Effect of moisture stress on alfalfa seed production and plant growth
by Larry Sherman Hicks

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agronomy
Montana State University

Abstract:
Moisture availability is a primary factor influencing alfalfa (Medicaqo sativa L.) seed yields. The objective of this study was to evaluate the effect of four applied moisture regimes (non, low, medium, and high) on alfalfa seed production. Four alfalfa cultivars ('Ladak 65', 'Vernal' , 'Apollo', and 'Thor'), with differing fall dormancies, were evaluated under a line-source sprinkler irrigation system in 1985 at Manhattan, Montana.

Cultivars matured in order of their fall dormancy level and with increased irrigation. Total evapotranspiration (ET) was similar among cultivars and was greatest in the high irrigation regime. Seasonal ET was similar among cultivars in all irrigation regimes except in the non-irrigated plots. Patterns of plant available water depletion were similar among cultivars in all irrigation regimes. Root penetration exhibited patterns similar to cultivar fall dormancy levels with Ladak 65 having the greatest root penetration. Ladak 65 acheived the greatest heights in all irrigation regimes. Internode length, biomass, total seed yield, and pure live seed increased with increased ET. A good relationship existed between increased biomass for increased total and pure live seed yield for all cultivars. Stem number per plant varied among cultivars with increased biomass. Internode length increased with increased biomass for all cultivars. Stems per plant, pods per stem, biomass water use efficiency (WUE), seed WUE, germination, hard seed, and seed weight all varied among cultivars with increased ET. The relationship between pods per stem and seed yield varied among cultivars. Total viable seed increased with increased ET for all cultivars except Ladak 65.

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Larry Sherman Hicks

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ABSTRACT

Moisture availability is a primary factor influencing alfalfa (Medicago sativa L.) seed yields. The objective of this study was to evaluate the effect of four applied moisture regimes (non, low, medium, and high) on alfalfa seed production. Four alfalfa cultivars ('Ladak 65', 'Vernal', 'Apollo', and 'Thor'), with differing fall dormancies, were evaluated under a line-source sprinkler irrigation system in 1985 at Manhattan, Montana.

Cultivars matured in order of their fall dormancy level and with increased irrigation. Total evapotranspiration (ET) was similar among cultivars and was greatest in the high irrigation regime. Seasonal ET was similar among cultivars in all irrigation regimes except in the non-irrigated plots. Patterns of plant available water depletion were similar among cultivars in all irrigation regimes. Root penetration exhibited patterns similar to cultivar fall dormancy levels with Ladak 65 having the greatest root penetration. Ladak 65 acheived the greatest heights in all irrigation regimes. Internode length, biomass, total seed yield, and pure live seed increased with increased ET. A good relationship existed between increased biomass for increased total and pure live seed yield for all cultivars. Stem number per plant varied among cultivars with increased biomass. Internode length increased with increased biomass for all cultivars. Stems per plant, pods per stem, biomass water use efficiency (WUE), seed WUE, germination, hard seed, and seed weight all varied among cultivars with increased ET. The relationship between pods per stem and seed yield varied among cultivars. Total viable seed increased with increased ET for all cultivars except Ladak 65.

CHAPTER I

INTRODUCTION

The first annual report of the Montana Farmers Institute in 1902 indicated that alfalfa was introduced into Montana around 1880. The date it was first cultivated for seed in the state is unknown.

Prior to World War II, most of the alfalfa seed produced in the United States came from Kansas, Oklahoma, Montana, Utah, and South Dakota. Although large acreages were harvested, average yields were usually below 110 kg ha^{-1}. Seed yields have increased dramatically in most areas since the advent of selective pesticides, improved germplasm, efficient pollinator utilization, and better cultural practices. However, Montana still averages approximately 135 kg ha^{-1}.

Irrigation is an important component in alfalfa seed production and crop management. Soil moisture may be a limiting factor in achieving desirable alfalfa seed yields. Improved irrigation management practices may be required to maximize alfalfa seed production. This study was initiated to evaluate the effects of varying levels of moisture stress on the seed yield of four alfalfa cultivars.

CHAPTER II

LITERATURE REVIEW

Crop

Alfalfa (Medicago sativa L.), is the oldest known domesticated forage. Bolton et al. (1972) reported that alfalfa has been used as a forage crop for 3300 years. Phylogenetic studies indicate southwestern Asia as the probable origin for alfalfa. Alfalfa became more diverse as it spread from northeast Persia to other parts of the world. Bolton et al. (1972) reported that alfalfa was brought to South America by the Spaniards in the 16th century.

The first recorded production of alfalfa in the United States was in Georgia in 1736. However, it did not tolerate the acid soils and humid climate (Martin et al., 1976; Bolton et al., 1972). Introduction into California from Peru in 1841 and from Chile in 1850 secured alfalfa's place in the United States (Martin et al., 1976). Alfalfa was well adapted to the sunny, dry climate and irrigated soils of the southwest and rapidly spread to neighboring states (Hendry, 1923). Introduction of a winter hardy alfalfa into Minnesota by Windelin Grimm during the mid 1880's further increased alfalfa's range of utilization (Martin et al., 1976).

The exact date alfalfa was introduced into Montana is unknown. Communications by W.B. Harlan indicate that alfalfa was seeded in the late 1800's in the Bitterroot Valley (Alexander, 1961). J.D. O'Donnell, a Yellowstone Valley rancher, is reported to have grown alfalfa in 1884 (Mont. Farmers Inst., 1902).

Alfalfa has world-wide distribution. However, it is largely confined to the temperate regions of the world. The United States, Argentina, and the Soviet Union are the leading producers, accounting for 70% of the world acreage (Bolton et al., 1972). The combined acreage of France, Italy, Canada, and Australia account for another 20%.

Wisconsin, Iowa, California and Minnesota are the leading alfalfa hay producing states in the U.S. (Clampet and Johnson, 1983). Montana ranks 11th in the nation in alfalfa hay production (Pratt and Lies, 1984). Madison, Fergus, Beaverhead, and Gallatin counties are the leading producers in Montana (Pratt and Lies, 1984). Total 1983 hay production in Montana was 2,441,275 metric tons on 473,481 hectares (Pratt and Lies, 1984). An average of 6,944 and 3,203 kg ha^{-1} of alfalfa hay were produced on 246,048 ha of irrigated land and 227,433 ha of non-irrigated land, respectively.

The United States produced 46,330 metric tons of alfalfa seed in 1980 with California, Idaho, Washington, and Nevada being the leading seed producing states (Clampet and

Johnson, 1981). Montana and South Dakota are ranked 8th in the U.S., each producing approximately 1,905 metric tons of alfalfa seed (Clampet and Johnson, 1981). Average seed yield for Montana in 1980 was 134.4 kg ha^{-1} (Clampet and Johnson, 1981). Average U.S. yield was 267 kg ha^{-1} and California produced 582 kg ha^{-1}(Clampet and Johnson, 1981).

Botanical Description

Alfalfa is an herbaceous perennial legume that may live 20 years or longer in dry climates (Martin et al., 1976). Flowers are born on loose racemes and vary in color from shades of purple to yellow or white (Ditterline et al., 1979). Seed pods have one to five spirals and contain several yellowish-green, kidney-shaped seeds (Ditterline et al., 1979). Alfalfa seedlings emerge with two cotyledons, followed by one unifoliolate leaf, with subsequent alternate, pinnately, trifoliolate leaves (Martin et al., 1976). Oblong leaflets are sharply toothed on the upper third of the margin and the tip terminates with the projection of the mid-rib (Martin et al., 1976). Approximatly 48% of the plant may be leaves (Kiesselbach et al., 1934). Stems arise from a fleshy crown and may grow to a height of one meter, with 5 to 25 stems per plant (Ditterline et al., 1976).

Alfalfa has four general root types; tap, branched, rhizomatous, and creeping (Smoliak and Bjorge, 1981). An alfalfa tap-root system may penetrate the soil in excess of nine meters (Martin et al., 1976). Carlson (1925) reported that all alfalfa cultivars develop branched root systems in compacted soil, while taproots predominate under porous conditions.

