# WATER USE, YIELD, AND WATER USE EFFICIENCY OF DIFFERENTIALLY IRRIGATED ALFALFA

by

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by

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(Under the instruction of Drs. E. T. Kanemasu, M. B. Kirkham, and L. R. Stone)

## ABSTRACT

The production of alfalfa on the Central Great Plains is often limited by precipitation. The effect of drought can be alleviated by the use of supplemental irrigation; however, competition for available resources restrict the expansion of irrigated agriculture. Through better understanding of the relationship between yield and water use, alfalfa production might be done more economically. The increased use of supplemental irrigation has increased the need for information on alfalfa water use.

Alfalfa (*Medicago sativa* L. Cody) was grown with seven levels of irrigation water to assess the affect of different irrigation levels on crop yield, water use, water use efficiency (WUE), stomatal resistance (SR), plant water potential, and canopy temperature. Canopy temperature was measured with an infrared thermometer in 1980, 1981, and 1982. In 1981 and 1982, plant water potential and stomatal resistance were measured with a pressure chamber and a stomatal porometer, respectively. In each year of the study, water use was determined from neutron probe measurements

taken to a depth of 3.12 m. The soil type was Eudora silt-loam. The alfalfa was irrigated (treatments were 0, 25, 50, 75, 100, 125, and 150 mm per irrigation) following each harvest.

Alfalfa was harvested four times during each year of the study (1980, 1981, and 1982) in late May, early July, early to mid August, and mid September at 10% bloom.

When soil water limited yield, a strong linear correlation existed between yield and water use. Water was a crucial factor limiting the yield of alfalfa in the drought year of 1980, and yield was proportional to water use. In 1981 and 1982, environmental conditions were favorable i. e., precipitation was more frequent and air temperatures were lower than in 1980, and consequently the yield of rainfed alfalfa was similar to that of the irrigated alfalfa. Seasonal precipitation amounts in 1981 and 1982 were 2.5 and 2.1 times that received in 1980 (263 mm). The high potential evapotranspiration (ET) and low yield in 1980 resulted in lower WUE than in either 1981 or 1982. In all years of the study, WUE declined with irrigation amount.

The average stomatal resistance of alfalfa grown in 1981 and 1982 was 145 s $m^{-1}$ and the leaf water potential of the alfalfa averaged -0.220 MPa, values similar to those cited in literature for non-water-stressed alfalfa.

In 1982, alfalfa was shown to have lower SR than grain sorghum (*Sorghum bicolor* L. Moench.), corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), pinto bean (*Phaseolus*

*vulgaris* L.), sunflower (*Helianthus annuus* L.), or pearl millet (*Pennisetum americanum* L.). A relationship between SR and ET was not firmly established for the crops; however, SR was found to be correlated with the difference between the temperature of crop canopy minus the temperature of the air.

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# CHAPTER 1

## WATER USE, YIELD, AND WATER USE EFFICIENCY OF DIFFERENTIALLY IRRIGATED ALFALFA

# ABSTRACT

Yield, water use, and water use efficiency (WUE) of 'Cody' alfalfa (Medicago sativa L.) grown with seven levels of irrigation (treatments were 0, 25, 50, 75, 100, 125, 150 mm per irrigation) were evaluated during the years 1980, 1981, and 1982. The water content of the soil was measured at about 10 day intervals during the growing seasons with a neutron probe. Crop yields were determined by harvesting three, 1 m x 1 m, samples in the proximity of the neutron access tubes in each plot. The samples were oven dried (7 days at 70 $^{o}$C) and reported on a dry matter basis.

Irrigation contributed significantly to the production of alfalfa in the droughty year of 1980, and yields were proportional to water use. In the wetter years of 1981 and 1982, the effect of irrigation on crop yield was less apparent. Even with irrigation, the yield of alfalfa was less in 1980 than in either 1981 or 1982. The WUE of alfalfa grown in 1980 averaged 127 kg $ha^{-1}$ $cm^{-1}$, 221 kg $ha^{-1}$ $cm^{-1}$ in 1981, and 176 kg $ha^{-1}$ $cm^{-1}$ in 1982. During all years of the study, WUE declined with irrigation amount.

# INTRODUCTION

Plant growth in semiarid regions of the western United States is limited more by water than by any other factor (Hide, 1954). In Kansas, annual lake evaporation may exceed 1300 mm while annual precipitation amounts range from approximately 400 mm in the western sections of the state to 1000 mm in the south-east portion (Midwest Plan Service, 1977). Alfalfa (Medicago saviva L.) may use water at a rate near the free-water evaporation rate during the growing season (Doss et al., 1964) when water is readily available. Water stress is likely to develop if the alfalfa must rely solely on water that is stored in the soil when the crop is dormant and on precipitation that is received during the growing season.

Water use efficiency (WUE) in the present study is defined as the above ground dry matter (kg $ha^{-1}$) divided by water use (cm). WUE is an attribute of the plant and its environment. In examining the water-plant relationship of several forage species commonly grown in Wyoming, Fairbourn (1982) reported greater water use by alfalfa than by the pasture and range grass species tested. While the alfalfa varieties used greater amounts of water, its water use efficiency was not, in most instances, significantly different from the grass species. The plants were grown in containers in a greenhouse and harvested four times. As part of the experiment, the containers were moved to the field and the plants were allowed to grow under field conditions. The water use efficiency of all the forage species declined when they were moved from the greenhouse to the field, and for alfalfa the ratio declined from 143 to 75 kg $ha^{-1}$ $cm^{-1}$. The change in WUE was ascribed to the added complexity of the field environment with such factors as wind, solar radiation intensity, lower air temperatures, and lower relative humidity.

In Nebraska, Daigger et al. (1970) reported that overall 86 kg of alfalfa dry matter was produced per centimeter of water used. With three cuttings annually, the alfalfa used water more efficiently during the first cutting (104 kg $ha^{-1}$ $cm^{-1}$) than succeeding harvests in July and August (89 and 65 kg $ha^{-1}$ $cm^{-1}$ for the second and third harvests, respectively). Values calculated from data presented by Bauder et al. (1978) in North Dakota, by Sammis (1981) in New Mexico, and by Donovan and Meek (1983) in California were 164, 120, and 108 kg $ha^{-1}$ $cm^{-1}$, respectively.

Where limited resources restrict the expansion of irrigated agriculture, the efficient use of water is important. Several investigators working with suboptimally irrigated alfalfa have reported forage production to be a linear function of water use (Bauder et al., 1978; Hanks et al., 1969; Metochis, 1980; Guitjens, 1982). Since the stomata are avenues of transport for water vapor and carbon dioxide, the processes of photosynthate production and transpiration are closely linked (Hsiao and Acevedo, 1974). When water stress develops, the stomatal aperture constricts to prevent plant desiccation and photosynthate production and transpiration are reduced. Waggoner (1966) likened the flux of gaseous diffusion to a series of conductors. He proposed that WUE might be improved by increasing the diffusive resistance to transpiration relative to the resistance to $CO_2$ diffusion. The argument was that since $CO_2$ and water vapor share similar paths, but $CO_2$ also has mesophyll resistance, reductions in transpiration due to increased stomatal resistance would increase the resistance to water loss more than the resistance to $CO_2$ uptake. He cited evidence involving antitranspirants that confirmed water use was more affected than $CO_2$ assimilation. The mesophyll cells may not represent a significant portion of the resistance to $CO_2$ diffusion, as water molecules and dissolved $CO_2$ penetrate cell membranes rapidly (Salisbury and Ross, 1978). Waggoner's approach to increasing the WUE of crops was, in effect, to change the resistance between the leaf and bulk air by chemically impeding transpiration. Ritchie (1974) and Guitjens (1982) found that limited irrigation, as opposed to full irrigation, improved the WUE of crops. Water may have been used more efficiently because less water was lost by evaporation from the soil surface or by deep percolation. It was suggested that the stomata of water-stressed plants had constricted, thus increasing the resistance to water loss.

Hsiao and Avedeco (1974) reported that transpiration and $CO_2$ uptake are proportional to potential gradients from within the leaf to the bulk air and are inversely proportional to the resistance to the fluxes of these gases. Carbon dioxide concentrations of the atmosphere remain constant over short periods of time; however, atmospheric water vapor concentration is subject to more variation. Maximov (1929) studied environmental influences on the WUE of plants and concluded that the amount of water lost by transpiration is proportional to the atmospheric water deficit, but this deficit does not affect the rate of $CO_2$ assimilation, except when the plant is near wilting and stomatal closure occurs. Arkley (1963) studied the relationship between plant growth and transpiration and maintained that an expression involving relative humidity was needed to characterize the yield-ET relationship.

The transpiration stream and $CO_2$ flux are more involved than just concentration gradients. Because photosynthesis and respiration are complex biological processes, they are sensitive to many more variables than the purely physical ones involved in the diffusion of gases (Lemon, 1966).

The effect of evaporation directly from the soil surface on the yield-ET relationship is not clearly understood, but evaporation may constitute a relatively large portion of the overall water use. Fairbourn (1982) found evaporation to be 34% of the total water use by alfalfa grown in containers. Hanks (1983) reasoned that since alfalfa covers the ground during most of the growing season and thus limits the amount of energy incident on the soil surface, the portion of ET that is evaporation is small. In simulating crop development and water use, Hanks had noted that when irrigation was applied frequently, yield was lower for a given water use than when irrigation was applied less frequently. He postulated that the difference was caused by more water being lost by evaporation from the soil surface when irrigation was more frequent.

In New Mexico, Sammis (1981) irrigated alfalfa with a range of water levels in a line source irrigation experiment and found yield and ET increased with irrigation amount. Further, he concluded, that yield increased linearly with ET. Based on data from five locations within the state, Sammis observed that the yield-ET relationship appeared to be transferable to different locations in New Mexico and was also statistically the same as the yield-ET relationship for Nevada, Nebraska, and North Dakota. He reasoned that this relationship might be utilized by resource planners to determine the impact of various water allocation decisions. Stewart and Musick (1982) studied the relationship between crop yields and water use and concluded that when yields were transpiration limited, strong linear correlations were found. However, when the relationship was found to be curvilinear, the nonlinearity was most pronounced at the higher evapotranspiration levels. They deduced that some of the water was not being used for productive purposes, but rather was being lost by deep drainage.

Hanks and Rasmussen (1983) argued that the yield-ET relationship is site specific and does not account for different climatic conditions. In an earlier publication, Hanks (1974) had described a model relating crop yield to water use. Water lost by evaporation from the soil surface and by deep percolation are incorporated into the model to distinguish evaporation from transpiration. A basic assumption of the model is that transpiration is the predominate factor influencing plant growth. For a given crop and year, the relation of relative transpiration to relative yield can be expressed as $Y/Yp=B(T/Tp)$ where Yp is potential yield (Y=actual yield) when transpiration (T) is equal to potential transpiration (Tp). B is the potential crop growth rate and is dependent on the type of crop grown and climate. The model attempts to take into account different climate and soil factors. It implies that reductions in yield are proportional to reductions in transpiration, when insufficient quantities of soil water inhibit growth. The fraction of actual to potential growth could be multiplied by the potential growth rate to determine the daily estimate of plant growth. These daily estimates are then summed to predict total dry matter production under deficit irrigation.

Although alfalfa has been irrigated for some time on the Great Plains, information on the water requirement of this crop is incomplete. The objective of this experiment was to determine the yield and water use of differentially irrigated alfalfa and to determine if yield could be described by water use.

# MATERIALS AND METHODS

The irrigation experiment with 'Cody' alfalfa was conducted during the growing seasons of 1980, 1981, and 1982 at the Evapotranspiration Research Site located 3 km southwest of Manhattan, Kansas. The geographic position of the site is 39 degrees north latitude and the elevation is 325 m above mean sea level.

Though subject to much variation, the normal annual precipitation for the area is 800 mm. Three-fourths of this amount is expected during the months of April through September in the form of convective storms. Since 1858, annual precipitation has ranged from 380 mm in 1860 to 1530 mm in 1951. The winters are cold and the length of the 0 °C frost-free period is approximately 178 days (Bark, 1959).

During the experiment, precipitation amounts were recorded at the research site and meteorological data (solar radiation and minimum and maximum air temperature) were provided by the Department of Physics, Kansas State University, from files held in the Climatalogical Library.

The soil is described by Jantz (1975) as the Eudora series, consisting of deep, nearly level soils that formed in coarse, silty alluvium on low terraces along the Kansas River . This soil is classified as a Fluventic Hapludoll. It is mixed, mesic, and is well drained.

The water holding capacity of the soil is approximately 0.24 $m^3m^{-3}$. Field capacity (0.32 $m^3m^{-3}$) was approximated from neutron probe readings taken 2 days after an irrigation and the lower limit of plant available soil water (0.08 $m^3m^{-3}$ at -1.5 MPa soil water potential) was determined by Anderson et al. (1982).

The experimental area was leveled and a grid of dikes were constructed prior to the seeding of 'Cody' alfalfa in 1978. Cody is a variety of alfalfa that was developed to resist spotted alfalfa aphids (Therioaphis maculata) (Sorensen et al., 1961). This variety initiates growth early in the spring, grows erect, recovers rapidly after cutting and has medium sized stems.

The experimental design was a randomized, complete-block design in which irrigation level was the only controlled variable. Seven irrigation treatments (six irrigation levels and one nonirrigated) were replicated six times. The treatments were 0, 25, 50, 75, 100, 125, and 150 mm per irrigation. Each of the 42 plots measured 9 m x 9 m and the field was bordered by 6 m of alfalfa.

Water was delivered to the alfalfa plots with 200 mm diameter gated surface pipe positioned on the dike. The depth of water applied to each plot was gauged with a meter stick and the field was irrigated following each harvest (Table 1.1).

