at the 95 percent confidence level; and (2) levels of soil moisture among treatments may not account for these differences in alfalfa yield. Therefore, four variables from the many monitored were placed in a stepwise multiple linear regression with yield. The results of this regression analysis are presented next.

Results of Multiple Regression Analysis. The SPSS (Statistical Package for the Social Sciences) computer program (Nie, et. al., 1970) was utilized to conduct a stepwise multiple linear regression using yield as the dependent variable. The four variables assumed to interact independently with yield were degree-days of average air temperature (Celsius-days), soil moisture-days for the total profile (cm-days), and soil temperature degree-days (Celsius-days) at both the 5 cm and 20 cm depths. The regression analysis was completed for both the spring-to-harvest and fall + spring-to-harvest time periods. However, since the results were essentially identical only the time period from spring-to-harvest was presented here. Table 27 shows the data used in the regression analysis. This data represents the mean of three replications in each treatment for yield and moisture-days and the degree-day regimes (based on one replication per treatment) of average air and soil temperatures.

Before proceeding with the discussion of the stepwise multiple linear regression, several observations with respect to the input variables require elaboration. Several statistically-significant correlations among the regression variables occurred. Table 28 lists the correlation matrix. Yield differences correlated at the 95 percent confidence level or above with moisture-days and both soil temperature regimes, but did not correlate highly with the treatment or air temperature variables. The negative correlation of yield with

Table 27. Data[1] Used for the "Spring-to-Harvest" Multiple-Regression Analysis of the Alfalfa Harvests

Date	Period	Treatment	Yield (tons/ha)	Moisture-Days (cm-days)	Degree-Days for Temperature Regimes (Celsius-Days) Air	Soil at 5 cm	Soil at 20 cm
3/1-7/11/78	2	1	7.01	5933	827	678	525
	2	2	6.96	5671	827	552	470
	2	3	7.13	6013	827	600	461
7/11-8/31/78	4	1	3.58	2044	722	800	722
	4	2	3.99	1969	722	766	703
	4	3	3.87	2241	722	754	670
3/1-7/2/79	6	1	5.83	6050	597	552	459
	6	2	5.61	5087	597	552	497
	6	3	5.74	6356	597	582	497
7/2-8/20/79	8	1	2.59	1631	702	801	729
	8	2	3.41	1864	702	705	686
	8	3	3.34	2080	702	709	672

[1]Yield and moisture-day regimes are the mean for all three replications in each treatment; degree-day regimes are for the average temperature.

Table 28. Correlation Coefficients of the Variables Used in the Step-wise Multiple Regression Analysis[1]

Variables	Treatment	Moisture-Days	Degree-Day Regimes Air	Degree-Day Regimes Soil at 5 cm	Degree-Day Regimes Soil at 20 cm
Yield	0.070	0.938**	0.308	-0.794*	-0.927**
Treatment		0.054	0.000	-0.200	-0.127
Moisture-Days			0.011	-0.876**	-0.974**
Air Temp.				0.190	0.004
Soil Temp. at 5 cm					0.946**

*denotes significance at the 95 percent level
**denotes significance at the 99 percent level

[1]Values were obtained from the SPSS Multiple Regression program (Nie, et. al., 1970).

soil temperature degree-days may indicate that as soil temperatures increase, yields decrease, or it may merely reflect the shorter time period and smaller yield inherent for the second cuttings of alfalfa. Treatment as a variable was not correlated significantly with any of the other variables examined. The soil moisture variable was very highly correlated with both regimes of soil temperature. The air temperature variable was poorly correlated with either soil temperature regime, suggesting independence between them. And, soil temperature degree-days at the 5 cm depth were very highly correlated with degree-days at the 20 cm depth, although not as highly as moisture-days and degree-days at the 20 cm depth. Thus, the independence initially assumed between soil temperature at both depths and between soil temperature and soil moisture was not valid.

Results of the degree-of-fit from the stepwise multiple regression are shown in Table 29. The program selected the variables in the following order: (1) Moisture-days, (2) air temperature degree-days, (3) soil temperature degree-days at the 20 cm depth, and (4) treatment. The program did not add the 5 cm depth soil temperature variable because of its "insufficient F-level". Nearly 88 percent of the variation in yield was explained by the variation in moisture-days. The degree-days for air temperature as a variable accounted for an additional nine percent of the yield variation. Soil temperature degree-days at the 20 cm depth

Table 29. Cumulative Proportion of Yield Variance[1] Explained by the Addition of Successive Variables[2]

Variable	R^2
Moisture-Days	0.8793
Air Temperature Degree-Days	0.9679
Soil Temperature Degree-Days at 20 cm	0.9743
Treatment	0.9744

[1]Values were obtained from the SPSS Multiple Regression program (Nie, et. al., 1970).

[2]Yield was the dependent variable.

accounted for another one percent. The treatment variable accounted for practically no additional yield variation. Less than three percent of the yield variation could not be accounted for by the variables included in the regression analysis.