Medicago sativa L. is the most commonly grown alfalfa (Clement, 1962). However, yellow-flowered alfalfa (M. falcata L.) is sometimes regarded as a subspecies of common alfalfa (Clement 1962). M. falcata is distinguished by yellow flowers, sickle-shaped pods, decumbent growth habit, low-set branched crowns, and branched roots (Clement, 1962).

Adaptation

Alfalfa is adapted to a wide range of climatic conditions. Accord (1972) reported that yellow-flowered alfalfa has survived temperatures below -62°C, and common alfalfa has survived temperatures in excess of 54.5°C.

Deep loam soils with porous subsoils are best for alfalfa production (Martin et al., 1976). Smoliak and Bjorge (1981) reported that alfalfa does not tolerate flooding, waterlogging, or poor internal soil drainage during the growing season.

Alfalfa grows on most soils in semi-arid regions except those with either high alkaline salts or shallow water tables (Martin et al., 1976). Alfalfa has moderate salt tolerance. According to Richards (1969), alfalfa tolerates an EC of 8 mmhos cm^{-1} before a 50% stand reduction occurs.

Alfalfa is very sensitive to soil acidity less than pH 6.0. (Smoliak and Bjorge, 1981). However, it may be grown on acid soils with lime amendments. (Martin et al., 1976). Alfalfa is relatively drought tolerant, but responds well to irrigation.

Stand Establishment

Good seedbed preparation is the key to alfalfa stand establishment. Cultivated soils should be packed to obtain a firm seedbed (Ditterline et al., 1979). Alfalfa may be direct drilled into cereal grain stubble with minimum tillage. Seeding depth is commonly 6 to 12 mm in heavy soils and slightly deeper on light soils (Martin et al., 1976).

Wiesner (1982) reported that seeding rates for alfalfa seed production in Montana range from .6 to 2.0 kg ha^{-1}. Wide row spacings out-yield dense stands for seed production. Irrigated and dryland alfalfa row spacings range from 61 to 92 and 122 to 244 cm in Montana, respectively (Wiesner, 1982). Additionally, 25-35 cm plant spacing within the row is important for maximum seed yields.

Harvest

Alfalfa seed production in many areas is a by-product of hay production (Smith, 1972). Seed is harvested when hay is not needed or when a good seed set occurs (Smith, 1972).

Seed production is best on vigorous plants. However, excessive soil moisture and fertility can induce lodging, delay and/or prolong flowering , and result in poor nectar production (Smith, 1972). Tysdal (1946) reported that the highest seed yields were obtained from upright plants growing in widely spaced rows.

Seed are usually ready for harvest 60 days after peak flowering, when 2/3 to 3/4 of the pods (curls) are brown (Smith 1972; Wiesner, 1982). Seed crops are directly combined or swathed then combined (Wiesner, 1982). Shattering losses are proportional to the amount of handling during harvest (Smith, 1981). Direct combining following plant defoliation with a desiccant spray is gaining popularity as a method of reducing handling losses during alfalfa seed harvest (Smith, 1981). Most alfalfa seed harvested in Montana is sprayed with desiccant and direct combined (Wiesner, 1982). Direct combining provides decreased wind-row losses from wind and rain (Wiesner, 1982). The crop must be swathed and allowed to dry in wind-rows if desiccants are not used (Wiesner, 1982). Swathing should be done early in the morning when a heavy dew is present to prevent seed loss (Wiesner, 1982).

Alfalfa seed should be at approximatly 13% moisture before combining (Wiesner, 1982). Additionally, seed should be checked often in storage for heating when combined at a high moisture content.

Economic Value

Alfalfa seed in the United States averaged \$0.54 kg^{-1} in 1980 (Clampet and Johnson, 1981). Additionally, total U.S. alfalfa seed production in 1980 was valued at \$115,000,000. Montana producers received an average of \$0.34 kg^{-1} for alfalfa seed and \$3,440,000 for a state total (Pratt and Lies, 1981).

Evapotranspiration (ET) and Water Use Efficiency (WUE)

Evaporation (E), transpiration (T), and water use efficiency (WUE) are important alfalfa production components. Stewart and Hagan (1969) reported that the physiological nature of alfalfa manifested through seasonal fall storage followed by spring retrieval of photosynthates alters the yield to ET relationship into a convex function. However, Arnold and Smeal (1984) reported that a highly significant linear relationship existed between alfalfa dry matter production and ET.

Precipitation, irrigation, solar radiation, temperature, humidity, and wind affect ET (Stewart and Hagan, 1969). Rosenberg (1969) reported that best ET measurements were obtained from well watered crops which exerted minimal canopy resistance. Well watered alfalfa demonstrated little resistance to ET and consumed as much or more water than other crops (Blad and Rosenberg, 1974; Rosenberg, 1969).

Rosenberg (1969) reported ET rates 25% higher in alfalfa than native pasture grown under the same conditions. Sharrett et al. (1983) reported that ET rates were significantly higher in irrigated than dryland alfalfa. Lower available soil water in dryland alfalfa resulted in lower leaf water potential, which reduced ET and raised canopy temperatures (CT) during the day. Early morning ET and CT did not differ appreciably between irrigated and non-irrigated alfalfa (Sharrett et al., 1983). Jabbar et al. (1984) reported that ET increased from morning to mid-day and that leaf water potential decreased during this time period in alfalfa with adequate soil moisture. Low temperatures may induce strong canopy resistance which leads to lower ET rates than are possible under atmospheric conditions at that time. (Rosenberg, 1969).

Alfalfa ET rates depend upon growth stage, (Peck et al., 1958), atmospheric demand, soil moisture regimes, and plant factors such as degree of ground cover and plant height (Stewart and Hagan, 1969). ET rates decreased significantly when alfalfa was harvested and increased during regrowth (Stewart and Hagan, 1969). Additionally, higher ET rates were observed in taller plants. Stewart and Hagan (1969) reported that ET rates differed among cultivars. Wit (1958), reported ET differences between 'Grimm', a winterhardy cultivar, and 'Hairy Peruvian', which is adapted to hot climates. Alfalfa ET reached maximum rates in late spring and declined as summer advanced.

Soil moisture content exhibits an important role in the ET rate. Stewart and Hagan (1969) reported that ET increased markedly above reference treatments as soil moisture regimes increased in wetness up to but not including saturation. Alfalfa growth and ET decreased when approximatly 80% of the available soil moisture was depleted (Stewart and Hagan, 1969).

Most net radiation is used in ET when soil moisture is available and crop cover shades the ground (Tanner and Lemon, 1962). Jabbar et al. (1984) reported that ET patterns followed the patterns of solar radiation. Net radiation provided energy sufficient to evaporate 7mm of water per day on clear summer days in Nebraska (Rosenberg and Shashi, 1978). Tanner and Lemon (1962) reported that alfalfa may use more energy than is supplied by radiant energy. This usually occurs in the spring when alfalfa is growing actively (Rosenberg, 1969). Advected sensible heat provides the additional energy consumed in the ET process (Rosenberg and Shashi, 1978; Tanner and Lemon, 1962).

Irrigation in the western states is limited primarily to areas surrounded by dryland or desert. Advected sensible heat is a major source of energy consumed when ET occurs in alfalfa under dry conditions (Rosenberg, 1969). Approximately 20 to 40% of the energy for ET in alfalfa may be supplied by advected sensible heat (Blad and Rosenberg, 1974). Rosenberg and Shashi (1978) reported that ET values rarely exceed 12 mm in alfalfa. Evapotranspiration values in alfalfa during a drought in Nebraska ranged from 4.75 to 14.22 mm of water per day and exceeded 10mm per day on one-third of the days.