Soil water was measured in the spring, before harvest time, after each irrigation, and at 7 to 10 day intervals between each harvest. The surface (75 mm) soil water content was measured gravimetrically and the volumetric soil water content was obtained by multiplying the water content by mass by the dry bulk density (1.4 Mg $m^{-3}$). The subsurface (0.075 m to 3.12 m) water content was determined with one of three neutron moisture meters (Troxler, Model 3601). Different probes had to be used because of maintenance problems. To have comparable calibrations for the probes, several access tubes were read with all instruments and the count ratios regressed to predict the count ratio of one probe taken as a reference. One aluminum neutron access tube was installed in the center of each plot. These tubes were capped and remained in the soil for the entire experimental period (3 years). The neutron source was lowered in 150 mm increments to a depth of 3.12 m and scaler counts of 15 seconds at each depth were taken.

The volumetric water content of each soil layer was multiplied by the layer thickness and summed together to obtain total profile water. Water use was calculated from a water budget in which the change in soil water over a given time period was added to the precipitation received. Evapotranspiration (ET) rates (mm $day^{-1}$) were obtained by dividing the water used by the number of days between probing dates. Deep percolation was assumed negligible and runoff was prevented. Soil water was measured after the field was irrigated so irrigation did not enter into the water balance.

The dry matter yield of alfalfa was determined by harvesting three samples, 1 m x 1 m, in the proximity of the neutron access tube in each plot at 10% bloom. The samples were oven dried (7 days at 70 °C) and weighed. The water use efficiency of the above ground alfalfa dry matter production was calculated by dividing the dry matter yield (kg $ha^{-1}$) by the water used (cm).

Statistical interpretations were facilitated using SAS (1974). An analysis of variance was performed on dry matter yield and water use data to test whether treatment means were significantly different. Regression analyses were performed to determine the form of the relationship between the amount of applied water and evapotranspiration, applied water and yield, and mean soil water content and yield. To determine if yield was related to water use, correlation analysis was used.

# RESULTS AND DISCUSSION

Alfalfa was harvested four times in each of the 3 years of the study (1980-1982): in late May, early July, early to mid August, and mid September (Table 1.1). The effect of irrigation on the dry matter yield of alfalfa was primarily dependent on the amount and distribution of precipitation received. Figure 1.1 shows the soil water content (3.12 m soil profile) of the nonirrigated and 150 mm irrigation treatment for each of the 3 years of the study. The year of 1980 was comparatively dry and evapotranspiration (ET) exceeded precipitation and irrigation. As a result, a net reduction of soil water occurred during the growing season regardless of irrigation treatment. Drought stress may have occurred at later stages of vegetative growth in the treatments receiving higher levels of water as the applied water was depleted following each irrigation. Seasonal precipitation amounts (Fig. 1.2) in 1981 and 1982 were 2.5 and 2.1 times that received in 1980 (263 mm). Monthly precipitation amounts were below normal during all the months alfalfa was grown in 1980; 2 of the 6 months in 1981; and 3 of the 6 months in 1982. ET approximated precipitation during the summers of 1981 and 1982, so irrigation was added to storage and increased soil water reserves.

Higher than normal temperatures had accompanied the drought in 1980 (Fig. 1.3). June, July, and August temperatures averaged 2.6 $^{o}$C above the normal in 1980 and

0.5 and 1.0 °C below the normal temperature for the same period in 1981 and 1982, respectively.

Irrigation had contributed significantly to the production of alfalfa in 1980. The yield results (Table 1.2) show that in 1980 the application of 25 mm of water per irrigation increased the average dry matter yield of alfalfa by 40% (0.59 Mg $ha^{-1}$) as compared to the nonirrigated treatment yield of 1.48 Mg $ha^{-1}$. Irrigation of 150 mm per irrigation increased the yield of alfalfa by 1.01 Mg $ha^{-1}$ or 68% more than the rainfed. These results show marked improvement of yield with limited irrigation under drought stress, an important consideration where resources are limiting.

Irrigation was most effective in 1980 during mid summer (representing the 3rd harvest) when the addition of 150 mm of water increased yield from 1.06 Mg $ha^{-1}$ for the rainfed treatment to 2.27 Mg $ha^{-1}$, an increase of 114%. Figure 1.4 shows the effect of low water availability on the dry matter yield of alfalfa during this harvest. The graph shows that the yield potential can be sustained if the average soil water content is maintained at a level greater than approximately 0.14 $m^3m^{-3}$. At 0.14 $m^3m^{-3}$, about 25% of the available soil water is present. Ritchie (1973) reported 80% of the extractable water to be freely available to corn roots. Low amounts of available water were also present for plant growth in the spring of 1981 prior to the first irrigation (mean soil water content=0.11 $m^3m^{-3}$) and conditions were conducive for an alfalfa weevil outbreak. Even with the severe insect damage and meager water supplies, the average yield of alfalfa was 2.45 Mg $ha^{-1}$, 0.45 Mg $ha^{-1}$ more than the average yield attained in mid and late summer in 1980. The effect of low water availability was less detrimental to dry matter production in early 1981 as compared to mid and late summer of 1980, possibly as a result of lower potential ET rates. The average ET rates of irrigated alfalfa during the August and September harvests in 1980 were 8.27 mm $day^{-1}$ compared with 3.17 mm $day^{-1}$ for the May harvest in 1981. Higher yields are attainable in the spring and Daigger et al. (1970) suggested that adequate soil water should be available during this time since the most forage is produced with the least amount of water.

Figure 1.5 shows the water depletion pattern of irrigated (150 mm treatment) and nonirrigated alfalfa during mid summer in 1980. For the period 23 June to 10 July, the depletion of soil water to a depth of 2.36 m was 157 mm by the irrigated treatment and 76 mm by the rainfed treatment. From the depths between 2.36 m and 3.12 m, the depletion was statistically similar, although 8 mm was depleted by the nonirrigated treatment and 1 mm was depleted by the irrigated treatment. Water use from this layer accounted for 11% of the water depleted by the nonirrigated and less than 1% of the water removed by the irrigated treatment. Hobbs (1953) determined that alfalfa was able to deplete water to depths of 5.5 m. However, Janson (1976) acknowledged that roots penetrating great depths are essentially survival organs and are largely irrelevant in terms of an irrigation program.

Table 1.3 shows that the mean WUE of alfalfa was lower in 1980 (127 kg $ha^{-1}cm^{-1}$) than in either 1981 or 1982 (221 and 176 kg $ha^{-1}cm^{-1}$, respectively). This may have been a response to temperatures above 30 $^{o}$C, the upper limit for optimal growth (Doorenbos and Kassam, 1979). Daily maximum temperatures exceeded 30 $^{o}$C for 101 of the days alfalfa was grown in 1980 and only 57 and 58 of the days in 1981 and 1982, respectively. For the 2nd, 3rd, and 4th harvests of each year of the study, alfalfa consumed water at a greater rate in 1980 than in either 1981 or 1982 (7.17 mm $day^{-1}$ compared to 4.61 and 5.43 mm $day^{-1}$, respectively). The alfalfa also produced less dry matter during these harvests (2.20 Mg $ha^{-1}$ in 1980; 3.31 Mg $ha^{-1}$ in 1981; 3.09 Mg $ha^{-1}$ in 1982). The combination of high potential ET and low yields in 1980 resulted in low WUE.

The WUE was negatively related to ET (Fig. 1.6) for each year of the study. These results contradict those of Carter and Sheaffer (1983). This inconsistency may be due to different irrigation management practices, severity of stress, or to the geographic position of the site. Guitjens (1982) had found that alfalfa used water more efficiently under soil water stress; however, he recognized that producing higher yields would require a shortening of the duration of stress when soil water deficits reduced ET.

In general, temperature determines the rate of crop growth and development (Doorenbos and Kassam, 1979), and consequently affects the length of the total growing period. In this study, higher temperatures had resulted in more rapid maturation and more frequent harvests. The thermal units required to produce a cutting was similar, as evidenced by the similar number of degree-days (GDD) for each harvest (Table 1.1). The mean GDD for the harvests was 688.3 as calculated with a threshold temperature of 5 $^{o}$C (Doorenbos and Kassam, 1979) and a standard deviation of approximately 3 days was found.

Yield and ET increased curvilinearly with irrigation amount (Fig. 1.7). The results show that the plants were not able to utilize all the applied water for productive purposes with the higher irrigation treatments, and water was added to storage or lost by deep percolation.

To determine if yield was related to ET, linear correlation analyses were performed using treatment means of the yield-ET data from each harvest. The regression results are presented in Table 1.4. The highest correlations were attained under the drought conditions experienced in 1980. For the second and third harvests in 1980, 85 and 77% of the variation in yield could be attributed to water use. In 1981 and 1982, water was not a major factor limiting the yield of alfalfa and low correlations were attained.

To normalize the yield-ET data, the data were transformed to relative values by expressing each as a fraction of the maximum yield and its associated water use. Values used represent the per harvest average for each year. The results are plotted in Fig. 1.8. Normalizing the data forced the different years to converge and improved the relationship between yield and ET. The relationship illustrates how alfalfa yield is affected by deficit irrigation; however, to make the relationship useful for prediction purposes, some estimator of potential yield must be devised. The efficiency by which alfalfa was able to utilize water resources differed from year to year.

When water was a major factor limiting the yield of alfalfa, e.g., 1980, the variation in yield was attributable to water use. Hanks et al.(1969) observed that where water was not limiting, plant growth was strongly related to weather factors. In the wet year of 1982, the two harvests prior to July (harvests 1 and 2) averaged 4.06 Mg $ha^{-1}$. Maximum temperatures exceeded 30 $^{o}C$ during 22 of the 30 days that alfalfa was grown in July and August, and average yield declined to 2.77 Mg $ha^{-1}$. Alfalfa yield was also low (2.41 Mg $ha^{-1}$) following the fall growth period. Minimum temperatures had fallen below 10 $^{o}C$ during 6 of the days in the growing period. The optimal temperature for growth is about 25 $^{o}C$ and growth decreases sharply when temperatures are above 30 $^{o}C$ and below 10 $^{o}C$ (Doorenbos and Kassam, 1979). Low yields late in the growing season were also reported by Carter and Sheaffer (1983), and they attributed this response to low temperatures that resulted in increased partitioning of assimilates to roots. The reduced fall yields were evident in 1981 and 1982, but not in 1980. A possible explanation is that in 1980 the alfalfa was recovering from severe drought stress. For all years inclusive, alfalfa produced the most forage early in the season, 3.30 Mg $ha^{-1}$ for the first harvest and 3.33 Mg $ha^{-1}$ for the second harvest, and less forage during the mid summer and fall harvests, 2.76 and 2.50 Mg $ha^{-1}$, respectively.

# CONCLUSIONS

The results of this study show that drought stress can affect alfalfa dry matter production at any time in the growing season. In the dry, hot summer of 1980, irrigation contributed significantly to the production of alfalfa and yields were proportional to water use. Even with irrigation, the yield of alfalfa was lower in 1980 than in either 1981 or 1982. The higher temperatures in 1980 as compared to 1981 and 1982 had resulted in more rapid maturation and more frequent harvests, because the thermal units required to produce a harvest were similar. The low yields and high water use associated with the drought in 1980 resulted in low WUE. During all 3 years of the study, WUE declined with irrigation amount.

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Table 1.1. Yield-sampling, field-harvesting, and irrigation dates. Growing degree days (GDD) were calculated using a base temperature of 5 $^0$C and extended from date field was harvested (machine) to date of yield sampling.

| Year | Cutting | Date: Sampling | Date: Machine | Date: Irrigation | Growing Degree Days |
|---|---|---|---|---|---|
| 1980 | 1st | --------+ | 3 June | -------‡ | ----* |
| | 2nd | 8 July | 11 July | 13 June | 764.0 |
| | 3rd | 6 Aug. | 7 Aug. | 14 July | 653.6 |
| | 4th | 6 Sept. | 8 Sept. | 11 Aug. | 692.2 |
| 1981 | 1st | 16 May | 26 May | ------- | ----- |
| | 2nd | 29 June | 6 July | 4 June | 644.7 |
| | 3rd | 5 Aug. | 9 Aug. | 8 July | 654.2 |
| | 4th | 18 Sept. | 18 Sept. | 11 Aug. | 673.1 |
| 1982 | 1st | 18 May | 21 May | ------- | ----- |
| | 2nd | 9 July | 16 July | ------⌘ | 812.5 |
| | 3rd | 16 Aug. | 18 Aug. | 19 July | 665.0 |
| | 4th | 24 Sept. | 26 Sept. | 24 Aug. | 635.0 |
| Mean GDD | | | | | 688.3 |
| Standard Deviation | | | | | 60.3 |

+ Yield samples not collected for this cutting.
‡ Field was irrigated following the 1st cutting of each year.
* Data insufficient to calculate GDD for spring growth.
⌘ Precipitation had prevented irrigation for the 2nd cutting in 1982.

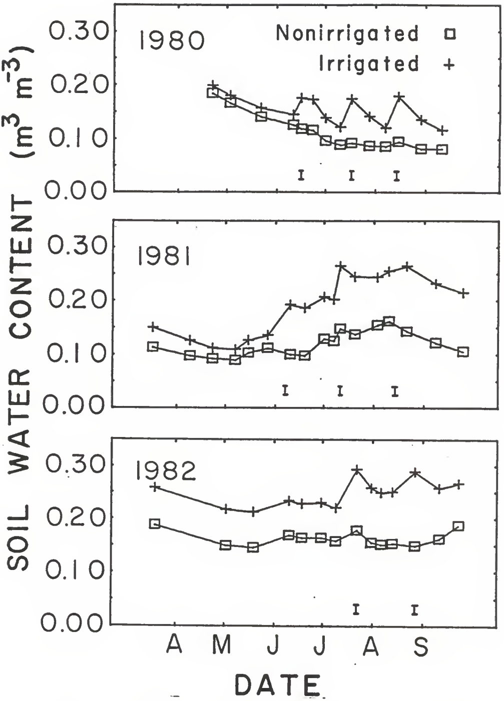


Fig. 1.1. Water content of the 3.12 m soil profile for the nonirrigated and irrigated (150 mm) treatments over time for 1980, 1981, and 1982. The abbreviation (I) shows the dates of irrigation.