The multiple linear regression program (Lund, 1978) was further used to regress yield singly against each variable of treatment, air temperature, soil moisture and soil temperature. Table 30 presents these relations. The results show that the measurement of soil temperature degree-days at the 20 cm depth (R^2=0.86) would have been nearly as predictive of yield as soil moisture-days (R^2=0.88). In a further analysis, the multiple linear regression of yield against soil temperature degree-days at 20 cm, air temperature degree-days and the treatment variables resulted in an R^2 of 0.959 as compared to an R^2 of 0.978 for yield against moisture-days, air temperature degree-days and the treatment variables.

Table 30. Results of Linear Regressions[1] of Yield (tons/ha) Against Other Single Variables

Variable	Equation	R^2
Treatment (X_1)	$4.65+0.134\ X_1$	0.005
Moisture-days (X_2)	$2.00+0.75E-03\ X_2$	0.879**
Air temperature (X_3)	$0.720+0.59E-02\ X_3$	0.095
Soil temp. at 5 cm (X_4)	$13.72-0.0131\ X_4$	0.631**
Soil temp. at 20 cm (X_5)	$12.81-0.0133\ X_5$	0.859**

[1]Values were obtained by the MREGRESS program (Lund, 1978).

*, ** denote significance at the 95 and 99 percent level, respectively.

Chapter 5

SUMMARY AND CONCLUSIONS

In 1977 a tri-state project investigating the effects of off-season irrigation practices on crop growth, soil moisture retention and soil temperature variation was initiated in Kansas, Montana, and South Dakota. Alfalfa and spring wheat were the two crops tested under various irrigation treatments at the Montana State University Agricultural Experiment Station near Bozeman.

Weather observations at the Bozeman 6W station during the project duration showed no prolonged trends, with the possible exception of below-average air temperatures during late 1978 and early 1979. Above-normal precipitation was received in September of both 1977 and 1978.

A randomized block design with three replications of each treatment was used. Irrigation treatments on spring wheat varied from a single yearly application (during the off season) to three irrigations per year. Alfalfa treatments received irrigation water applications varying from one per year (off-season) to four per year. Each irrigation filled the soil profile to field capacity. A total of two spring wheat harvests and five alfalfa cuttings were collected.

Differences in the spring wheat yield data analyzed for the 1978 season showed statistical significance between certain treatments at the 95 percent confidence level. However, no detailed analysis of the yield was pursued since the timing of the irrigations was in question.

Only the 1979 second cutting (8/20/79) of alfalfa showed a difference between treatment dry matter yield significant at the 95 percent confidence level. It is worth noting that precipitation levels for June and August of 1979 were near normal but the July 1979 precipitation was below the normal for the 1958-70 base period. Also, average air temperatures for June, July and August of 1979 were greater than the base period averages. In order to investigate this single occurrence of yield differences between the treatments, four variables were entered in a multiple linear regression with yield as the dependent variable. This regression analysis resulted in the following observations: (1) Moisture-days (a term defined as the product of the average centimeters of water in the soil profile and the time interval (in days) between selected dates) for the total soil profile correlated highly with both soil temperature degree-day regimes, especially with degree-days at the 20 cm depth; (2) soil temperature, as expressed in degree-days (above a base of 4.44C), at the 5 cm depth was highly related to the soil temperature degree-days at 20 cm; (3) average air temperature, also expressed in degree-days (above a base of 4.44C), was not highly correlated with either soil temperature degree-day regime; and (4) alfalfa yield was found to correlate best (R^2=0.88) with soil moisture-days, but the similar correlation of yield with soil temperature degree-days at 20 cm was nearly as high (R^2=0.86). Caution should be used in interpreting these relationships, however, as the project generated only twelve reliable yield harvests. Also, soil temperature data was not replicated within the treatments.

Examination of the moisture-days and soil temperature degree-days over period (PA9) prior to the 8/20/79 alfalfa harvest revealed that the low yield from the fall irrigation, Treatment I, as compared to the treatments with higher amounts of applied water, corresponded with a larger value of soil temperature degree-days and a lower value of moisture-days (Table 27). This combination of low profile water and high soil temperature did not occur in the other periods between alfalfa harvests. It is difficult to discern whether the alfalfa yield variations observed on 8/20/79 were the result of (a) detrimental levels of moisture stress, (b) detrimental levels of soil temperature, or (c) both.

It is most important to note that the limited amount of irrigation water applied to Treatment I, the fall irrigation, did not produce any significant difference in yield except for the second harvest of 1979. Similarly, yield differences between Treatments II and III, which received two and four applications of irrigation water per year, respectively, never attained levels of significance. Indeed, the average yield from Treatment III usually was slightly less than that of Treatment II, possibly indicating that either the optimum level of soil moisture for alfalfa yield was exceeded and/or the accumulation of soil temperature degree-days did not reach an optimum level. Furthermore, the fall irrigation treatment did not always exhibit the lowest yield of the three irrigation treatments, particularly for the first cutting in each season. Possibly, an optimum irrigation scheme for alfalfa at the Agronomy Farm may be a fall irrigation followed by another application after the first cutting, the latter of which may not usually be required.