Total ET should include nocturnal ET. Rosenberg (1969) reported that nocturnal ET is common during the alfalfa growing season. This is due to strong temperature inversions which result in a downward delivery of sensible heat. Nocturnal ET was greatest in spring and lowest during summer. Nocturnal ET has accounted for 20% of the daily total water consumption in alfalfa with as much as 1 mm of water per night being transpired.

Jabbar et al. (1984) reported that transpiration may equal ET in alfalfa when the canopy covers the soil surface. However, this is doubtful in alfalfa grown for seed due to wide row-spacing. Tanner and Lemon (1962) reported that transpiration is influenced by both plant and soil factors. Plant factors include leaf area, root proliferation, plant type and physiological age (Tanner and Lemon, 1962). Soil factors affecting evaporation include soil moisture content, soil moisture suction, and water transmission (Tanner and Lemon, 1962). The plant is the major area of resistance to water transmission in the soil-plant system with soil resistance becoming the major area only near the plant wilting point (Jabbar et al., 1984).

Soil water content is crucial in transpiration. Gardner and Ehlig (1963) reported that transpiration rates should be proportional to available soil water content at wilting. The lower limits of water available for transpiration may occur at suctions above -1.5 MPa. Ogata et al. (1960) reported that transpiration is determined largely by weather conditions following irrigation. However, increased suction gradients as soil moisture becomes depleted lead to a continuous decreasing transpiration rate. Gardener and Ehlig (1963) reported that the transpiration rate increased as soil water increased in alfalfa.

Alfalfa production per unit of water use is greatest under low evaporative conditions (Stewart and Hagan, 1969). Additionally, yield per unit of water use declined as ET rate increased with seasonal progression from summer to fall. In New Mexico, peak water-use of 0.96 cm day^{-1} occurred during late June and July (Arnold and Smeal, 1985). Stewart and Hagan (1969) reported a positive correlation between evaporation pan data and alfalfa yield produced under good field conditions. Alfalfa forage yield increased linearly with ET (Gomez et al., 1985). However, WUE decreased as yield increased with ET under good field conditions (Stewart and Hagan, 1969). Conversely, forage quality was generally lower with high ET rates (Gomez et al., 1985; Jensen et al., 1985). Additionally, whole plant nitrogen percentage decreased linearly with ET (Gomez et al., 1985). Water use efficiency is less in arid than temperate regions at high temperatures with sufficient soil moisture.

Moisture Stress on Alfalfa Seed Production

Alfalfa seed yield may vary with time and location. This is due to the interaction between plant factors and soil moisture availability (Goldman and Dovrat, 1980). Blinn (1910) reported that proper soil moisture is important for alfalfa seed production. Soil moisture suction between -0.2 and -0.8 MPa produced optimum alfalfa seed yields when the soil was kept continuously moist and irrigation water was not applied during heavy bloom (Taylor et al., 1959). In contrast, alfalfa forage yields did not exhibit such an optimum. Forage yield increased with increased amounts of water as soil moisture suction decreased to field capacity (Mayernak et al., 1985; Taylor et al., 1959). Additionally, irrigation throughout the season increased forage yield over irrigation supplied early in the season.

Moisture stress greatly affected alfalfa vegetative growth (Rahman, 1973). Growth was greatly reduced by decreased soil moisture before reaching the permanent wilting point. Naylor et al. (1985) reported that alfalfa decreased in forage yield, acid detergent fiber, cell wall content, lignin, cellulose, and hemicellulose, and increased in leaf and ash percentage as water stress increased. Pandey et al. (1984) reported that harvest index declined as water decreased in cowpea (Vigna unguiculata L.), mungbean (Vigna radiata L.), soybean (Glycine max L.), and peanut (Arachis hypogaea L.) suggesting that seed yield was more sensitive to moisture stress than total plant yield. Taylor et al. (1959) reported that alfalfa seed yields were reduced if soil moisture was reduced to -1.5 MPa before harvest.

Alfalfa plants must be mature to fill seed pods to obtain maximum yields (Yamada et al., 1973). However, vegetative growth must be suppressed to promote flowering in alfalfa. Suppression of vegetative growth favored the formation of alfalfa seed more than increased vegetative growth (Fuelleman, 1934). Alter (1920) reported that stress on alfalfa is needed to force seed setting. Blinn (1910) reported that heaviest alfalfa seed yields resulted when plants grew slowly. Similar to alfalfa, good beet (Beta vulgaris L.) seed yields were obtained by keeping soil moisture near the minimum requirement for plant growth (Blinn, 1910).

The amount of soil moisture at flowering and during pod maturation is important for good alfalfa seed yields (Willis and Bopp, 1910; Martin, 1915; Hollowell, 1929). Reduced alfalfa seed yields were observed if plants were irrigated during the bloom stage (Taylor et al., 1959). They also reported that highest seed yields in alfalfa were obtained by maintaining continuous soil moisture from the initiation of spring growth until flowering. Goldman and Dovrat (1980) reported that 80 mm of applied water reduced seed yields when conditions favored vegetative growth. Yamada et al. (1973) reported that 122 cm of water was needed to fill the soil profile and insure good alfalfa seed yields on dry California soils. Cohen et al. (1972) reported irrigation (replenishment of soil moisture) timing and amount markedly affected alfalfa flower intensity. Moderate rates of applied water (90 mm) before flowering in alfalfa did not affect seed yield; however, seed yields decreased at high rates (150 mm) (Goldman and Dovrat, 1980). Moderate water rates applied to dry soils at mid-flowering markedly increased alfalfa seed yields; but, seed yield was less affected by water applied after flowering (Goldman and Dovrat, 1980).

Taylor et al. (1959) concluded that there is an optimum soil moisture for maximum alfalfa seed yields. Extremely dry or wet soil may affect the proper functioning of flowers for alfalfa seed production. Flowering and seed set in alfalfa was prolonged under wet conditions (Goldman and Dovrat, 1980). Tysdal (1946) reported no difference in response of four alfalfa cultivars to three soil moisture regimes (high, medium, and low).

Martin (1915) reported that alfalfa seed crop failure is usually due to an excess or an insufficiency of soil moisture during pod maturation. Thompson and Fick (1981) reported that wet or flooded conditions reduce alfalfa forage yields and decrease stand life in alfalfa. Root growth was inhibited and top growth was reduced 50% after flooding at 34°C. However, alfalfa may tolerate longer periods of flooding at lower temperatures. Tysdal (1946) reported that alfalfa lodged and produced two to five times less seed yield with more shrivelled seed under excessive irrigation. Forty-percent soil moisture resulted in greater seed yield and more seed per 100 grams of fresh weight than from alfalfa plants grown at 20 or 30% soil moisture in greenhouse experiments.

Lack of sufficient subsoil moisture contributed to suppressed alfalfa seed yield during the first and/or second year of production (Yamada et al., 1973). Taylor et al. (1959) reported that maximum alfalfa seed yields may be obtained if mean soil moisture suction is not allowed to exceed -0.2 MPa.

Soil moisture stress may affect seed yield components. Pandey et al. (1984) reported that flower and pod development, ovule number per pod, and seed filling contribute to high seed yields in grain legumes. Tysdal (1946) reported that fresh weight, number of pods per raceme, flowers per plant, stems and seed per plant, 100 seed weight and grams of seed per 100 grams of fresh weight all increased from low (20%) to high (40%) soil moisture. The number of racemes per plant was highest in medium (30%) soil moisture in greenhouse grown alfalfa. Alfalfa seed yield under field conditions was consistently higher in low compared to high moisture regimes at three different row spacings (Tysdal, 1946). Additionally, high moisture plots produced the most seed. Moisture interactions were attributed to differential affects of irrigation timing.

Moderate air temperature, low humidity, and soil moisture below optimum produced alfalfa vegetative growth which was conducive to the storage of high organic root reserves (Grandfield, 1945). The range of variation in carbohydrate content with change in water supply differs among species and also at various stages of growth within a species (Rahman, 1973). A wide range of carbohydrate variation was demonstrated in alfalfa at preflower, end of flowering, and fruiting stages (Rahman, 1973).