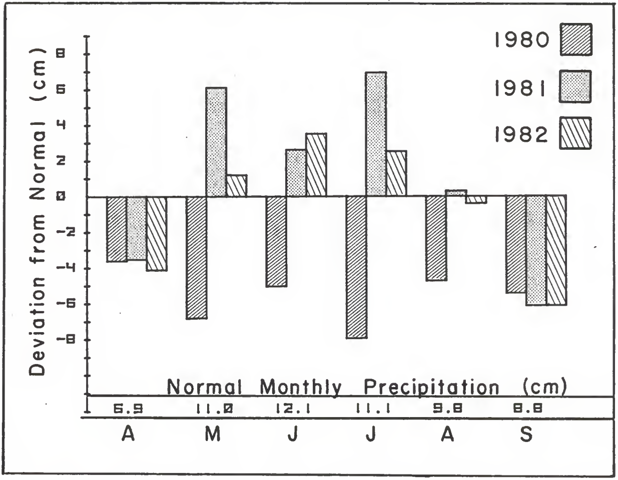


Fig. 2.1. Normal monthly precipitaion for the months Apr.-Sept. and the deviation from normal experienced in 1980, 1981, and 1982.

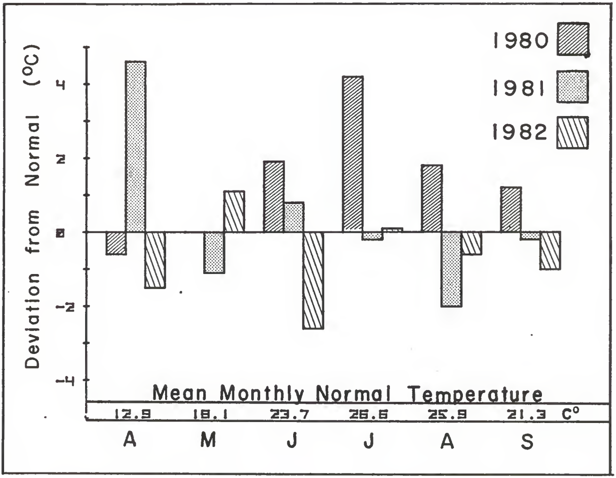


Fig. 1.3. Normal monthly temperature for the months Apr.-Sept. and the deviation from normal experienced in 1980, 1981, and 1982.

Table 1.2. Effect of different levels of irrigation on the dry matter yield of alfalfa (Mg ha$^{-1}$).

| Year | Cutting | Irrigation amount (mm) 0[+] | 25 | 50 | 75 | 100 | 125 | 150 | Mean |
|---|---|---|---|---|---|---|---|---|---|
| 1980 | 1st | ----[‡] | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | 2nd | 2.08b | 2.60ba | 2.50ba | 2.82b | 2.69ba | 2.83b | 2.72b | 2.61 |
| | 3rd | 1.06b | 1.81a | 1.95a | 2.29a | 2.12a | 2.05a | 2.27a | 1.94 |
| | 4th | 1.30c | 1.80b | 2.09ba | 2.32a | 2.13ba | 2.41a | 2.47a | 2.07 |
| | Total | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | Mean | 1.48 | 2.07 | 2.18 | 2.48 | 2.31 | 2.43 | 2.49 | 2.21 |
| 1981 | 1st | 2.28a | 2.31a | 2.65a | 2.38a | 2.50a | 2.32a | 2.74a | 2.45 |
| | 2nd | 3.15b | 3.35a | 3.38a | 3.36a | 3.36a | 3.42a | 3.46a | 3.35 |
| | 3rd | 3.51a | 3.58a | 3.54a | 3.48a | 3.65a | 3.61a | 3.60a | 3.57 |
| | 4th | 2.96a | 2.94a | 3.07a | 3.01a | 3.11a | 2.97a | 3.08a | 3.02 |
| | Total | 11.90 | 12.18 | 12.64 | 12.23 | 12.62 | 12.32 | 12.88 | |
| | Mean | 2.98 | 3.05 | 3.16 | 3.06 | 3.16 | 3.08 | 3.22 | 3.10 |
| 1982 | 1st | 4.21a | 3.99a | 4.15a | 3.83a | 4.07a | 4.16a | 4.18a | 4.18 |
| | 2nd | 4.21a | 4.07a | 4.14a | 4.02a | 3.99a | 4.15a | 4.08a | 4.09 |
| | 3rd | 2.68a | 2.94a | 2.74a | 2.83a | 2.74a | 2.74a | 2.69a | 2.77 |
| | 4th | 2.26b | 2.39a | 2.49a | 2.43a | 2.42a | 2.39a | 2.48a | 2.41 |
| | Total | 13.36 | 13.39 | 13.52 | 13.11 | 13.22 | 13.44 | 13.43 | |
| | Mean | 3.34 | 3.35 | 3.38 | 3.28 | 3.31 | 3.36 | 3.36 | 3.36 |

[+] Treatment effects significantly different at the 0.05 level only if followed by different letters. Duncan's multiple range test was used.

[‡] Yield samples not taken for 1st cutting.

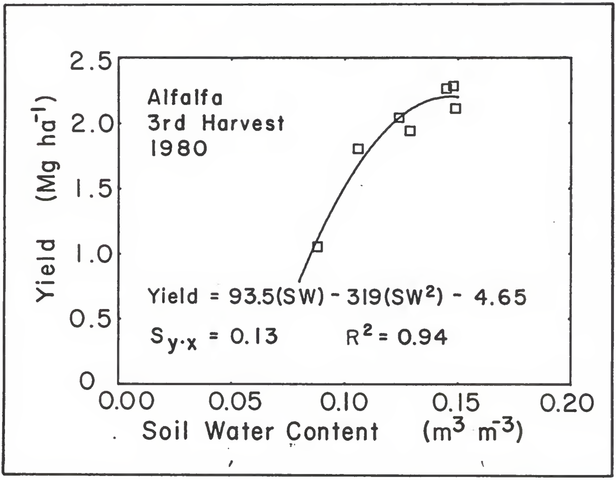


Fig. 1.4. Relationship between alfalfa dry matter yield and mean soil water content averaged over the 3rd harvest in 1980.

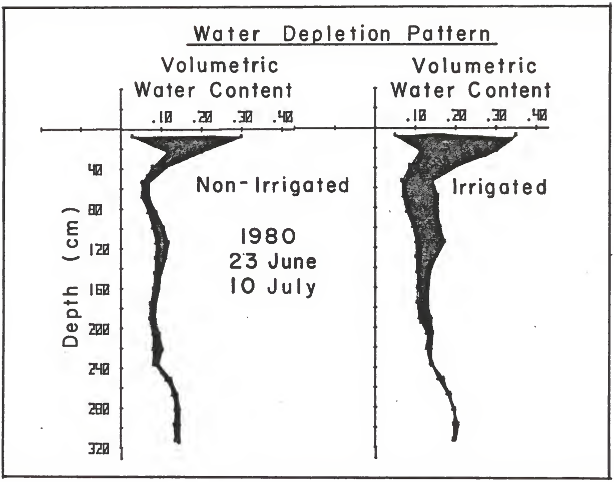


Fig. 1.5. Depletion of soil water to a depth of 3.12 m by nonirrigated and irrigated (150 mm treatment) alfalfa between 23 June and 10 July in 1980.

Table 1.3. Effect of irrigation on the water-use-efficiency of alfalfa (kg ha$^{-1}$ cm$^{-1}$).

| | | Irrigation amount (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | cutting | 0+ | 25 | 50 | 75 | 100 | 125 | 150 | Mean |
| 1980 | 1st | ---‡ | --- | --- | --- | --- | --- | --- | --- |
| | 2nd | 147b | 145b | 120ab | 133b | 93a | 127b | 126b | 127 |
| | 3rd | 238c | 158bc | 105ab | 110ab | 92a | 117ab | 121ab | 134 |
| | 4th | 181c | 133bc | 107b | 113b | 80a | 100ab | 112b | 118 |
| | Mean | 189 | 145 | 111 | 119 | 88 | 115 | 120 | 127 |
| 1981 | 1st | 142a | 135a | 147a | 130a | 128a | 125a | 134a | 134 |
| | 2nd | 626b | 328a | 315a | 381ab | 268a | 263a | 385ab | 367 |
| | 3rd | 252b | 222b | 230b | 230b | 208b | 205b | 167a | 216 |
| | 4th | 180a | 204a | 135a | 177a | 171a | 152a | 154a | 168 |
| | Mean | 300 | 222 | 207 | 230 | 194 | 186 | 210 | 221 |
| 1982 | 1st | 175a | 160a | 184a | 156a | 166a | 166a | 167a | 168 |
| | 2nd | 184a | 177a | 187a | 183a | 168a | 176a | 170a | 178 |
| | 3rd | 170a | 174a | 149a | 158a | 144a | 133a | 126a | 151 |
| | 4th | 378e | 217d | 203cd | 178bcd | 166abc | 153ab | 146a | 206 |
| | Mean | 227 | 182 | 181 | 169 | 161 | 157 | 152 | 176 |

+ Treatment effects significantly different at the 0.05 level only if followed by different letters. Duncan's multiple range test was used.

‡ Yield samples not taken for 1st cutting.

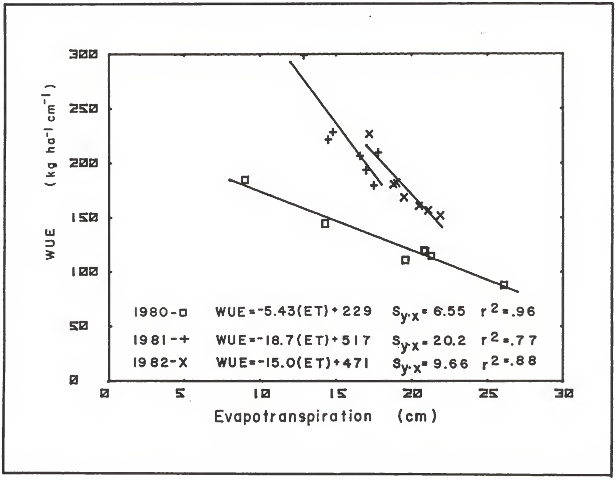


Fig. 1.6. Relationship between the water use efficiency of alfalfa and evapotranspiration for 1980, 1981, and 1982. Each point represents a treatment mean expressed on a per cutting basis.

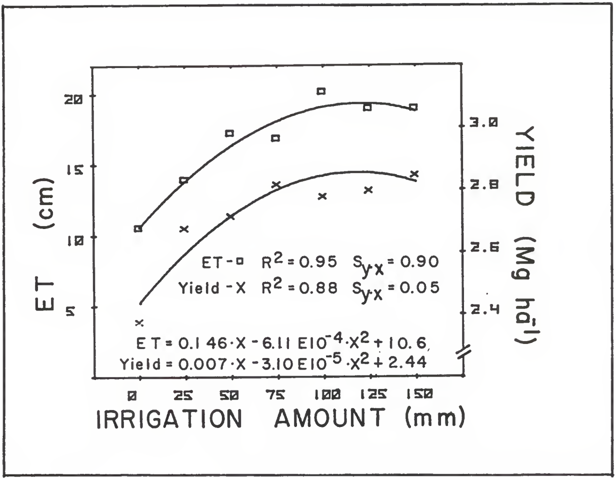


Fig. 1.7. Effect of different levels of irrigation on alfalfa yield and evapotranspiration (ET). Each point is a treatment mean (3 years) expressed on a per cutting basis.

Table 1.4. Yield=A(ET)+B, the regression of yield (Mg $ha^{-1}$) verses evapotranspiration (ET in mm), and the regression coefficients for the slope (A) and the intercept (B).

| Year | Harvest | Number of Observations | $A^{+}$ | B | $F_{value}$ | Coefficient of Determination |
|---|---|---|---|---|---|---|
| 1980 | 1st | - | ------ | ----- | ----- | ----- |
| | 2nd | 7 | 0.0039 | 1.793 | 4.01 | 0.44 |
| | 3rd | 7 | 0.0061 | 0.931 | 28.90 | 0.85* |
| | 4th | 7 | 0.0054 | 1.039 | 16.70 | 0.77* |
| 1981 | 1st | 7 | 0.0089 | 0.821 | 5.18 | 0.51 |
| | 2nd | 7 | 0.0027 | 3.091 | 5.56 | 0.53 |
| | 3rd | 7 | 0.0015 | 3.307 | 3.37 | 0.40 |
| | 4th | 7 | 0.0012 | 2.792 | 1.99 | 0.28 |
| 1982 | 1st | 7 | -0.0041 | 5.073 | 0.42 | 0.08 |
| | 2nd | 7 | -0.0007 | 4.261 | 0.03 | 0.01 |
| | 3rd | 7 | -0.0016 | 3.064 | 0.69 | 0.12 |
| | 4th | 7 | 0.0016 | 2.204 | 6.70 | 0.57* |

+ Equation significant at the 0.05 level ($F_{0.95}$=6.61) only if followed by *.

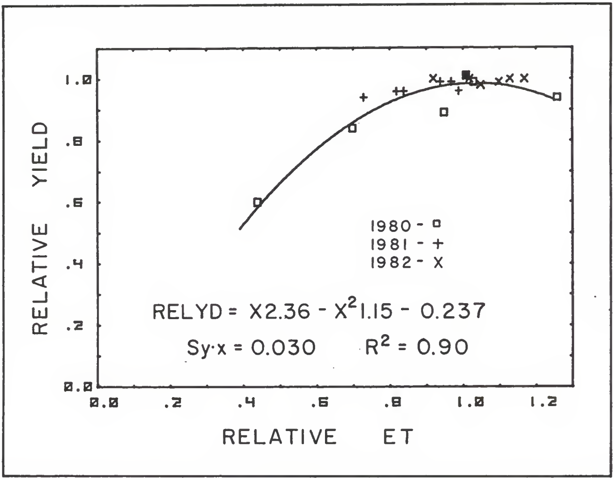


Fig. 1.8. Relative yield versus relative evapotranspiration (ET). The yields were normalized to the highest yield and its associated evapotranspiration for each treatment and year (1980, 1981, and 1982).