In review, the author feels that all three objectives, as proposed in Chapter One, have been adequately investigated.

Conclusions

Based on the somewhat limited data from this three-year project the following conclusions can be made:

1. In some years, a single application of irrigation water in the fall would be sufficient for alfalfa production on deep soils.

2. In years when moisture stress is severe and/or soil temperature is above optimum late in the season, an additional irrigation beyond the fall application should be done soon after removal of the first cutting.

3. Both soil moisture-days and soil temperature at the 20 cm

depth, as expressed in degree-days above a base of 4.44C (40F0, can be used to predict alfalfa yield accurately.

4. Four applications of irrigation water per year appeared to suppress alfalfa yield slightly.

5. High soil temperatures occurring late in the growing season may be more detrimental to alfalfa yield than cold soil temperatures at the onset of the growing season.

6. Alfalfa yield data monitored during the growing season resulted in statistically better correlations between independent variables than a corresponding analysis with the inclusion of off-season data.

7. A high correlation existed between soil temperature degree-days at the 5 cm depth and at the 20 cm depth.

8. Moisture-days, a term used to express the level of water in the profile over a given time period, correlated particularly well with the 20 cm regime of soil temperature degree-days.

Recommendations for Further Research

An initial concern in this project was that high levels of over-winter soil moisture would detrimentally affect crop yield by lowering the early spring soil temperatures. The results of this study suggest that the real emphasis might be a concern whether soil temperature later in the growing season exceeds some optimum level. It may be more appropriate to paraphrase the adage "A wet soil is a cold soil" to "A dry soil is a hot soil". Further research should be conducted with respect to determination of the optimum range of soil temperature degree-days which, if not attained or if exceeded, results in a significant yield loss. That is, what is the range of soil temperature degree-days below which and above which crop yield becomes adversely affected?

Could the build-up of soil temperature degree-days be predicted? If this could be done accurately, then irrigation could be scheduled with particular aim towards moderating this build-up. In this way an irrigation treatment could be used either to delay or lengthen the accumulation of soil temperature degree-days. Possibly there exists the more intricate relationship between degree-days and the different stages of crop growth, the time to flowering, for example. If time-to-maturity and soil temperature degree-day accumulation were correlated then it may be possible to regulate the optimum harvest date through irrigation scheduling.

It would also be valuable to know at what soil depth the best correlation between soil temperature degree-days and yield occurs. This would require soil temperature measurement at regular intervals down to one meter at least, rather than the somewhat shallow depths monitored in this study. In conjunction, certain of the existing soil temperature prediction equations could be utilized to see how accurately they predict the variation in this research data.

Another aspect of the soil temperature regime that needs investigation is the time lag of soil temperature regimes with respect to soil moisture levels and profile depth. For example, when did the various irrigation treatments reach a certain level of soil temperature degree-days? The research data would also allow comparisons of the time lag on an hourly basis between the various irrigation treatments.

The realm of water-use efficiency among treatments was not analyzed in this thesis and also needs investigation.

Beginning in the summer of 1978 soil temperature and soil moisture under fallow were also monitored. This data could be analyzed for comparative differences between cropped and uncropped regimes. Water movement within and out of the soil profiles should be investigated for all plots.

Other questions might also be addressed: (1) Can the accumulation of soil temperature degree-days after the season's final harvest and prior to the first killing frost be used to assess the level of carbohydrate reserves in alfalfa roots? (2) If protein content were more important than dry matter yield, what would be the differences in the management of irrigation scheduling? (3) How would the proposed irrigation scheduling be affected by soil type? (4) Could such a management scheme be developed based on the percentage of the clay fraction in the soil profile, for example? (5) How would the peak seasonal load requirements of energy and water be affected by off-season irrigation? (6) To what extent will off-season irrigation practices allow a reduction in system components?

Also, another irrigation treatment should be examined in which a single irrigation is applied after the first alfalfa cutting. Possibly a yearly application at this time would be sufficient for alfalfa growth. This scheme would have to rely on natural precipitation in the pre-season, which would be easier to assess than the build-up of late-season soil temperature levels.

Finally, experience gained while working with this project permits the author to remark on several aspects of project management. The spring wheat yield data was rendered useless with respect to the aims of this thesis because of unfamiliarity with the determination of the different growth stages. A protein analysis on both the wheat grain and the alfalfa dry matter should have also been done. Pre- and post-seasonal soil fertility measurements might have also been performed. Replications were needed on the soil temperature measurements. A more accurate means of determining daily maximum and minimum soil temperature was needed, possibly with a continuous recorder for average soil temperature. Also, control plots to which no water was applied other than natural precipitation may have served as a better reference base for treatment yields. For example, such control plots could have been very valuable in interpreting the effect of the above-normal precipitation during September of 1977 and 1978 on plot yields.

In retrospect, a more accurate plan for processing the data and therefore best methods for monitoring the data should have been outlined prior to commencement of the project.

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