The rate of total nonstructural carbohydrate accumulation in roots, followed by a period of depletion, was much greater in plants under moisture stress than plants grown with unlimited soil moisture (Grandfield, 1945; Cohen et al., 1972). High root carbohydrates levels were positively correlated with alfalfa seed yields (Grandfield, 1945; Dovrat et al., 1969). High alfalfa root and crown carbohydrate reserves produced more stems and buds (Willard et al., 1934), larger quantities of seed, more pods per stem, more seed per pod, and a higher percent pod set (Dobrenz and Massengale, 1966), greater number of racemes per stem, and more pods per raceme (Dovrat et al., 1969) than plants with low carbohydrate reserves. However, Dobrenz and Massengale (1966) reported that the number of racemes per stem were consistently negatively correlated with carbohydrate fractions in the roots. Cohen et al. (1972) reported that stored root carbohydrates were positively correlated with alfalfa seed weight. Total available non-structural carbohydrates became limited due to increased vegetative growth. This resulted in a lower percentage of pod set in alfalfa plants with high flowering intensity at high soil moisture levels (Cohen et al., 1972). Cultural practices designed to increase carbohydrate root reserves in alfalfa during the growing season may maximize alfalfa seed yields.

CHAPTER III

MATERIALS AND METHODS

Moisture stress affects vegetative and reproductive plant growth. The effects of moisture stress on alfalfa growth and seed yield components were evaluated in 1985 on the John Schutter Farm, Manhattan, MT. Four alfalfa cultivars of varying fall dormancy levels (Ladak 65, Vernal, Apollo, and Thor) were utilized, with Ladak 65 being the most dormant.

Site Description

The experiment was established in 1984 on a site previously cropped to barley (Hordeum vulgare L.). The soil was a Manhattan very fine, sandy-loam (coarse-loamy, mixed, Typic Calciborolls). Composite soil samples of five cores replication^{-1} were taken on 15 May at 0 to 30 and 30 to 60 cm to determine initial soil fertility. Samples were analyzed by standard soil test methods in the Montana State University Soil and Plant Testing Laboratory. The cumulative analyses indicated the presence of 140, 256, and 2216, kg ha^{-1} of N, P, and K, respectively. The soil had an electrical conductivity (EC) of 0.7 mmhos, medium effervescence, and pH and organic matter content at 0 to 30 and 30 to 60 cm of 8.4, 8.7 and 1.64, 0.62 %, respectively. Bulk densities at 20 cm increments from 0 to 400 cm were 1.32, 1.30, 1.29, 1.33, 1.30, 1.33, 1.40, 1.36, 1.34, 1.39, 1.39, 1.36, 1.37, 1.35, 1.40, 1.41, 1.41, 1.43, 1.44, and 1.45, respectively.

Additional soil samples were taken on 2 June 1985. Samples were analyzed as in 1984. Cumulative analyses indicated the presence of 76, 83, 1597, and 73, kg ha^{-1} of N, P, K, S, and 0.3, 52.1, 5.4 c mol kg^{-1} of Na, 1/2 Ca, and 1/2 Mg, respectively.

Experimental Design

A modified randomized complete block, split-block design was utilized with two replications on either side of a line-source irrigation system. Four main irrigation treatments (2.4 x 4.8 m) of increasing moisture (non-irrigated, low, medium and high) were applied at right angles from the line-source on both sides. Main plot irrigation treatments were fixed due to the systematics of the line-source system, and could not be tested statistically by analysis of variance (ANOVA) (Hanks et al., 1980). However, the cultivars were randomized at right angles to the pipe to afford a valid statistical analysis for cultivar differences and irrigation by cultivar interactions. Main plot effects were analyzed by linear regression as described by Hanks et al. (1980).

Planting and Establishment

The experimental site was preplant incorporated with EPTC (S-ethyl dipropylthiocarbamate) at 0.77 l ha^{-1} on 4 May 1984 and roller packed to insure a firm seedbed. Seed were planted on 18 June 1984 with a coneseed planter to a depth of 13 mm. Seeding rate was 60 seeds $meter^{-1}$ of linear row. Eight row plots with sixty-one cm row spacings were utilized. Wiesner (1982) reported that 61 to 92 cm row spacings produced the best yields under irrigation in Montana. Commercial granular Rhizobium inoculum specific for alfalfa was added to the seed prior to planting.

The experimental area was irrigated uniformly (13 mm) immediately after planting followed by four day interval irrigations (6.5 mm) until full emergence. Subsequent irrigations (13 mm) during the establishment year were applied at 14 day intervals. Five centimeters of water were applied late in the fall to fill the soil profile. Plants were thinned to one plant every 30 cm when they were approximately 25 cm in height. Plots were hand-weeded throughout the growing season when necessary.

Meteorological Observations

Precipitation, temperature, and humidity were measured with standard weather instruments and recorded daily (Appendix, Table 18). Evaporation was recorded by measuring daily water loss from No. 1 wash tubs as described by Bauder et al. (1982) (Appendix, Table 18).

Irrigation System

Irrigation treatments were applied with a line-source sprinkler system similar to the one described by Hanks et al. (1976). Model 25 sprinklers with 4 mm nozzles (Rain Bird Sprinkler Manufacturing Co., Glendora , California) were utilized. The system was operated at approximately 379.5 kPa producing a 15 m wetting radius and a discharge rate of 0.34 l s^{-1} per sprinkler head. The main irrigation line consisted of 7.6 cm aluminium pipe with hook and latch couplings. Sprinklers were placed on 2.5 x 60 cm risers spaced 4.6 m apart.

In 1985, only two irrigations were applied due to insufficient water as a result of drought. Additional irrigations were originally planned.

Evaporative losses from evaporation pans in the medium irrigation regime were used to schedule irrigations. Cumulative evaporation from pans is a good estimate of crop water use (Bauder et al., 1982). Fifteen centimeters of water were placed in the pans at the initiation of the growing season. Irrigations were applied on 17 May and 20 June 1985 when approximately 15 cm of water were evaporated. Collection cups were placed in the center of each subplot at canopy level to determine the amount of applied water. Irrigations were applied when wind speed was less than 8 kmph and at successive intervals to control runoff.

Pollination

Alfalfa leafcutter bees, Megachile rotundata (Fabriscus), were used as pollinators. Alfalfa leafcutter bees are the most reliable pollinator for alfalfa seed production in northern regions (Hobbs 1973). Eight liters (25,000 larva) of leafcutter bees and four loose grooved bee boards were placed in a shelter facing southeast on 30 June 1985. Buckwheat (Fagopyrum sagittatum L.) was planted in 12 m rows at both ends of the field on 18 May and 1 June to provide bee nesting material.

Soil Moisture Determinations

Soil moisture determinations were made with a neutron probe (Cambell, Model 503DR Hydroprobe) at 20 cm intervals. Neutron probe access tubes (1120 160 psi PVC pipe with a 43 mm internal diameter) were placed 400 cm deep in the center of each plot on 4 April 1985 . Initial probe readings were taken on 24 April 1985 and at 14 to 21 day intervals. Additional measurements were taken prior to and 24 hours after each irrigation.

Plant available water (PAW) in 1985 was the difference between the soil moisture content and the permanent wilting point (PWP). PWP was 9.5, 8.5, 6.8, 6.0, 5.8, 5.9, 6.2, 6.3, 6.4, 5.9, 6.1, 6.6, 6.1, 6.2, 6.4, 6.7, 6.8, 7.1, 7.9, and 8.2, at 20 centimeter increments from 0 to 400 centimeters. PWP values were determined by pressure plate extractions at -1.5 MPa. Plant available water was calculated at 20 cm intervals to 400 cm on one side of the pipe (location two).

Root Penetration

Root penetration was determined by depletion of PAW at 20 cm increments. Water depletion in the lower soil profile was attributed to root penetration when a 5 % or greater reduction in plant available water occurred between observation dates.