# CHAPTER 2

# EVALUATION OF CANOPY TEMPERATURE, STOMATAL RESISTANCE, AND PLANT WATER POTENTIAL OF DIFFERENTIALLY IRRIGATED ALFALFA

# ABSTRACT

Plant water potential, stomatal resistance, and canopy temperature of 'Cody' alfalfa (*Medicago sativa* L.) grown with different levels of irrigation were studied. In 1980, 1981, and 1982, canopy temperature was measured with an infrared thermometer. In 1981 and 1982, stomatal resistance and plant water potential measurements were taken with a stomatal porometer and a pressure chamber, respectively. The water content of the soil was measured at about 10 day intervals with a neutron probe.

The midday canopy temperature of well-watered alfalfa averaged 3.2 °C below the temperature of the air for the 3 years of the study and this difference was found to be correlated with atmospheric water vapor deficit. In 1980, canopy temperature was shown to exceed air temperature when soil water deficits caused plant water stress.

In 1981 and 1982 weather factors were favorable for growth and the stomatal resistance of alfalfa averaged 145 s $m^{-1}$ and the mean leaf water potential was 0.220 MPa. Values similar to those cited in literature for non-water-stressed alfalfa.

In 1982, the stomatal resistance of alfalfa was found to be significantly lower than that of well-watered grain sorghum (*Sorghum bicolor* L. Moench), corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), pinto bean (*Phaseolus vulgaris* L.), sunflower (*Helianthus annuus* L.), and pearl

millet (<u>Pennisetum americanum</u> L.). Although the relationship between stomatal resistance and water use for the different crops was not well established, stomatal resistance and canopy-minus-air temperature were found to be correlated ($r^2$=0.53, P=0.10).

# INTRODUCTION

Plant water deficits occur when transpiration exceeds root absorption. In order to maintain a functional plant water potential when stressed, stomatal movement is one of the primary mechanisms by which the plant exercises control over transpiration (Slayter, 1966). Stomatal closure, as indicated by increased leaf diffusive resistance, is induced as plant water potentials decrease to a threshold value (Hsiao, 1973).

The severity of water deficits on plant growth is influenced by atmospheric factors as well as soil water status. Ritchie (1974) acknowleged that plant growth is controlled directly by water deficits in plants and only indirectly by soil water deficits. Taylor and Haddock (1956) asserted that, as water is removed from the soil, additional energy must be expended by plants to maintain a constant transpiration rate because of decreasing soil water potentials. When plants are subjected to a high evaporative demand, Peters (1960) found growth to be profoundly influenced by soil water potential; however, at low evaporative demands, growth is less affected by soil water potential. Denmead and Shaw (1960) reasoned that since the decline in relative transpiration rate results from a loss of turgor in the plant, the soil water content at which plants wilt will also increase as potential transpiration increases.

The onset of plant water stress is most likely to occur during periods of peak potential transpiration rates during midday. van Bavel (1967) monitored the leaf diffusive resistance of alfalfa (Medicago sativa L.) that was irrigated and then allowed to deplete soil water reserves to -1.5 MPa soil water potential. Stomatal regulation became evident 20 days after the irrigation. The canopy resistance then showed a diurnal course with low values after sunrise, increasing during early afternoon, and then decreasing. With the progression of soil water depletion, the magnitude and duration of stomatal closure increased and the ratio of actual to potential evapotranspiration decreased. Carter and Sheaffer (1983a) showed that at midmorning, well-watered alfalfa offered little diffusive resistance to water loss (30 s $m^{-1}$). At moderate plant water deficits, stomatal resistance was lowest during morning and late afternoon and was highest at midday. Under extreme plant water stress, stomatal resistance remained high the entire day (330 to 1000 s $m^{-1}$).

Hsiao and Acevedo (1974) discussed metabolic and physiological aspects of plant water relations. They emphasized that practically all plant activities could be disrupted by severe water stress; however, some hormonal, enzymatic, or physiological process may be altered in even reasonably well irrigated fields, depending on the sensitivity of that process to water deficit. Cell growth, cell wall synthesis, protein synthesis, and nitrate reductase level were deemed sensitive to moderate water deficits while stomatal opening, $CO_2$ assimilation, and abscisic acid accumulation were less sensitive.

Salisbury and Ross (1978) stated that cell expansion requires that turgor pressure be established in cells by osmosis. When water deficits occur, the plant water pressure potential decreases and cell expansion is inhibited. An adaptive response of plants to water deficits is the alteration of cellular osmotic concentration. Cutler et al. (1977) reported 20 to 60% greater solute concentrations in cotton (Gossypium hirsutum L.) leaves from a nonirrigated treatment than in leaves from a frequently irrigated treatment. In a latter publication, Cutler et al. (1980) reported solute potentials of leaves of conditioned rice (Oryza sativa L.) plants to be 0.3 to 0.5 MPa more negative than plants that had no stress history but were at similar leaf water potential. They observed that turgor was maintained to more negative leaf water potentials in conditioned plants. Thomas et al. (1976) observed a similar osmotic adjustment in drought conditioned cotton and found stomata to remain open at lower leaf water potentials than plants not previously conditioned.

Carter and Sheaffer (1983b) measured leaf water potentials of differentially irrigated alfalfa and found the midday leaf water potential of irrigated alfalfa to range from -0.7 to -1.3 MPa throughout the season. Leaf water potentials attained -2.7 to -4.0 MPa for stressed alfalfa and little growth occurred at potentials of less than -1.5 MPa. Their results showed a close association between forage yield and cumulative leaf water potential.

Ritchie (1974) hypothesized that at the beginning of the day, the leaf and soil water potentials are approximately equal. Following the onset of stress, Hall and Larson (1982) found predawn leaf water potential to decline linearly with soil water potential. Ehrler et al. (1978) found the leaf water potential curves for stressed and nonstressed wheat (Triticum durum L.) paralleled each other; however, the leaf water potential of stressed wheat was more negative and did not return to the predawn value after sunset. This hysteresis effect was also noted in alfalfa by Sharratt et al. (1983), who found hysteresis to be more pronounced in nonirrigated than irrigated alfalfa.

Plant temperature is an indicator of the response of the plant to environmental factors such as radiation, air temperature, relative humidity, wind speed, and soil water availability (Gates, 1964). Transpiration has a cooling effect (Salisbury and Ross, 1978) owing to the high latent heat of vaporization of water. A reduction in the transpiration rate by stressed plants decreases latent heat exchange and plant temperatures increase (Tanner, 1963). Ansari and Loomis (1959) noted that vaseline coated leaves were 1 to 3 $^{o}$C warmer than transpiring leaves. Sumayao et al. (1980) found that when more than 35% of the available soil water had been depleted, corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) leaves lost turgor, stomatal resistance increased, and leaf temperature rose above air temperature because of the reduced transpiration rate. The results of Wiegand and Namken (1966) verify those of Sumayao and colleagues in that variations in plant water stress significantly alter leaf temperature and leaf-minus-air temperature.

Idso et al. (1981) devised a technique of quantifying water stress using an infrared thermometer and a psychrometer. They found that for well-watered alfalfa, canopy temperatures were less than air temperature and that canopy-minus-air temperature was highly correlated with atmospheric saturation vapor pressure deficit (VPD). The degree of stress could be quantified by indexing the well-watered minus drought stressed canopy temperatures with VPD. Idso et al. (1981) had recognized the ability of the infrared thermometer to assess rapidly plant water deficits caused by inadequate soil water reserves.

Alfalfa consumed more water than most other crops (Blad and Rosenberg, 1974; Fritschen, 1967; Fairbourn, 1982). Blad and Rosenberg (1974) found that the ET rate of alfalfa was greater than for a pasture (predominately a mixture of grasses). Further, they found, that alfalfa consumed a large portion of advected sensible heat (ET exceeded the net radiation equivalent) while sensible heat was generated rather than consumed by the pasture (ET was less than the net radiation equivalent). The ET of the pasture was not limited by energy supply but rather by the limiting supply of water. Blad and Rosenberg (1974) surmised that the pasture used less water than the alfalfa because of one or more of the following: greater stomatal resistance, higher root or plant resistance to water movement, a less aerodynamically rough canopy, or because of less biomass (leaf area). Alfalfa offered a low resistance to water vapor diffusion and under favorable soil conditions had a root system that was in contact with a soil volume several times larger than grass (Jensen, 1973).

This study was conducted to characterize the alfalfa water balance, by measuring stomatal resistance, pressure potential, and canopy temperature and to determine if leaf diffusive resistance was a factor contributing to differences in water use between different crops. Canopy temperature measurements taken in 1980 and 1981 were reported by Kirkham et al. (1983). Kirkham et al. (1983) studied the effect of different levels of irrigation on the canopy temperature of alfalfa. In this paper, canopy temperature was compared with soil water content to determine the soil water content at which plant water stress will occur.

# MATERIALS AND METHODS

The experiment was conducted during the summers of 1980, 1981, and 1982 at the Evapotranspiration Research Site, located 3 km southwest of Manhattan, KS. 'Cody' alfalfa was seeded in the fall of 1978. The soil type was Eudora silt loam (coarse-silty, mixed, mesic, Fluventic Hapludoll). The water holding capacity of the upper 1.6 m soil profile was approximately 0.24 $m^3m^{-3}$. Field capacity was approximated from neutron probe readings taken 2 days after an irrigation, and the lower level of plant available, soil water (0.08 $m^3m^{-3}$ at -1.5 MPa potential) was determined by Anderson et al. (1982).

Soil water content was measured at about 10 day intervals with a neutron probe to a depth of 3.12 m in each of the 42 plots in the study area. The water content of the soil surface (76 mm) was determined gravimetrically.

The experimental design was randomized, complete-block. Seven irrigation treatments (0, 25, 50, 75, 100, 125, and 150 mm per irrigation) were replicated six times. Each plot measured 9 m x 9 m and was enclosed in a grid of berms to prevent runoff. The field was irrigated following each harvest.

Stomatal resistance measurements were taken in 1981 and 1982 on fully expanded, sunlit leaves near the apical meristem on six plants from one plot of the nonirrigated and from six plants from one plot of the 150 mm treatment using a stomatal porometer (Delta-T Devices, Mk II, Burwell, England). The mainstem was then excised and transferred to the pressure chamber for water potential determination. Canopy temperature measurements were taken in paired north-south directions at an oblique angle to the cropped surface using an infrared thermometer (Telatemp Corp., Model 44, Fullerton, Calif.). In 1980 and 1981, six paired canopy temperature measurements were taken of each plot. In 1982, the temperature measurements were restricted to the nonirrigated and 150 mm treatments. Psychrometric readings were taken at the beginning and end of each run. Dates that canopy temperature, stomatal resistance, and plant water potential were measured are given in Tables 2.1 and 2.2.

Stomatal resistance, evapotranspiration (ET), and canopy temperature measurements of several row crops that were grown adjacent to the alfalfa experiment in 1982 were compared with the alfalfa measurements. The row crops grown were sorghum, corn, soybean (*Glycine max* L. Merr.), pinto bean (*Phaseolus vulgaris* L.), sunflower (*Helianthus annuus* L.), and pearl millet (*Pennisetum americanum* L.).

Multiple regression analysis (SAS, 1974) was used to quantify the relationship between canopy-minus-air temperature (Tc-Ta) and soil water content when soil water deficits caused plant water stress on 28 July 1980. To strengthen the relationship between (Tc-Ta) and VPD reported by Kirkham et al. (1983) for non-water-stressed alfalfa, (Tc-Ta) and VPD measurements taken in 1982 were combined with measurements taken in 1980 and 1981 using linear regression. A t-statistic was used to compare the stomatal resistance of alfalfa with that of the row crops. Also, t-tests were used to determine if differences due to irrigation treatment existed in canopy temperature, stomatal resistance, and pressure potential of alfalfa.

# RESULTS AND DISCUSSION

Yield results (Table 1.2) showed that irrigation in the wet summers of 1981 and 1982 (precipitation amounts were 658 and 552 mm for the months April-September of 1981 and 1982, respectively) were of little benefit in increasing alfalfa production . Soil water was not a crucial factor limiting yield, and hence, plant water deficits were not readily apparent.

Low precipitation amounts in 1980 (263 mm during the months April-September) resulted in significant yield reductions in the nonirrigated alfalfa treatment. Kirkham et al. (1983) compared canopy temperatures of the different treatments and concluded that irrigated plots had a cooler canopy temperature than did the nonirrigated. It was noted that differences in canopy temperature due to irrigation treatment were not evident. Figure 2.1 is a graph of the canopy temperature minus the temperature of the air (Tc-Ta) versus the soil water content of each plot when high evaporative demand (6.18 kPa atmospheric water vapor pressure deficit) and soil water deficits caused plant water stress (1430 CDT, 28 July 1980). The curve fitted to the data shows that canopy temperature exceeded air temperature (39.4 $^{o}$C) as the soil water content was depleted to below approximately 0.08 $m^3m^{-3}$, the lower limit of plant available, soil water.

In the wet summer of 1981, precipitation approximated evapotranspiration, and consequently, irrigation water was added to the soil water reservoir. Kirkham et al. (1983) concluded that precipitation was adequate for alfalfa growth in 1981 and found no significant treatment differences in (Tc-Ta). While large differences in soil water content were apparent between the nonirrigated and the 150 mm treatment as shown in Fig. 1.1 for the year of 1981, potential ET rates were low and the nonirrigated alfalfa was able to maintain transpiration at the potential rate.