Evapotranspiration

Evapotranspiration (ET) consist of crop transpiration and soil surface evaporation. Seasonal ET was determined at location two for each treatment by the equation: ET = soil moisture content at planting + precipitation + irrigation - soil moisture content at the following measurement period. Total ET was the cummulative of seasonal ET calculated at both locations. Total ET was used to evaluate plant growth and yield parameters.

Growth and Yield Measurements

Plant height was measured in location two at ten day intervals from 4 April until 24 July 1985. Measurements were terminated when the non-irrigated plants attained maximum height and the high irrigated plants lodged.

Two square meters adjacent to the access tubes were harvested when 2/3 to 3/4 of the seed pods turned brown to black in color. Smith (1972) and Wiesner (1982) reported highest seed yields when 2/3 to 3/4 of the pods are brown to black. Harvest measurements consisted of number of plants per harvested area, basal stems plant^{-1}, number of pods stem^{-1}, length of the third internode from the crown, total biomass, and seed yield. Basal stems plant^{-1}, number of pods stem^{-1}, and third internode length from the crown were determined by random selection of ten stems within the harvest area.

Plants were initially processed through a Vogel rubber-roller thresher for straw removal. Seed were removed by three successive runs through a resilient tapered thresher (Hannaford "Seedmaster", Model MkII) and cleaned with an Oregon "Continuous" seed-blower.

Water Use Efficiency

Water use efficiency (WUE) was used to determine the production of a given yield component per unit of water consumed by evapotranspiration. WUE determinations were made for total biomass and seed yield for each cultivar within each irrigation regime.

Seed Quality

Seed from all cultivars utilized for quality determinations was open pollinated. Consequently, seed utilized in quality determinations were not genetically pure within each cultivar.

A Precision Divider (Gamet MFG Co.) was used to reduce seed samples to a 5 to 10 g representative sample for quality analyses. Germination was determined by utilizing four replications of 50 seeds which were placed on moist blotters in standard germination boxes in a 20°C germinator for 7 days. Number of germinated, dead + abnormal, and hard seeds were determined. Seed weight was determined by using four replications of 1,000 seeds from each sample.

Pure live seed (PLS) was calculated by multipling percent total viable seed by total seed yield for each cultivar within each irrigation regime.

Statistical Methods

Data were analyzed with the Plant and Soil Science Discovery computer system and the M.S.U. Computing Service Vax780 using SAS. Main plot effects were analyzed by linear regression. Figures were constructed using the graphics package Tellagraf on the M.S.U. CP-6 main frame computer.

CHAPTER IV

RESULTS AND DISCUSSION

Water Application

A line-source irrigation system produces identical water application on both sides of the pipe under ideal conditions. Differential water application between sides of the pipe occurred in 1985 (Appendix, Table 16). Variable water application was attributed to above ground wind and side-hill slope. Variable water application between sides resulted in variations in evapotranspiration (ET), biomass, and seed yield. Experimental results in 1985 are presented as two locations because of differential water application.

Environment

Environmental data are given in Appendix, Table 19. Growing season precipitation was limited in 1985 due to drought conditions. Total growing season precipitation was 140 mm. Most of the precipitation occurred in May and August with 71 and 40.5 mm, respectively. July temperatures were highest with a mean high and low of 29° and 20° C., respectively. Humidity was highest in August and the early part of September. Evaporative demand was highest in May and decreased throughout the growing season.

Growing Season

Maximum growing season length from initial green-up in late March until harvest in September was 157 days (Table 1). Plants matured in sequential order from the non to high irrigation regime. Regression analysis indicated a good relationship between increased days to maturity and increased evapotranspiration for all cultivars (Table 2). In general cultivars matured in relation to their fall dormancy level with Ladak 65 maturing first.

Table 1. Growing season length for each cultivar within each irrigation treatment in 1985 at the John Schutter Farm, Manhattan, MT.

Cultivar	Harvest Date	Total Days
Ladak 65		
Non-Irr.	8/6	127
Low	8/9	130
Medium	8/19	140
High	8/29	150
Vernal		
Non-Irr.	8/6	127
Low	8/13	134
Medium	8/29	150
High	9/5	157
Apollo		
Non-Irr.	8/13	134
Low	8/26	147
Medium	9/5	157
High	9/5	157
Thor		
Non-Irr.	8/13	134
Low	8/26	147
Medium	9/5	157
High	9/5	157

Table 2. Regression analyses for the effect of increased days to maturity and evapotranspiration for all cultivars in 1985 at both locations at the John Schutter Farm, Manhattan, MT.

Cultivar	Intercept	Slope	Prob.	R^2
Ladak 65	-1,388	13.6	0.0003	0.90
Vernal	-997	10.3	0.0001	0.95
Apollo	-1,226	11.4	0.0007	0.87
Thor	-1,375	12.4	0.0017	0.83

Evapotranspiration

Total Evapotranspiration (ET). Total ET was similar at both locations for each cultivar except in the non-irrigated regimes (Table 3). Differences were attributed to variable water application resulting from winds and side-hill slope.

Table 3. Total evapotranspiration at both locations for all cultivars at four irrigation regimes in 1985 at the John Schutter Farm, Manhattan, MT.

	Evapotranspiration (mm) Irrigation Regime			
Cultivar	Non-Irr.	Low	Medium	High
Location 1				
Ladak 65	258	393	526	645
Vernal	268	401	509	639
Apollo	291	423	509	609
Thor	280	428	510	634
Location 2				
Ladak 65	362	419	580	626
Vernal	345	406	543	639
Apollo	340	418	540	635
Thor	335	401	539	668

Total ET was greatest in the high irrigated plots. These results agree with reports by Sharrett et al. (1983) and Stewart and Hagan (1969).

Total ET was greater in all treatments than the total precipitation and irrigation in 1985 (Appendix, Table 17). This may be attributed to a fall irrigation in 1984 which filled the soil profile. Water use above the added crop year moisture indicated depletion of stored moisture at lower depths in the soil profile. Deep root penetration could be responsible for the additional moisture consumed in ET.

Total ET from one season may indicate potential soil moisture levels needed to produce a crop the next year. This information could be useful in irrigation management to insure maximum yields in succeeding years.

Water consumption among cultivars was similar within an irrigation regime. However, growing season length varied as much as 13 days among cultivars within an irrigation treatment (Table 1). This would indicate that the same amount of water was needed to produce a seed crop regardless of the cultivar or length of time to mature the crop.

Seasonal ET. Seasonal ET moisture data were collected for location two to determine if differential ET occurred among cultivars within each irrigation regime. All cultivars exhibited similar seasonal ET patterns within each irrigation regime (Fig. 1, 2, 3, 4) except during mid-season under non-irrigation. These cultivar variations

(Figure 1) may have resulted from either non-uniform canopy cover or variable plant density.

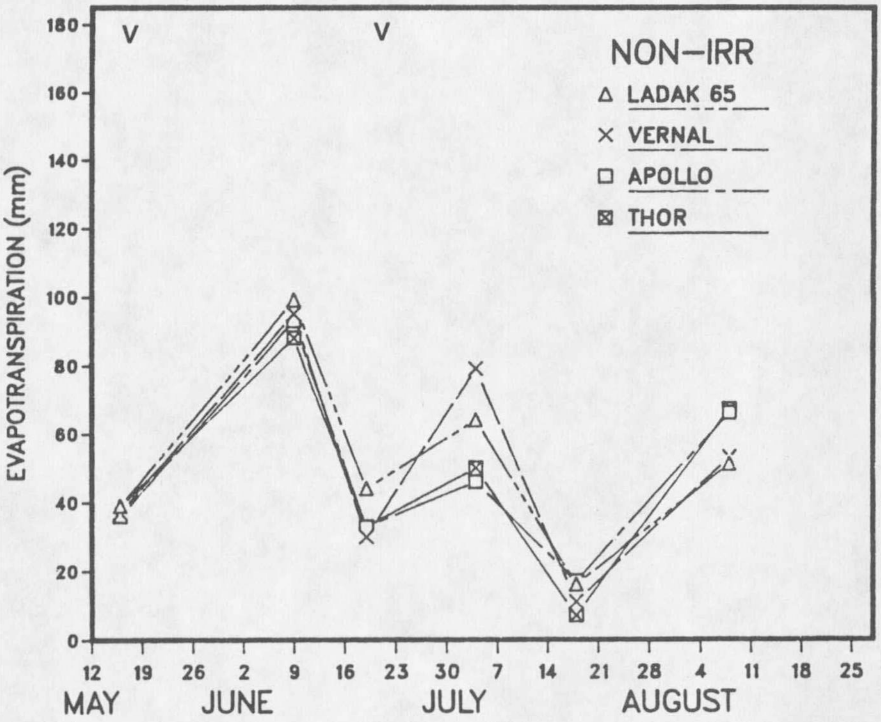

Figure 1. The effect of time on evapotranspiration (ET) under non-irrigation at location two for all cultivars in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

Rosenberg and Shashi (1978) reported that alfalfa ET rates were maximal in late spring and declined as summer advanced. Our experiment exhibited similar results.

Seasonal ET may be used to monitor crop water use as plants make transitional changes in growth and development. A seasonal ET model may have potential in the development of more efficient irrigation management practices.

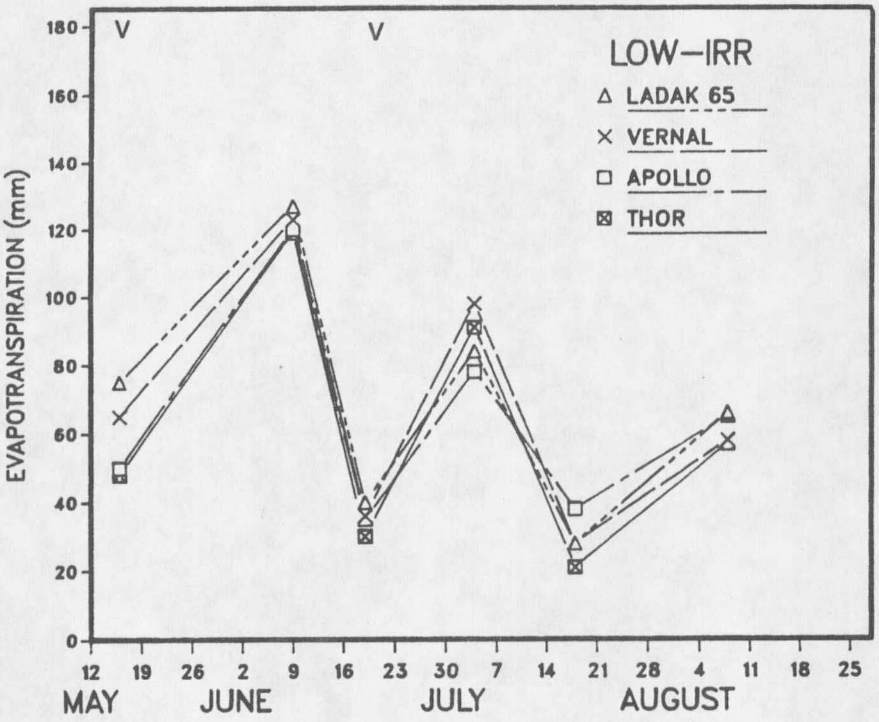

Figure 2. The effect of time on evapotranspiration (ET) under low irrigation at location two for all cultivars in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

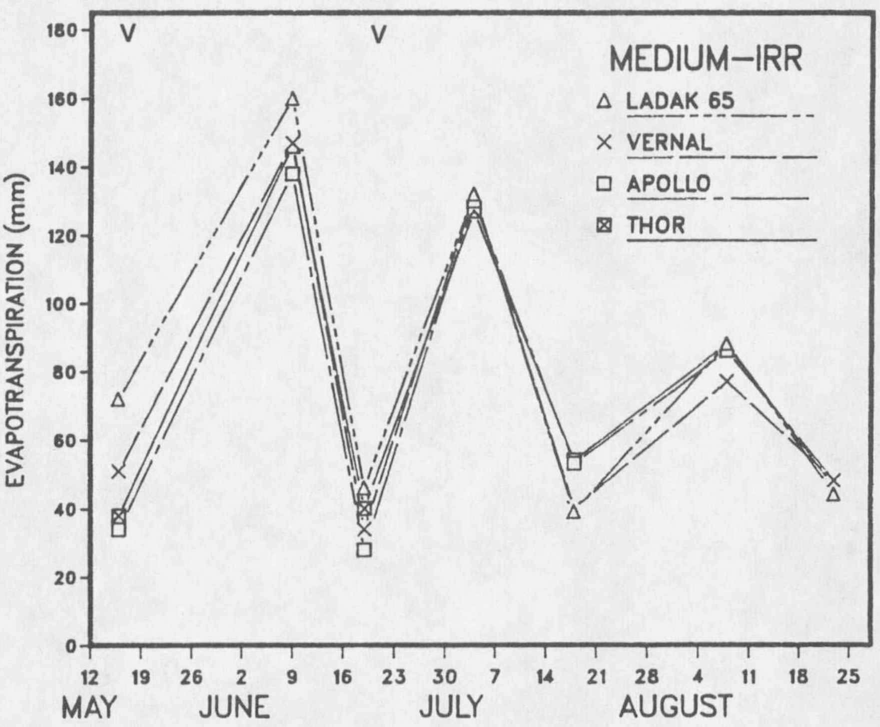

Figure 3. The effect of time on evapotranspiration (ET) under medium irrigation at location two for all cultivars in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

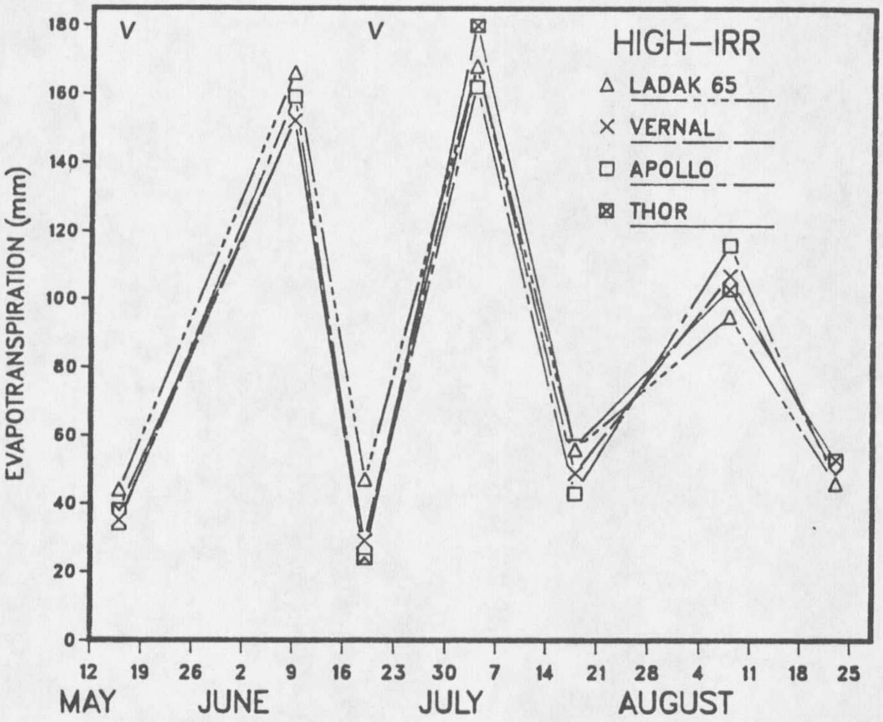

Figure 4. The effect of time on evapotranspiration (ET) under high irrigation at location two for all cultivars in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

Soil Moisture Depletion

Irrigations replenished plant available water to varying degrees within each treatment (Fig. 5, 6, 7, 8). However, irrigations applied in 1985 were not sufficient to maintain plant available water throughout the season resulting in a net decrease in stored soil moisture in all irrigation regimes. Additional irrigations were not applied in 1985 due to drought conditions. Ladak 65 had equal or lower PAW than the other cultivars in all irrigation regimes at the initiation of the season. Additionally, Ladak 65 had the least amount of PAW in all irrigation regimes as the season progressed. This may be the result of deep root penetration or extraction of soil moisture at greater tensions.