A large amount of soil water was available for plant growth in the wet year of 1982. To determine if differences in (Tc-Ta) existed between the nonirrigated and the 150 mm treatment, a t-test was performed using the treatment means. In general, significant treatment differences were not evident at the 95% level of confidence. Replicated infrared thermometer data taken on 3 August 1982 showed no significant treatment differences to occur early in the day; however, by mid-afternoon (at the 1423 and 1635 CDT sampling times) the irrigated treatment had a significantly cooler canopy temperature (Fig. 2.2). The lack of measurable precipitation in the 12-day period prior to canopy temperature measurements and high ET potential had resulted in slight water deficit; however, yield reductions were not evident between the two treatments. Evapotranspiration averaged 8.6

mm $day^{-1}$ for the nonirrigated treatment compared with 11.4 mm $day^{-1}$ for the irrigated treatment (31 July to 6 August).

The most prominent feature of the canopy temperature measurements was that the temperature of the alfalfa canopy was almost always less than ambient air temperature during the day when soil water was not limiting. The magnitude of the difference in midday (measurements taken between 1100 and 1700 CDT) (Tc-Ta) for non-water-stressed alfalfa averaged -3.2 $^{o}$C for the 3 years of the study and was correlated ($r^2$=0.63) with atmospheric water vapor pressure deficit (Fig. 2.3). The regression equation found, (Tc-Ta)=0.11-1.21(VPD), appeared similar to the regression equation, (Tc-Ta)=0.58-1.96(VPD), presented by Idso et al. (1981).

Stomatal resistance and plant water potential were not measured in the dry year of 1980, so details of the plant response to drought stress are lacking.

Results show that with an essentially unrestricted supply of soil water, alfalfa was able to maintain a high water potential with meteorological conditions conducive for high transpiration potential, i.e., 25 watts per $m^2$ net radiant energy, a -6.5 $^{o}$C difference in canopy-minus-air temperature, and a southerly wind averaging 5.4 m $sec^{-1}$ for the day (from replicated data, 3 Aug. 1982). Differences in stomatal resistance and pressure potential due to irrigation treatment (nonirrigated and 150 mm treatment) failed to be significant at the 95% level of confidence at any sampling time, so the data were combined and reported as a single value for each time (Table 2.1). Figure 2.2 shows the stomatal resistance and plant water potential for several sampling times on 3 August. Leaf diffusion resistance decreased after sunrise as the stomata opened in response to increasing solar radiation. During the day, it appeared that root water absorption and transpiration were approximately equal throughout the day so the plant water potential remained high (-0.25 MPa $\pm$0.12 MPa). The critical water status for stomatal closure was not reached and stomatal resistance remained low (125 s $m^{-1}$ $\pm$34 s $m^{-1}$). Similar values for stomatal resistance and alfalfa water potential were reported by Carter and Sheaffer (1983a and 1983b) for non-water-stressed alfalfa. Further, while the yield of the alfalfa was high, the stems were weak and often resulted in lodging.

The detection of short term drought stress by the infrared thermometer and not by stomatal resistance or plant water potential measurements on 3 August may have occurred because a larger sampling area and more measurements were taken with the portable infrared thermometer than with the stomatal porometer or the pressure chamber.

In 1981 and 1982, stomatal resistance was similarly low. The average stomatal resistance of alfalfa in 1982 was 139 s $m^{-1}$ $\pm$65 s $m^{-1}$, and was significantly less than that of the row crops: corn (735 s $m^{-1}$), grain sorghum (416 s $m^{-1}$), pearl millet (363 s $m^{-1}$), soybean (573 s $m^{-1}$), sunflower (351 s $m^{-1}$), and pinto bean (552 s $m^{-1}$).

It would seem reasonable that crops offering little resistance to the diffusion of water vapor would transpire more water and have lower canopy temperatures than crops with higher stomatal resistance. To examine the correlation between stomatal resistance and crop water use, average stomatal resistance and daily evapotranspiration over a period of 22 days for the alfalfa and 35 days for the row crops were compared. The time periods coincided and were in late July to early August in 1982 when plant cover was complete. Mean daily evapotranspiration was 9.73 mm $day^{-1}$ for the alfalfa and daily water use by the row crops ranged from 6.06 mm $day^{-1}$ for pinto bean to 9.43 mm $day^{-1}$ for sunflower. Values of the stomatal resistance and evapotranspiration of the different crops are presented in Table 3. Subsequent correlation analysis indicated that stomatal resistance is not the only factor determining water use as the correlation coefficient was low ($r^2$=0.22). Leaf area, radiation load, and aerodynamic roughness are also factors that govern water use. Crop canopies exibiting low stomatal resistance tended to be cooler ($r^2$=0.53, P=0.10, Fig. 2.4) than crops exibiting higher stomatal resistance.

# CONCLUSIONS

With the favorable growing conditions experienced in 1981 and 1982, alfalfa offered little resistance to the diffusion of water vapor. The alfalfa was able to maintain a high water potential without stomatal regulation. The alfalfa proved to maintain a lower stomatal resistance than corn, grain sorghum, pearl millet, soybean, sunflower, and pinto bean in 1982. Although alfalfa and sunflower exibited low resistance to the loss of water vapor and high evapotranspiration potential, the relationship between stomatal resistance and evapotranspiration was not firmly established. Stomatal resistance and canopy-minus-air temperature between the different crops was found to be correlated.

Canopy temperature measurements taken with an infrared thermometer show that the temperature of the alfalfa canopy is likely to be less than the temperature of the air during the daytime. Midday canopy temperatures averaged 3.2 $^{o}C$ (1980, 1981, 1982) below air temperature; however, this difference was shown to be correlated with atmospheric water vapor pressure deficit.

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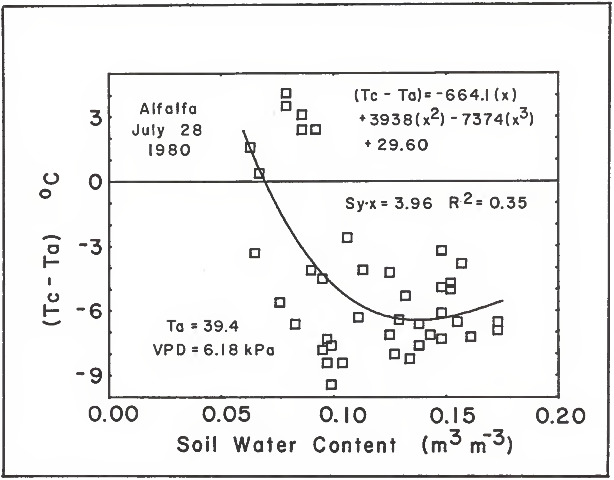


Fig. 2.1. The relationship between soil water content and canopy-minus-air (Tc-Ta) temperature of alfalfa when high evaporative demand and soil water deficits caused plant water stress in 1980. Each point represents the Tc-Ta of one plot.

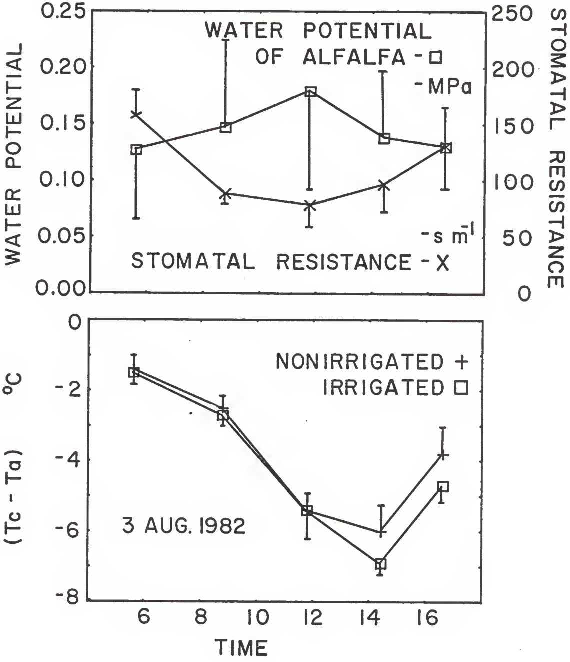


Fig. 2.2. Canopy-minus-air temperature (Tc-Ta), stomatal resistance, and the water potential of alfalfa at several sampling times on 3 Aug. 1982. The plant water potential and stomatal resistance are overall means while Tc-Ta are for the nonirrigated and irrigated (150 mm) treatments. Error bars represent one standard deviation from the mean.

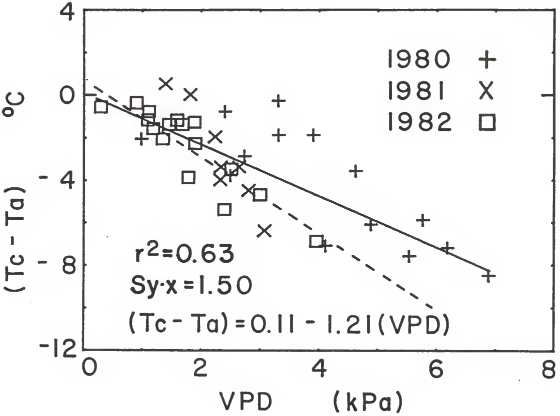


Fig. 2.3. The relationship between canopy-minus-air temperature (Tc-Ta) and atmospheric water vapor pressure deficit (VPD) for non-water-stressed alfalfa. Measurements were taken between 1100 and 1700 CDT in 1980, 1981, and 1982. The dashed line represents the equation presented by Idso et al. (1981) for alfalfa.

Table 2.1. Date and time stomatal resistance and leaf water potential measurements were taken in 1981 and 1982 for alfalfa. Each value is the mean of the irrigated (150 mm) and nonirrigated treatment.

| Date | Time (CDT) | Stomatal Resistance ($s\ m^{-1}$) | Plant Water Potential MPa |
|---|---|---|---|
| 810827 | 1400 | 121 | 0.203 |
| 810830 | 830 | 148 | 0.153 |
| 810830 | 1135 | 105 | 0.146 |
| 810830 | 1400 | 171 | 0.202 |
| 810909 | 1300 | 127 | 0.275 |
| 810917 | 1100 | 244 | 0.200 |
| 811005 | 1100 | 155 | 0.277 |
| 820616 | 810 | 47 | 0.259 |
| 820616 | 910 | 83 | 0.253 |
| 820616 | 1040 | 152 | 0.380 |
| 820616 | 1125 | 258 | 0.185 |
| 820616 | 1240 | 247 | 0.223 |
| 820616 | 1350 | 125 | 0.143 |
| 820616 | 1450 | 196 | ----- |
| 820616 | 1600 | 306 | 0.312 |
| 820629 | 645 | --- | 0.085 |
| 820629 | 735 | 89 | 0.108 |
| 820629 | 835 | 74 | 0.133 |
| 820629 | 920 | 94 | 0.173 |
| 820629 | 1026 | 133 | 0.386 |
| 820629 | 1126 | 120 | 0.450 |
| 820629 | 1259 | 131 | 0.158 |
| 820629 | 1400 | 125 | 0.240 |
| 820629 | 1529 | 152 | 0.294 |
| 820629 | 1635 | 137 | 0.350 |
| 820629 | 1755 | 194 | 0.314 |
| 820803 | 644 | 151 | 0.128 |
| 820803 | 935 | 89 | 0.148 |
| 820803 | 1210 | 79 | 0.180 |
| 820803 | 1510 | 97 | 0.139 |
| 820803 | 1700 | 131 | 0.131 |

Table 2.2. Date and time of infrared thermometer readings. Canopy temperature (Tc), temperature of air (Ta) and canopy-minus-air-temperature (Tc-Ta) for non-water-stressed alfalfa.

| Date YMD | Time (CDT) | Tc $C^o$ | Ta $C^o$ | (Tc-Ta) $C^o$ | VPD kPa |
|---|---|---|---|---|---|
| 800624 | 1430 | 30.7 | 33.6 | -2.9 | 2.73 |
| 800627 | 1335 | 32.6 | 41.1 | -8.5 | 6.88 |
| 800701 | 1330 | 31.3 | 38.9 | -7.6 | 5.53 |
| 800722 | 1420 | 29.4 | 29.7 | -0.3 | 3.30 |
| 800728 | 1520 | 32.2 | 39.4 | -7.2 | 6.18 |
| 800801 | 1400 | 33.3 | 39.2 | -5.9 | 5.76 |
| 800818 | 1200 | 32.0 | 33.9 | -1.9 | 3.31 |
| 800819 | 1417 | 32.8 | 34.7 | -1.9 | 3.90 |
| 800820 | 1345 | 30.0 | 30.8 | -0.8 | 2.40 |
| 800825 | 1320 | 30.6 | 36.7 | -6.1 | 4.88 |
| 800826 | 1100 | 27.4 | 34.4 | -7.1 | 4.11 |
| 800827 | 1200 | 22.3 | 24.4 | -2.1 | 0.98 |
| 800829 | 1500 | 32.0 | 35.6 | -3.6 | 4.62 |
| 800902 | 1230 | 27.3 | 31.1 | -3.8 | 2.49 |
| 810609 | 1500 | 32.2 | 36.6 | -3.4 | 2.33 |
| 810617 | 1100 | 21.6 | 26.1 | -4.5 | 2.80 |
| 810624 | 1530 | 28.3 | 34.7 | -6.4 | 3.07 |
| 810713 | 1010 | 29.0 | 33.1 | -4.1 | 2.53 |
| 810818 | 1540 | 23.9 | 23.9 | 0.0 | 1.81 |
| 810821 | 1530 | 24.7 | 28.1 | -3.4 | 2.64 |
| 810827 | 1500 | 24.4 | 23.9 | 0.5 | 1.39 |
| 810829 | 1130 | 25.4 | 29.4 | -4.0 | 2.32 |
| 810908 | 1141 | 22.5 | 24.4 | -2.0 | 2.23 |
| 820629 | 0645 | 16.4 | 18.3 | -1.9 | 0.00 |
| 820629 | 0735 | 21.7 | 20.4 | 1.3 | 0.04 |
| 820629 | 0835 | 23.1 | 22.0 | 1.1 | 0.11 |
| 820629 | 0920 | 25.3 | 24.5 | 0.8 | 0.47 |
| 820629 | 1026 | 26.9 | 26.0 | 0.9 | 0.52 |
| 820629 | 1126 | 28.1 | 28.5 | -0.4 | 0.90 |
| 820629 | 1255 | 29.6 | 31.0 | -1.4 | 1.68 |
| 820629 | 1400 | 29.6 | 31.0 | -1.4 | 1.45 |
| 820629 | 1525 | 28.8 | 30.0 | -1.2 | 1.09 |
| 820629 | 1635 | 26.8 | 30.7 | -3.9 | 1.78 |
| 820629 | 1755 | 28.3 | 30.6 | -2.3 | 1.90 |
| 820725 | 1305 | 30.0 | 31.2 | -1.2 | 1.59 |
| 820729 | 1051 | 26.2 | 27.0 | -0.8 | 1.11 |
| 820730 | 1252 | 24.9 | 27.0 | -2.1 | 1.35 |
| 820730 | 1511 | 25.4 | 27.0 | -1.6 | 1.18 |
| 820803 | 0535 | 23.5 | 25.0 | -1.5 | 0.70 |
| 820803 | 0845 | 25.3 | 28.0 | -2.7 | 1.27 |
| 820803 | 1145 | 29.0 | 34.4 | -5.4 | 2.39 |
| 820803 | 1423 | 30.1 | 37.0 | -6.9 | 3.96 |
| 820803 | 1635 | 29.8 | 34.5 | -4.7 | 3.00 |
| 820812 | 1100 | 22.4 | 23.0 | -0.6 | 0.29 |
| 820830 | 1418 | 30.7 | 32.0 | -1.3 | 1.88 |
| 820903 | 1425 | 26.0 | 29.5 | -3.5 | 2.51 |

Table 2.3. Stomatal resistance, canopy-minus-air temperature and evapotranspiration of different crops grown in 1982.

| Crop | SR ($s\ m^{-1}$) | (Tc-Ta) ($^{o}C$) | ET ($mm\ day^{-1}$) |
|---|---|---|---|
| corn | 735 | -2.50 | 8.51 |
| grain sorghum | 416 | -2.65 | 7.31 |
| millet | 363 | -2.92 | 7.77 |
| soy bean | 573 | -2.87 | 8.06 |
| sunflower | 351 | -3.62 | 9.43 |
| pinto bean | 552 | -2.62 | 6.06 |
| alfalfa | 139 | -3.33 | 9.73 |

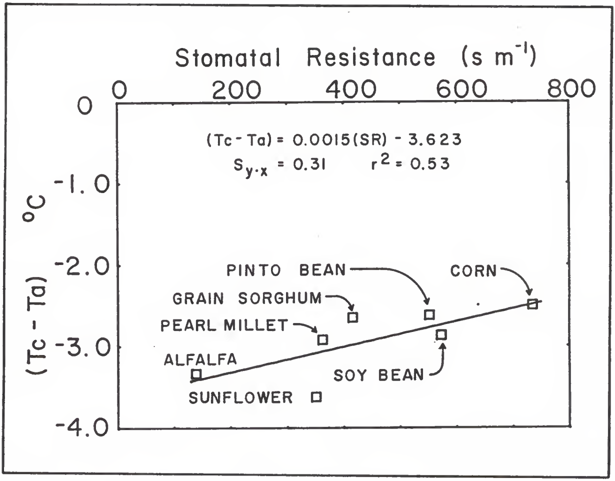


Fig. 2.4. The relationship between seasonal values of canopy-minus-air temperature (Tc-Ta) and stomatal resistance of several crops grown in 1982.

# APPENDIX

Maximum and minimum air temperature, solar radiation, and net solar radiation for 1980, 1981, and 1982.

Tmax Maximum air temperature ($^{o}C$)
Tmin Minimum air temperature ($^{o}C$)
Rs Solar radiation (MJ $day^{-1}$)
Rn Net long wave solar radiation (MJ $day^{-1}$)
Hemispherical net radiometer (ser. no. 6875)
Calibration - 0.03388 cal $cm^{-2}$ $min^{-1}$/mV

| Date | Tmax | Tmin | Rs | Rn |
|---|---|---|---|---|
| 800321 | 14 | -5 | 21.5 | ---- |
| 800322 | 18 | 3 | 12.6 | ---- |
| 800323 | 16 | 3 | 5.5 | ---- |
| 800324 | 3 | -1 | 7.6 | ---- |
| 800325 | 3 | -2 | 5.3 | ---- |
| 800326 | 9 | 2 | 1.8 | ---- |
| 800327 | 9 | 4 | 4.4 | ---- |
| 800328 | 9 | 7 | 1.5 | ---- |
| 800329 | 9 | 6 | 1.1 | ---- |
| 800330 | 7 | 2 | 2.8 | ---- |
| 800331 | 13 | 1 | 22.6 | ---- |
| 800401 | 15 | 6 | 12.9 | ---- |
| 800402 | 11 | 1 | 2.6 | ---- |
| 800403 | 8 | 3 | 4.9 | ---- |
| 800404 | 14 | 0 | 23.5 | ---- |
| 800405 | 21 | 3 | 21.2 | ---- |
| 800406 | 21 | 8 | 21.4 | ---- |
| 800407 | 18 | 7 | 8.9 | ---- |
| 800408 | 16 | 7 | 16.9 | ---- |
| 800409 | 17 | 3 | 23.4 | ---- |
| 800410 | 23 | -1 | 22.1 | ---- |
| 800411 | 18 | 3 | 4.0 | ---- |
| 800412 | 13 | -1 | 23.5 | ---- |
| 800413 | 13 | -1 | 25.2 | ---- |
| 800414 | 12 | -1 | 22.7 | ---- |
| 800415 | 21 | -2 | 25.7 | ---- |
| 800416 | 19 | 5 | 9.7 | ---- |
| 800417 | 13 | 6 | 5.4 | ---- |
| 800418 | 19 | 7 | 21.1 | ---- |
| 800419 | 26 | 5 | 24.8 | ---- |
| 800420 | 31 | 11 | 25.4 | ---- |
| 800421 | 32 | 12 | 26.1 | ---- |
| 800422 | 30 | 15 | 25.9 | ---- |
| 800423 | 27 | 11 | 23.4 | ---- |
| 800424 | 22 | 8 | 24.6 | ---- |
| 800425 | 18 | 6 | 16.8 | ---- |
| 800426 | 17 | 8 | 12.4 | ---- |
| 800427 | 17 | 8 | 16.5 | ---- |
| 800428 | 24 | 4 | 27.0 | ---- |
| 800429 | 24 | 3 | 27.0 | ---- |
| 800430 | 23 | 6 | 24.8 | ---- |

| | | | | |
|---|---|---|---|---|
| 800501 | 21 | 8 | 15.9 | ---- |
| 800502 | 26 | 7 | 24.8 | ---- |
| 800503 | 26 | 11 | 15.9 | ---- |
| 800504 | 27 | 7 | 21.9 | ---- |
| 800505 | 28 | 11 | 23.0 | ---- |
| 800506 | 28 | 12 | 24.5 | ---- |
| 800507 | 23 | 11 | 25.3 | ---- |
| 800508 | 16 | 2 | 29.1 | ---- |
| 800509 | 22 | 0 | 21.5 | ---- |
| 800510 | 28 | 12 | 23.6 | ---- |
| 800511 | 24 | 11 | 10.0 | ---- |
| 800512 | 24 | 12 | 18.4 | ---- |
| 800513 | 23 | 8 | 23.6 | ---- |
| 800514 | 23 | 3 | 26.7 | ---- |
| 800515 | 22 | 12 | 15.9 | ---- |
| 800516 | 19 | 11 | 2.2 | ---- |
| 800517 | 17 | 13 | 6.6 | ---- |
| 800518 | 18 | 12 | 13.2 | ---- |
| 800519 | 22 | 8 | 21.5 | ---- |
| 800520 | 25 | 9 | 18.6 | ---- |
| 800521 | 26 | 8 | 24.4 | ---- |
| 800522 | 26 | 11 | 23.7 | ---- |
| 800523 | 27 | 11 | 25.6 | ---- |
| 800524 | 27 | 14 | 20.2 | ---- |
| 800525 | 34 | 19 | 22.5 | ---- |
| 800526 | 32 | 18 | 22.2 | ---- |
| 800527 | 29 | 19 | 17.7 | ---- |
| 800528 | 30 | 17 | 19.0 | ---- |
| 800529 | 31 | 19 | 22.9 | ---- |
| 800530 | 27 | 14 | 30.2 | ---- |
| 800531 | 26 | 15 | 7.6 | ---- |
| 800601 | 29 | 18 | 20.4 | ---- |
| 800602 | 30 | 22 | 25.6 | ---- |
| 800603 | 33 | 17 | 25.3 | ---- |
| 800604 | 31 | 22 | 20.3 | ---- |
| 800605 | 34 | 23 | 28.7 | ---- |
| 800606 | 34 | 24 | 21.5 | ---- |
| 800607 | 31 | 23 | 23.5 | ---- |
| 800608 | 23 | 13 | 26.0 | ---- |
| 800609 | 27 | 13 | 28.7 | ---- |
| 800610 | 30 | 13 | 29.6 | ---- |
| 800611 | 32 | 15 | 29.3 | ---- |
| 800612 | 32 | 21 | 18.5 | ---- |
| 800613 | 36 | 23 | 27.5 | ---- |
| 800614 | 38 | 23 | 28.9 | ---- |
| 800615 | 34 | 22 | 29.0 | ---- |
| 800616 | 27 | 18 | 19.3 | ---- |
| 800617 | 28 | 13 | 29.4 | ---- |
| 800618 | 32 | 18 | 28.4 | ---- |
| 800619 | 30 | 21 | 23.2 | ---- |
| 800620 | 23 | 14 | 10.6 | ---- |
| 800621 | 28 | 13 | 25.3 | ---- |
| 800622 | 32 | 17 | 25.9 | ---- |

| | | | | |
|---|---|---|---|---|
| 800623 | 33 | 18 | 29.4 | ---- |
| 800624 | 34 | 19 | 28.5 | ---- |
| 800625 | 36 | 22 | 26.4 | ---- |
| 800626 | 36 | 25 | 28.1 | ---- |
| 800627 | 43 | 26 | 28.1 | ---- |
| 800628 | 37 | 23 | 27.1 | ---- |
| 800629 | 33 | 16 | 29.5 | ---- |
| 800630 | 43 | 19 | 27.9 | ---- |
| 800701 | 40 | 27 | 27.7 | ---- |
| 800702 | 34 | 19 | 22.7 | ---- |
| 800703 | 32 | 19 | 23.3 | ---- |
| 800704 | 39 | 23 | 26.9 | ---- |
| 800705 | 38 | 26 | 25.1 | ---- |
| 800706 | 40 | 27 | 29.0 | ---- |
| 800707 | 40 | 27 | 29.1 | ---- |
| 800708 | 40 | 28 | 28.3 | ---- |
| 800709 | 42 | 28 | 25.2 | ---- |
| 800710 | 43 | 27 | 27.9 | ---- |
| 800711 | 43 | 26 | 28.2 | ---- |
| 800712 | 40 | 24 | 27.2 | ---- |
| 800713 | 42 | 26 | 28.3 | ---- |
| 800714 | 43 | 28 | 28.3 | ---- |
| 800715 | 42 | 27 | 28.3 | ---- |
| 800716 | 38 | 27 | 28.7 | ---- |
| 800717 | 42 | 23 | 25.2 | ---- |
| 800718 | 39 | 28 | 17.8 | ---- |
| 800719 | 42 | 24 | 27.2 | ---- |
| 800720 | 41 | 24 | 18.2 | ---- |
| 800721 | 32 | 21 | 21.3 | ---- |
| 800722 | 31 | 17 | 29.2 | ---- |
| 800723 | 33 | 14 | 27.7 | ---- |
| 800724 | 38 | 18 | 27.4 | ---- |
| 800725 | 34 | 22 | 7.9 | ---- |
| 800726 | 32 | 18 | 24.9 | ---- |
| 800727 | 33 | 15 | 26.1 | ---- |
| 800728 | 41 | 19 | 26.6 | ---- |
| 800729 | 42 | 21 | 26.8 | ---- |
| 800730 | 42 | 28 | 25.5 | ---- |
| 800731 | 37 | 24 | 16.4 | ---- |
| 800801 | 41 | 24 | 25.9 | ---- |
| 800802 | 37 | 26 | 20.5 | ---- |
| 800803 | 41 | 20 | 26.2 | ---- |
| 800804 | 36 | 21 | 15.1 | ---- |
| 800805 | 34 | 20 | 10.7 | ---- |
| 800806 | 36 | 21 | 24.9 | ---- |
| 800807 | 38 | 27 | 26.1 | ---- |
| 800808 | 38 | 26 | 26.2 | ---- |
| 800809 | 38 | 26 | 25.0 | ---- |
| 800810 | 39 | 26 | 22.8 | ---- |
| 800811 | 32 | 19 | 24.6 | ---- |
| 800812 | 37 | 20 | 22.3 | ---- |
| 800813 | 38 | 22 | 23.8 | ---- |
| 800814 | 35 | 22 | 7.3 | ---- |