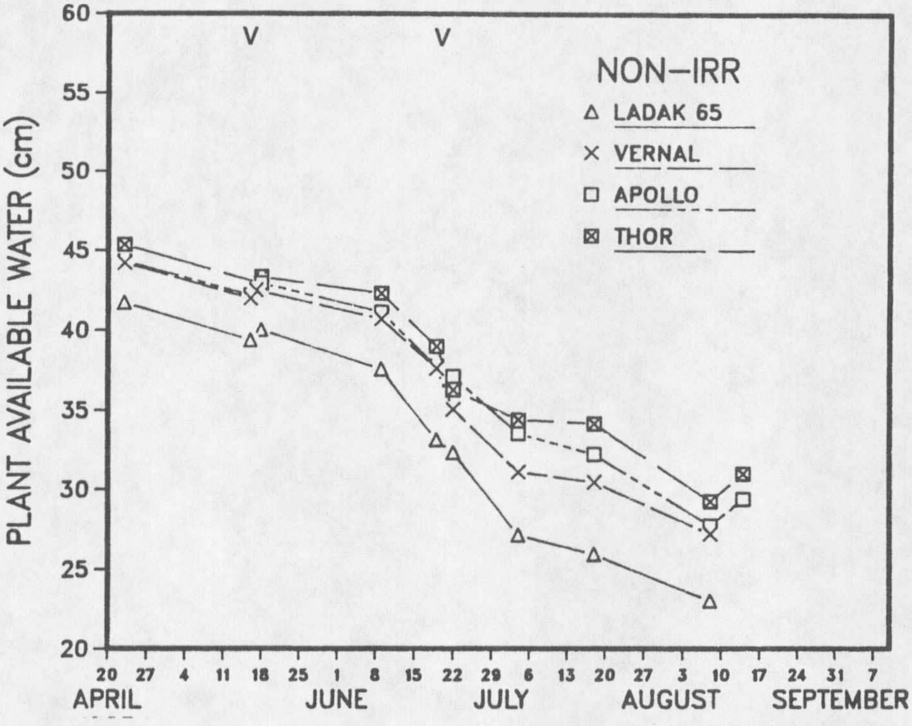

Figure 5. The effect of time on plant available water in the non-irrigated regime for all cultivars at location two in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

The slight increase in plant available water at the end of the season for Apollo and Thor may be attributed to late season precipitation in the non-irrigated plots (Figure 5).

Late season precipitation may also account for the leveling off of PAW depletion in the low irrigated plots (Figure 6). Stabilization of PAW depletion at the end of the season by Thor in the medium irrigation (Figure 7) and Ladak 65 in the high irrigation treatments (Figure 8) may indicate either the onset of dormancy or complete senescence.

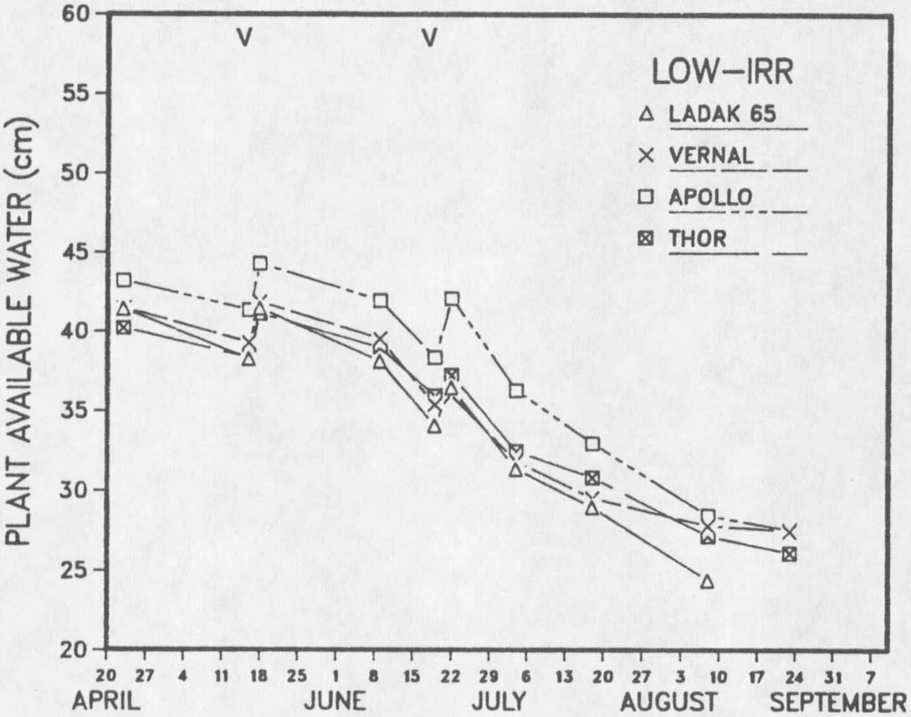

Figure 6. The effect of time on plant available water in the low irrigated regime for all cultivars at location two in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

Plant available water is a good indicator of stored soil moisture. It may be used to determine irrigation timing and rate of application needed to produce a specified amount of crop growth. Plant available water data might be used to determine whether a fall or spring irrigation is desirable. A fall irrigation would be most benefical if PAW was low and irrigation cost were minimal.

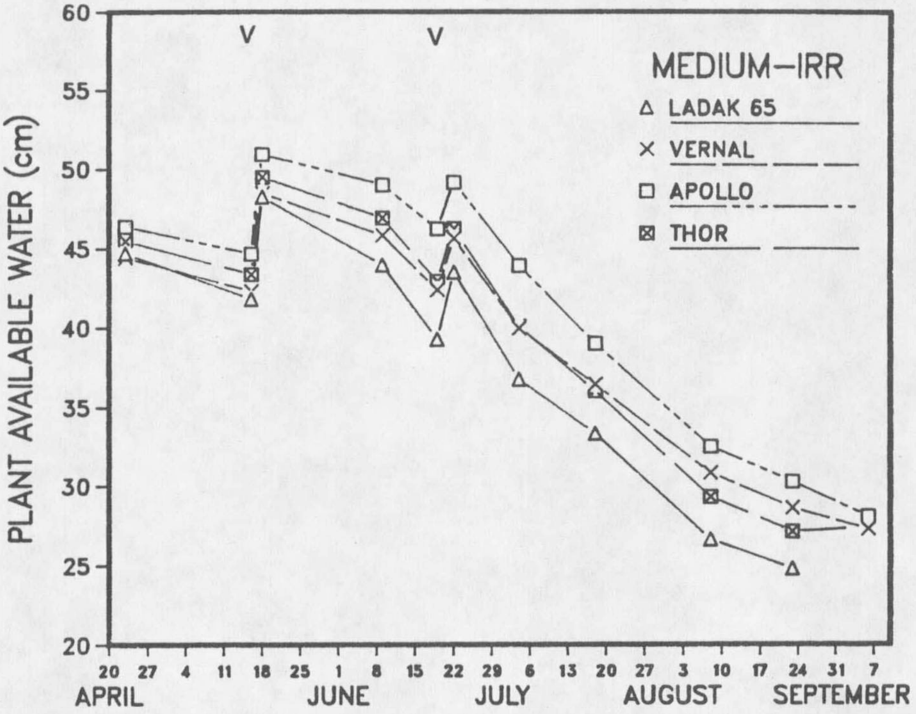

Figure 7. The effect of time on plant available water in the medium irrigated regime for all cultivars at location two in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