| | | | | |
|---|---|---|---|---|
| 800815 | 27 | 21 | 6.4 | ---- |
| 800816 | 34 | 22 | 18.9 | ---- |
| 800817 | 32 | 21 | 20.2 | ---- |
| 800818 | 36 | 22 | 24.7 | ---- |
| 800819 | 36 | 25 | 23.9 | ---- |
| 800820 | 33 | 27 | 16.9 | ---- |
| 800821 | 32 | 14 | 24.6 | ---- |
| 800822 | 32 | 17 | 16.3 | ---- |
| 800823 | 32 | 16 | 23.8 | ---- |
| 800824 | 38 | 22 | 23.4 | ---- |
| 800825 | 39 | 23 | 23.5 | ---- |
| 800826 | 39 | 21 | 23.5 | ---- |
| 800827 | 33 | 19 | 16.2 | ---- |
| 800828 | 34 | 18 | 14.8 | ---- |
| 800829 | 36 | 21 | 22.7 | ---- |
| 800830 | 36 | 23 | 16.3 | ---- |
| 800831 | 36 | 20 | 19.5 | ---- |
| 800901 | 29 | 17 | 22.8 | ---- |
| 800902 | 34 | 17 | 23.0 | ---- |
| 800903 | 36 | 21 | 22.5 | ---- |
| 800904 | 33 | 22 | 20.0 | ---- |
| 800905 | 37 | 22 | 21.3 | ---- |
| 800906 | 37 | 22 | 20.2 | ---- |
| 800907 | 35 | 23 | 15.4 | ---- |
| 800908 | 36 | 24 | 19.5 | ---- |
| 800909 | 29 | 18 | 20.1 | ---- |
| 800910 | 26 | 12 | 17.5 | ---- |
| 800911 | 33 | 17 | 9.9 | ---- |
| 800912 | 37 | 24 | 20.5 | ---- |
| 800913 | 31 | 19 | 20.7 | ---- |
| 800914 | 24 | 15 | 15.7 | ---- |
| 800915 | 27 | 16 | 9.4 | ---- |
| 810526 | 27 | 12 | 26.2 | ---- |
| 810527 | 27 | 18 | 16.6 | ---- |
| 810528 | 24 | 18 | 6.9 | ---- |
| 810529 | 28 | 17 | 21.5 | ---- |
| 810530 | 26 | 17 | 24.6 | ---- |
| 810531 | 26 | 10 | 27.9 | ---- |
| 810601 | 29 | 10 | 27.9 | ---- |
| 810602 | 29 | 18 | 21.0 | ---- |
| 810603 | 28 | 18 | 23.8 | ---- |
| 810604 | 24 | 18 | 10.9 | ---- |
| 810605 | 30 | 18 | 25.5 | ---- |
| 810606 | 31 | 21 | 26.5 | ---- |
| 810607 | 33 | 20 | 25.8 | ---- |
| 810608 | 36 | 23 | 26.7 | ---- |
| 810609 | 36 | 23 | 26.2 | ---- |
| 810610 | 32 | 19 | 19.8 | ---- |
| 810611 | 24 | 14 | 10.5 | ---- |
| 810612 | 32 | 18 | 26.3 | ---- |
| 810613 | 31 | 23 | 21.2 | ---- |
| 810614 | 32 | 24 | 16.0 | ---- |
| 810615 | 29 | 14 | 14.1 | ---- |

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|---|---|---|---|---|
| 810616 | 25 | 11 | 30.8 | ---- |
| 810617 | 29 | 15 | 29.8 | ---- |
| 810618 | 26 | 18 | 16.4 | ---- |
| 810619 | 29 | 14 | 23.4 | ---- |
| 810620 | 31 | 19 | 18.1 | ---- |
| 810621 | 30 | 17 | 17.9 | ---- |
| 810622 | 25 | 18 | 10.2 | ---- |
| 810623 | 33 | 19 | 25.5 | ---- |
| 810624 | 36 | 25 | 28.1 | ---- |
| 810625 | 32 | 21 | 28.5 | ---- |
| 810626 | 28 | 19 | 8.3 | ---- |
| 810627 | 32 | 18 | 18.4 | ---- |
| 810628 | 33 | 23 | 28.2 | ---- |
| 810629 | 32 | 21 | 18.3 | ---- |
| 810630 | 27 | 21 | 15.1 | ---- |
| 810701 | 29 | 19 | 22.4 | ---- |
| 810702 | 31 | 21 | 18.6 | 10.0 |
| 810703 | 28 | 21 | 11.6 | 8.0 |
| 810704 | 29 | 21 | 15.7 | 8.0 |
| 810705 | 31 | 20 | 26.4 | 14.7 |
| 810706 | 31 | 20 | 27.0 | 13.1 |
| 810707 | 31 | 21 | 24.5 | 16.4 |
| 810708 | 33 | 23 | 24.9 | 16.2 |
| 810709 | 34 | 21 | 27.8 | 16.4 |
| 810710 | 35 | 23 | 28.8 | 16.2 |
| 810711 | 37 | 26 | 28.2 | 15.5 |
| 810712 | 37 | 27 | 27.5 | 8.5 |
| 810713 | 36 | 26 | 27.6 | 16.7 |
| 810714 | 38 | 26 | 26.8 | 13.9 |
| 810715 | 35 | 25 | 23.3 | 12.6 |
| 810716 | 33 | 24 | 23.3 | 12.9 |
| 810717 | 31 | 22 | 15.2 | 8.3 |
| 810718 | 29 | 22 | 10.7 | 5.1 |
| 810719 | 32 | 23 | 18.6 | 12.3 |
| 810720 | 32 | 22 | 20.2 | 10.8 |
| 810721 | 30 | 18 | 16.4 | 7.5 |
| 810722 | 29 | 20 | 17.4 | 5.7 |
| 810723 | 31 | 22 | 24.3 | 11.6 |
| 810724 | 30 | 21 | 9.0 | 3.4 |
| 810725 | 29 | 21 | 21.4 | 10.3 |
| 810726 | 26 | 20 | 13.9 | 7.0 |
| 810727 | 27 | 19 | 13.6 | 5.4 |
| 810728 | 26 | 16 | 8.5 | 2.9 |
| 810729 | 27 | 15 | 11.5 | 6.7 |
| 810730 | 30 | 19 | 16.2 | 10.0 |
| 810731 | 31 | 21 | 18.4 | 6.5 |
| 810801 | 34 | 22 | 25.1 | 13.9 |
| 810802 | 32 | 21 | 20.0 | 12.4 |
| 810803 | 33 | 22 | 25.2 | 13.1 |
| 810804 | 35 | 22 | 25.5 | 13.4 |
| 810805 | 34 | 21 | 22.8 | 11.1 |
| 810806 | 30 | 21 | 9.1 | 3.1 |
| 810807 | 28 | 18 | 26.2 | 10.3 |

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|---|---|---|---|---|
| 810808 | 30 | 16 | 24.9 | 10.0 |
| 810809 | 30 | 19 | 21.1 | 8.2 |
| 810810 | 27 | 16 | 23.6 | 10.1 |
| 810811 | 28 | 14 | 25.4 | 11.1 |
| 810812 | 29 | 15 | 24.4 | 10.5 |
| 810813 | 28 | 21 | 7.9 | 3.4 |
| 810814 | 34 | 24 | 23.8 | 11.8 |
| 810815 | 32 | 22 | 16.5 | 7.7 |
| 810816 | 28 | 21 | 20.5 | 9.3 |
| 810817 | 23 | 17 | 14.8 | 7.0 |
| 810818 | 24 | 13 | 23.3 | 9.8 |
| 810819 | 26 | 12 | 23.6 | 7.8 |
| 810820 | 27 | 11 | 24.6 | 11.6 |
| 810821 | 29 | 12 | 24.6 | 11.4 |
| 810822 | 31 | 14 | 23.8 | 10.6 |
| 810823 | 26 | 20 | 7.1 | 4.3 |
| 810824 | 31 | 17 | 21.3 | 11.0 |
| 810825 | 29 | 22 | 7.2 | 2.6 |
| 810826 | 28 | 18 | 17.4 | 9.5 |
| 810827 | 26 | 18 | 12.4 | 6.5 |
| 810828 | 27 | 15 | 14.5 | 7.5 |
| 810829 | 32 | 16 | 22.8 | 11.8 |
| 810830 | 36 | 24 | 18.2 | 7.8 |
| 810831 | 31 | 21 | 17.7 | 11.0 |
| 810901 | 24 | 15 | 21.8 | 9.3 |
| 810902 | 27 | 11 | 22.0 | 10.3 |
| 810903 | 31 | 15 | 15.6 | 7.7 |
| 810904 | 27 | 17 | 15.6 | ---- |
| 810905 | 31 | 19 | 18.8 | ---- |
| 810906 | 27 | 21 | 4.6 | ---- |
| 810907 | 26 | 19 | 20.0 | ---- |
| 810908 | 28 | 11 | 22.3 | ---- |
| 810909 | 30 | 11 | 22.2 | ---- |
| 810910 | 31 | 14 | 21.7 | ---- |
| 810911 | 31 | 20 | 12.3 | ---- |
| 810912 | 30 | 14 | 19.9 | ---- |
| 810913 | 32 | 13 | 19.0 | ---- |
| 810914 | 28 | 18 | 19.4 | ---- |
| 810915 | 24 | 13 | 17.5 | ---- |
| 810916 | 18 | 11 | 17.4 | ---- |
| 810917 | 18 | 4 | 19.4 | ---- |
| 810918 | 23 | 2 | 20.4 | ---- |
| 810919 | 29 | 11 | 20.3 | ---- |
| 810920 | 31 | 15 | 19.8 | ---- |
| 810921 | 28 | 14 | 17.2 | ---- |
| 810922 | 23 | 14 | 17.0 | ---- |
| 810923 | 32 | 14 | 14.9 | ---- |
| 810924 | 26 | 19 | 4.4 | ---- |
| 820520 | 26 | 16 | 14.1 | ---- |
| 820521 | 23 | 13 | 20.9 | ---- |
| 820522 | 21 | 12 | 16.9 | ---- |
| 820523 | 24 | 12 | 23.1 | ---- |
| 820524 | 22 | 16 | 9.2 | ---- |

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|---|---|---|---|---|
| 820525 | 23 | 17 | 13.7 | ---- |
| 820526 | 21 | 12 | 12.7 | ---- |
| 820527 | 27 | 10 | 28.1 | ---- |
| 820528 | 27 | 18 | 15.5 | ---- |
| 820529 | 27 | 16 | 22.9 | ---- |
| 820530 | 26 | 15 | 17.6 | ---- |
| 820531 | 22 | 13 | 14.3 | ---- |
| 820601 | 21 | 5 | 28.4 | 12.0 |
| 820602 | 18 | 12 | 10.8 | 3.7 |
| 820603 | 18 | 12 | 7.5 | 3.2 |
| 820604 | 21 | 13 | 14.3 | 7.4 |
| 820605 | 23 | 12 | 21.3 | 9.4 |
| 820606 | 31 | 20 | 18.7 | 10.3 |
| 820607 | 28 | 12 | 25.5 | ---- |
| 820608 | 32 | 19 | 20.5 | ---- |
| 820609 | 28 | 17 | 24.8 | ---- |
| 820610 | 24 | 8 | 29.1 | 12.9 |
| 820611 | 22 | 14 | 11.9 | 3.7 |
| 820612 | 26 | 14 | 22.9 | 11.5 |
| 820613 | 27 | 15 | 16.7 | 8.1 |
| 820614 | 30 | 18 | 13.8 | 6.5 |
| 820615 | 28 | 17 | 21.5 | 6.6 |
| 820616 | 24 | 13 | 29.7 | 13.6 |
| 820617 | 29 | 13 | 21.7 | 9.5 |
| 820618 | 24 | 18 | 17.6 | 7.5 |
| 820619 | 26 | 13 | 26.7 | 12.5 |
| 820620 | 29 | 16 | 27.2 | 11.6 |
| 820621 | 30 | 14 | 21.7 | 9.1 |
| 820622 | 28 | 14 | 28.0 | 13.0 |
| 820623 | 27 | 17 | 16.5 | 7.2 |
| 820624 | 29 | 18 | 17.7 | 8.5 |
| 820625 | 27 | 19 | 19.9 | 8.3 |
| 820626 | 28 | 17 | 22.0 | 10.3 |
| 820627 | 26 | 19 | 13.8 | 5.4 |
| 820628 | 31 | 19 | 24.6 | 10.4 |
| 820629 | 34 | 19 | 26.6 | 14.9 |
| 820630 | 29 | 22 | 18.7 | 10.3 |
| 820701 | 26 | 20 | 11.2 | 6.9 |
| 820702 | 34 | 21 | 25.5 | 14.6 |
| 820703 | 37 | 22 | 28.7 | 15.4 |
| 820704 | 36 | 24 | 28.2 | 15.5 |
| 820705 | 33 | 24 | 21.9 | 10.3 |
| 820706 | 32 | 22 | 24.8 | 10.5 |
| 820707 | 31 | 15 | 18.0 | 10.4 |
| 820708 | 31 | 17 | 20.5 | 7.2 |
| 820709 | 30 | 21 | 21.7 | 11.2 |
| 820710 | 28 | 19 | 22.7 | 12.5 |
| 820711 | 31 | 17 | 28.5 | 14.7 |
| 820712 | 32 | 17 | 26.4 | 11.5 |
| 820713 | 33 | 20 | 22.0 | ---- |
| 820714 | 33 | 21 | 26.7 | ---- |
| 820715 | 33 | 22 | 18.5 | ---- |
| 820716 | 36 | 25 | 27.2 | ---- |

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|---|---|---|---|---|
| 820717 | 37 | 26 | 26.9 | ---- |
| 820718 | 36 | 26 | 22.7 | ---- |
| 820719 | 34 | 26 | 21.6 | 9.1 |
| 820720 | 37 | 24 | 27.1 | 12.4 |
| 820721 | 36 | 22 | 25.6 | 12.1 |
| 820722 | 32 | 22 | 26.1 | 12.4 |
| 820723 | 32 | 19 | 28.0 | 12.4 |
| 820724 | 33 | 21 | 27.5 | 11.5 |
| 820725 | 33 | 21 | 26.8 | 11.5 |
| 820726 | 34 | 21 | 25.6 | ---- |
| 820727 | 32 | 22 | 19.9 | ---- |
| 820728 | 29 | 20 | 24.9 | ---- |
| 820729 | 30 | 17 | 20.9 | ---- |
| 820730 | 30 | 19 | 26.4 | 11.4 |
| 820731 | 33 | 14 | 26.5 | 12.9 |
| 820801 | 35 | 21 | 25.6 | 13.6 |
| 820802 | 37 | 24 | 25.5 | 13.6 |
| 820803 | 39 | 26 | 25.9 | 13.2 |
| 820804 | 39 | 22 | 23.1 | 12.2 |
| 820805 | 31 | 22 | 16.5 | 9.7 |
| 820806 | 31 | 23 | 17.6 | 9.7 |
| 820807 | 31 | 23 | 16.4 | 9.9 |
| 820808 | 33 | 21 | 25.1 | 15.0 |
| 820809 | 31 | 18 | 24.0 | 13.2 |
| 820810 | 24 | 15 | 5.9 | 3.2 |
| 820811 | 23 | 14 | 11.0 | 6.9 |
| 820812 | 29 | 18 | 13.0 | 6.1 |
| 820813 | 28 | 19 | 24.4 | 14.9 |
| 820814 | 26 | 21 | 5.7 | 3.4 |
| 820815 | 29 | 21 | 17.0 | 9.5 |
| 820816 | 27 | 22 | 7.4 | 5.8 |
| 820817 | 29 | 19 | 20.4 | 8.9 |
| 820818 | 31 | 18 | 22.5 | 10.5 |
| 820819 | 34 | 21 | 22.7 | ---- |
| 820820 | 31 | 22 | 9.7 | ---- |
| 820821 | 30 | 17 | 23.3 | 9.5 |
| 820822 | 36 | 22 | 23.2 | 11.2 |
| 820823 | 30 | 19 | 20.3 | 10.6 |
| 820824 | 26 | 19 | 10.4 | 2.2 |
| 820825 | 27 | 12 | 23.2 | 10.3 |
| 820826 | 29 | 18 | 13.5 | 6.9 |
| 820827 | 24 | 19 | 6.8 | 4.5 |
| 820828 | 24 | 18 | 8.9 | 6.0 |
| 820829 | 33 | 21 | 15.1 | 8.7 |
| 820830 | 34 | 20 | 22.6 | 11.6 |
| 820831 | 33 | 21 | 13.9 | 7.8 |
| 820901 | 34 | 24 | 18.1 | 10.0 |
| 820902 | 31 | 20 | 23.2 | 11.0 |
| 820903 | 32 | 14 | 22.7 | 10.2 |
| 820904 | 33 | 15 | 21.8 | 9.1 |
| 820905 | 32 | 20 | 16.2 | 6.5 |
| 820906 | 26 | 18 | 8.2 | 3.1 |
| 820907 | 27 | 18 | 14.4 | 7.1 |

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|---|---|---|---|---|
| 820908 | 28 | 19 | 10.3 | 3.2 |
| 820909 | 31 | 21 | 13.8 | ---- |
| 820910 | 34 | 22 | 18.7 | ---- |
| 820911 | 32 | 22 | 15.0 | 7.4 |
| 820912 | 32 | 23 | 15.9 | 8.1 |
| 820913 | 24 | 16 | 11.5 | 4.7 |
| 820914 | 21 | 14 | 5.1 | 3.3 |
| 820915 | 18 | 13 | 12.5 | 6.5 |
| 820916 | 22 | 12 | 8.3 | 4.6 |
| 820917 | 24 | 14 | 4.3 | 1.7 |
| 820918 | 22 | 8 | 20.5 | 8.9 |
| 820919 | 26 | 10 | 15.4 | 7.3 |
| 820920 | 17 | 6 | 19.8 | 8.4 |
| 820921 | 18 | 3 | 20.5 | ---- |
| 820922 | 25 | 4 | 20.0 | ---- |
| 820923 | 26 | 16 | 10.3 | ---- |
| 820924 | 23 | 10 | 19.2 | ---- |
| 820925 | 19 | 6 | 18.1 | ---- |
| 820926 | 23 | 6 | 15.4 | ---- |

Depletion of soil water (mm) and precipitation (mm) in 1980

| Dates within probe period from | to | days | precipitation | Irrigation treatments (mm) 0 | 25 | 50 | 75 | 100 | 125 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|
| 800422 | 800503 | 11 | 0.0 | 57.8 | 60.7 | 57.0 | 67.7 | 62.5 | 51.3 | 57.5 |
| 800503 | 800522 | 19 | 27.7 | 79.1 | 77.2 | 63.7 | 71.8 | 77.0 | 75.5 | 72.0 |
| 800522 | 800611 | 20 | 52.6 | 44.4 | 48.2 | 46.8 | 49.8 | 31.0 | 41.7 | 37.5 |
| 800611 | 800616 | 5 | 0.0 | 21.8 | -41.3 | -84.0 | -74.6 | -191.8 | -128.5 | -95.8 |
| 800616 | 800623 | 7 | 33.0 | 8.0 | 22.8 | 29.0 | 8.8 | 41.5 | 16.8 | 10.3 |
| 800623 | 800701 | 8 | 0.0 | 61.8 | 67.7 | 93.0 | 98.7 | 123.8 | 96.2 | 104.7 |
| 800701 | 800710 | 9 | 15.5 | 23.0 | 39.5 | 36.3 | 55.7 | 74.2 | 60.2 | 51.5 |
| 800710 | 800717 | 7 | 0.0 | -10.7 | -77.8 | -153.8 | -129.6 | -170.6 | -147.6 | -159.5 |
| 800717 | 800728 | 11 | 16.3 | 16.8 | 64.7 | 93.7 | 85.4 | 115.8 | 84.8 | 99.3 |
| 800728 | 800807 | 10 | 8.1 | 3.7 | 26.2 | 56.8 | 79.2 | 90.5 | 67.2 | 64.8 |
| 800807 | 800815 | 8 | 34.5 | -28.0 | -90.0 | -139.8 | -144.7 | -223.0 | -204.3 | -179.3 |
| 800815 | 800829 | 14 | 8.6 | 41.3 | 89.2 | 121.5 | 123.2 | 152.7 | 132.2 | 132.3 |
| 800829 | 800911 | 13 | 20.8 | 1.7 | 17.0 | 44.3 | 52.2 | 83.8 | 78.7 | 59.2 |

Depletion of soil water (mm) and precipitation (mm) in 1981

| Dates within probe readings from | to | days | precipitation | Irrigation treatments (mm) 0 | 25 | 50 | 75 | 100 | 125 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|
| 810317 | 810409 | 24 | 23.9 | 48.5 | 61.4 | 57.3 | 70.9 | 69.1 | 65.0 | 75.0 |
| 810409 | 810423 | 14 | 34.0 | 15.5 | 12.7 | 19.8 | 11.1 | 28.1 | 14.9 | 42.6 |
| 810423 | 810507 | 14 | 22.4 | 9.0 | 15.4 | 22.8 | 20.9 | 20.7 | 13.3 | 8.2 |
| 810507 | 810515 | 8 | 61.2 | -42.4 | -47.8 | -49.8 | -54.5 | -44.8 | -35.8 | -53.5 |
| 810515 | 810527 | 12 | 82.9 | -27.0 | -29.4 | -27.4 | -33.3 | -44.9 | -34.9 | -28.3 |
| 810527 | 810610 | 14 | 42.1 | 36.0 | -43.5 | -70.3 | -110.8 | -155.8 | -174.3 | -175.8 |
| 810610 | 810619 | 9 | 52.4 | 7.5 | 20.0 | 20.0 | 40.5 | 46.2 | 46.4 | 18.8 |
| 810619 | 810701 | 12 | 92.0 | -97.1 | -55.3 | -54.3 | -86.3 | -59.9 | -54.7 | -64.4 |
| 810701 | 810707 | 6 | 22.1 | 12.4 | 23.4 | 17.0 | 33.3 | 24.5 | 26.6 | 15.0 |
| 810707 | 810711 | 4 | 55.9 | -71.1 | -128.4 | -98.3 | -99.5 | -168.3 | -156.5 | -196.5 |
| 810711 | 810720 | 9 | 40.1 | 32.9 | 45.2 | 42.5 | 43.2 | 67.0 | 45.0 | 63.7 |
| 810720 | 810803 | 14 | 109.2 | -52.7 | -33.1 | -37.6 | -40.9 | -40.7 | -10.4 | 3.0 |
| 810803 | 810810 | 7 | 19.3 | -21.8 | -31.7 | -30.6 | -31.2 | -36.3 | -30.1 | -34.9 |
| 810810 | 810821 | 11 | 42.9 | 58.2 | 24.8 | -48.5 | -8.8 | -36.6 | -89.4 | -29.4 |
| 810821 | 810908 | 18 | 30.5 | 64.9 | 45.8 | 108.5 | 71.3 | 74.7 | 90.6 | 102.7 |
| 810908 | 810925 | 17 | 12.2 | 49.0 | 51.9 | 53.2 | 52.8 | 61.2 | 65.7 | 51.8 |

Depletion of soil water (mm) and precipitation (mm) in 1982

| Dates within probe readings from | to | days | precipitation | Irrigation treatments (mm) 0 | 25 | 50 | 75 | 100 | 125 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|
| 820319 | 820502 | 44 | 45.7 | 120.6 | 129.4 | 109.6 | 121.0 | 128.1 | 118.0 | 126.8 |
| 820502 | 820519 | 16 | 62.2 | 12.0 | 12.0 | 6.9 | 16.0 | 9.3 | 20.0 | 15.2 |
| 820519 | 820610 | 23 | 136.9 | -72.5 | -71.1 | -66.3 | -84.5 | -75.0 | -70.4 | -65.8 |
| 820610 | 820618 | 8 | 20.6 | 15.4 | 12.3 | 5.5 | 15.8 | 17.7 | 13.0 | 16.2 |
| 820618 | 820630 | 12 | 64.5 | -0.9 | -0.6 | -0.2 | 4.5 | 5.3 | 8.4 | -7.3 |
| 820630 | 820709 | 9 | 45.5 | 19.1 | 22.8 | 15.4 | 17.2 | 22.5 | 17.4 | 31.0 |
| 820709 | 820722 | 13 | 90.4 | -63.3 | -117.3 | -170.9 | -135.8 | -185.5 | -216.9 | -227.8 |
| 820722 | 820731 | 9 | 0.0 | 71.6 | 71.6 | 114.4 | 85.4 | 98.2 | 95.6 | 111.1 |
| 820731 | 820806 | 6 | 39.9 | 11.8 | 4.9 | 19.8 | 17.4 | 24.7 | 28.3 | 28.2 |
| 820806 | 820813 | 7 | 39.6 | -5.2 | 12.5 | -29.9 | -4.1 | -12.0 | 2.7 | -5.0 |
| 820813 | 820827 | 14 | 18.5 | 12.5 | -35.1 | -41.9 | -72.6 | -88.5 | -109.3 | -119.5 |
| 820827 | 820911 | 15 | 32.8 | -40.9 | 60.8 | 72.4 | 72.7 | 75.1 | 82.1 | 96.7 |
| 820911 | 820923 | 12 | 66.8 | -79.9 | -50.7 | -49.5 | -35.8 | -29.4 | -25.5 | -27.9 |

# WATER USE AND YIELD OF DIFFERENTIALLY IRRIGATED ALFALFA

by

MATTHEW NEIL MATULKA

B. S., Kansas State University

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agronomy

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1985

Water Use, Yield, and Water Use
Efficiency of Differentially Irrigated Alfalfa

by

Matthew Neil Matulka

(Under the instruction of Drs. E. T. Kanemasu,
M. B. Kirkham, and L. R. Stone)

## ABSTRACT

The production of alfalfa on the Central Great Plains is often limited by precipitation. The effect of drought can be alleviated by the use of supplemental irrigation; however, competition for available resources restrict the expansion of irrigated agriculture. Through better understanding of the relationship between yield and water use, alfalfa production might be done more economically. The increased use of supplemental irrigation has increased the need for information on alfalfa water use.

Alfalfa (*Medicago sativa* L. Cody) was grown with seven levels of irrigation water to assess the affect of different irrigation levels on crop yield, water use, water use efficiency (WUE), stomatal resistance (SR), plant water potential, and canopy temperature. Canopy temperature was measured with an infrared thermometer in 1980, 1981, and 1982. In 1981 and 1982, plant water potential and stomatal resistance were measured with a pressure chamber and a stomatal porometer, respectively. In each year of the study, water use was determined from neutron probe measurements

taken to a depth of 3.12 m. The soil type was Eudora silt-loam. The alfalfa was irrigated (treatments were 0, 25, 50, 75, 100, 125, and 150 mm per irrigation) following each harvest.

Alfalfa was harvested four times during each year of the study (1980, 1981, and 1982) in late May, early July, early to mid August, and mid September at 10% bloom.

When soil water limited yield, a strong linear correlation existed between yield and water use. Water was a crucial factor limiting the yield of alfalfa in the drought year of 1980, and yield was proportional to water use. In 1981 and 1982, environmental conditions were favorable i. e., precipitation was more frequent and air temperatures were lower than in 1980, and consequently the yield of rainfed alfalfa was similar to that of the irrigated alfalfa. Seasonal precipitation amounts in 1981 and 1982 were 2.5 and 2.1 times that received in 1980 (263 mm). The high potential evapotranspiration (ET) and low yield in 1980 resulted in lower WUE than in either 1981 or 1982. In all years of the study, WUE declined with irrigation amount.

The average stomatal resistance of alfalfa grown in 1981 and 1982 was 145 s $m^{-1}$ and the leaf water potential of the alfalfa averaged -0.220 MPa, values similar to those cited in literature for non-water-stressed alfalfa.

In 1982, alfalfa was shown to have lower SR than grain sorghum (*Sorghum bicolor* L. Moench.), corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), pinto bean (*Phaseolus* *vulgaris* L.), sunflower (*Helianthus annuus* L.), or pearl millet (*Pennisetum americanum* L.). A relationship between SR and ET was not firmly established for the crops; however, SR was found to be correlated with the difference between the temperature of crop canopy minus the temperature of the air.