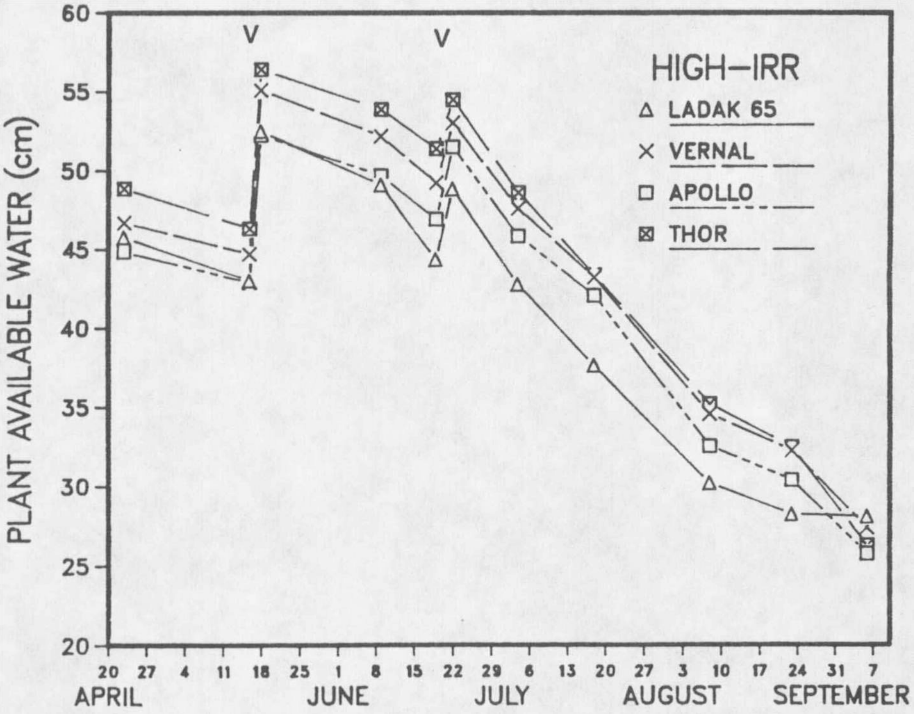

Figure 8. The effect of time on plant available water in the high irrigated regime for all cultivars at location two in 1985 at the John Schutter Farm, Manhattan, MT. Arrows indicate time of irrigations.

Root Penetration

Ladak 65 had the deepest root penetration from 4 July to harvest at all irrigation levels (Fig. 9, 10, 11, 12) with the exception of Vernal, in the non-irrigated regime, where the roots of both penetrated to 340 cm.

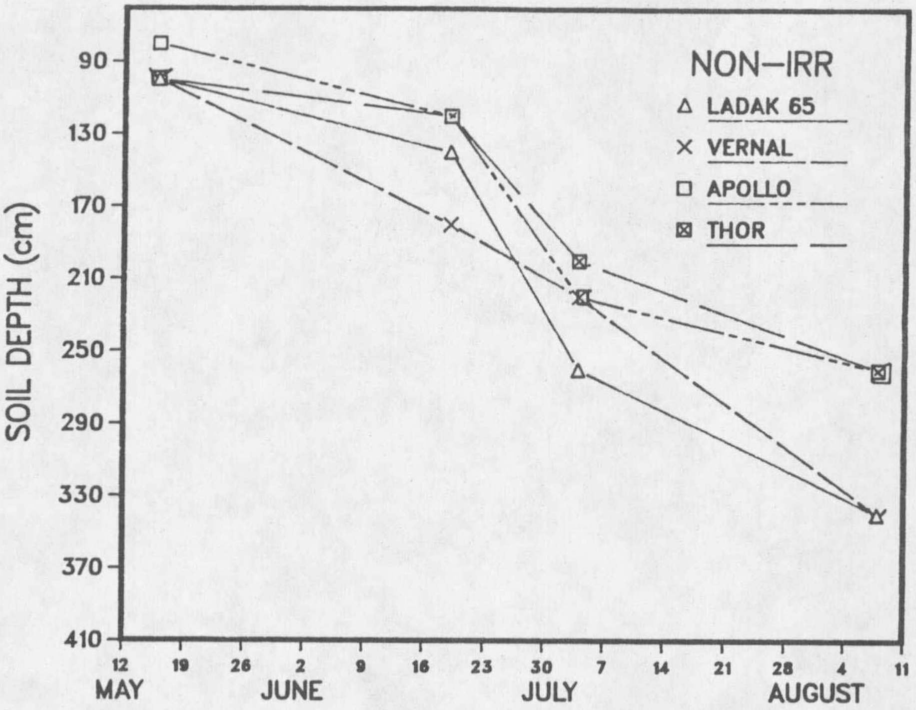

Figure 9. Root penetration with progression of the season at location two for all cultivars in the non-irrigated regime in 1985 at the John Schutter Farm, Manhattan, MT.

Root growth of Thor was slower than the other cultivars during the early portion of the season in the low irrigated plots (Figure 10). Apollo root penetration stabilized at approximately 260 cm by the end of the growing season in the medium irrigated plots (Figure 11).

In general, higher irrigation regimes had deeper root penetration as a result of a longer growing season. However, on 8 August root penetration for all cultivars in the non-irrigated regime was deepest or equal to the other irrigation regimes. Ladak 65 had the deepest root penetration of any cultivar at 360 cm in the medium irrigated plots. These data suggest that roots penetrate deeper under dry conditions in order to extract soil moisture. However, dry conditions result in early maturity and onset of dormancy resulting in less time for maximum root growth.

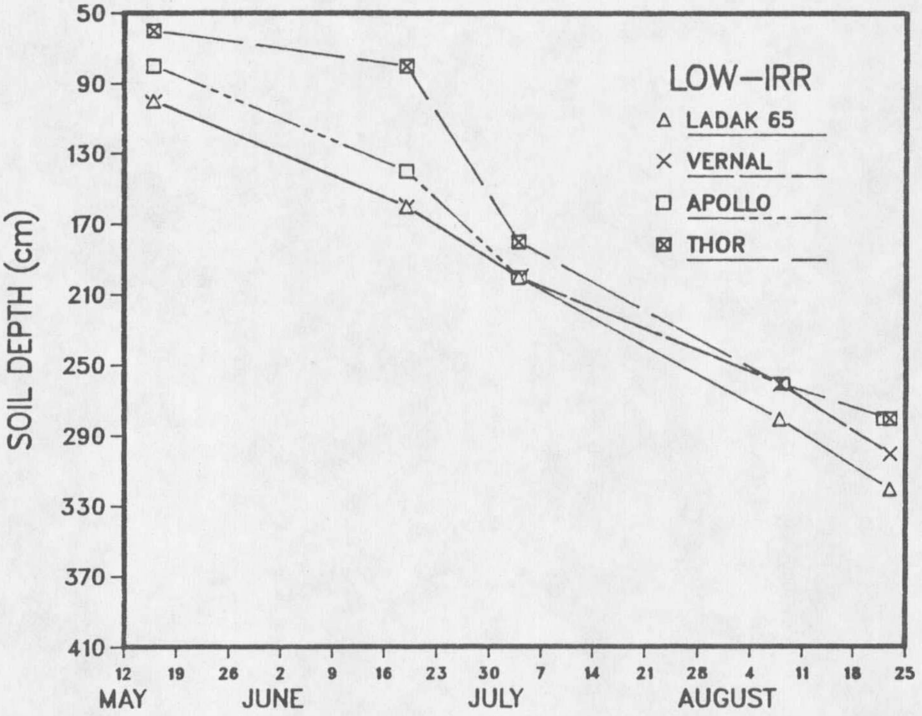

Figure 10. Root penetration with progression of the season at location two for all cultivars in the low irrigated regime in 1985 at the John Schutter Farm, Manhattan, MT.