Environmental Guide to Alfalfa Growth, Water Use, and Yield in Minnesota

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Station Bulletin 581 — 1987 (Item No. AD-SB-3277)
Minnesota Agricultural Experiment Station
University of Minnesota

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INTRODUCTION

Alfalfa (Medicago sativa L.) is an important agricultural crop in Minnesota, where it is grown to enhance soil conservation, for green manure, for forage, and as a cash crop. Minnesota is now the third leading alfalfa producing state with 7 percent of the national acreage (2.0 million acres). The current value of the Minnesota alfalfa crop is estimated at $11 million.

Alfalfa is called the queen of the forages because of its longevity, high yield, and high nutritive value. It is grown over a wide range of latitudes from the tropics to the Canadian provinces. The ability of alfalfa to adapt to arid and humid environments and to regions having temperatures as high as 120°F or as low as -83°F has resulted in its worldwide distribution.

Four aspects of alfalfa in Minnesota are discussed in this bulletin: a brief history, growth characteristics, water relations, and the effect of climate on growth and yield. The information contained in this bulletin comes from Minnesota-based studies and is for cultivars appropriate for the region. Research from other sources is also used to provide information not covered by Minnesota studies.

This environmental guide is intended to be of value in the application of alfalfa responses to the environment. Some relations may be of only local application (e.g., calendar days), whereas others have much broader application (e.g., growing degree days and potential evapotranspiration). The relations developed in this guide can be used to estimate alfalfa maturity, potential production at various stages of development, water use and irrigation requirements, and yields.

HISTORY

Alfalfa has been used as a fodder in Asia since at least 1300 BC (4). It is also believed to be the first crop in the world to be domesticated solely for forage. Alfalfa was first brought from Europe to the Americas by Spanish and Portugese explorers. It was introduced to South America in the 17th century and into North America in the 18th century. Its importance in American agriculture was noted as early as 1793 by John Spurrier in his book entitled Practical Farmer (8). However, it was not until the 1850s that alfalfa was successfully cultivated in the north-central United States. Wendelin Grimm, a German immigrant, introduced alfalfa into Carver County, Minnesota, in 1858. Through natural selection a winter-hardy ecotype was developed, and the cultivar Grimm was released in 1901. An indication of the increased usage of alfalfa from its introduction into Minnesota is shown in Figure 1. The harvested acreage increased from about 670 in 1899 to 2.5 million in 1962. Much of the gain in acreage over this time was due to the development of adaptable winter-hardy cultivars with resistance to bacterial wilt (Corynebacterium insidosium).

GROWTH CHARACTERISTICS

The number of alfalfa harvests taken during a growing season depends on the yield and quality needs of the producer. Typically, four harvests are taken in southern, and two or three harvests are taken in northern Minnesota, where low temperatures limit the growing season length. With a four-cut harvest system in southern Minnesota, three cuttings are typically taken before early September and a fourth following a killing frost that usually occurs about mid-October. Timing of individual harvests before September is influenced by the relative value to the producer of forage yield, forage quality, or stand persistence. For dairy producers requiring forage with high nutrient concentration, alfalfa is harvested at bud initiation. Highest yields of nutrients are obtained at one-tenth flower, while highest forage yield and stand persistence occur from harvesting at full bloom. With three harvests the season is divided into the following growing periods: (a) spring growth: from the last killing frost temperature (about 27°F) in spring to the first harvest in late May or early June, (b) early

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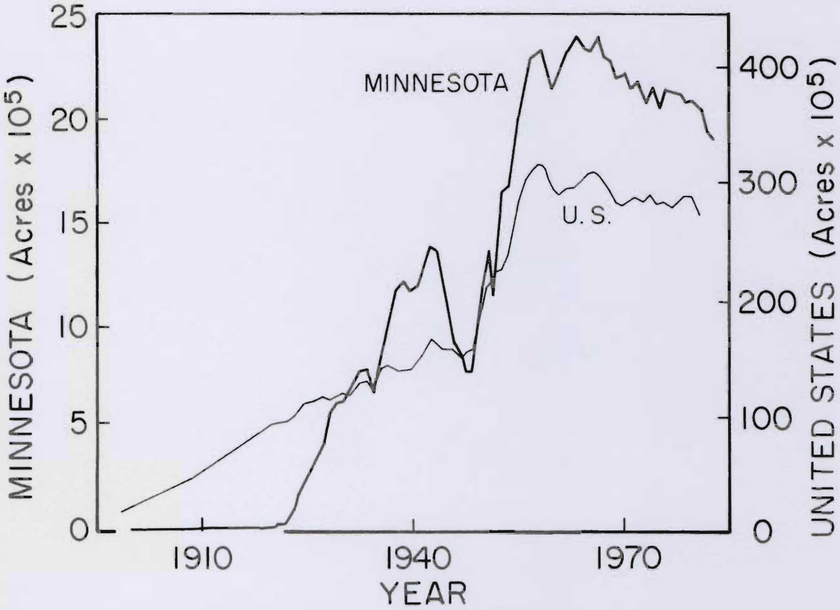

Figure 1. Total land area in alfalfa annually harvested in Minnesota and the United States, 1899-1983.

summer growth: from the first to the second harvest in mid-July, and (c) late summer growth: from the second to the third harvest in late August. Each cutting is made at approximately one-tenth flower, often termed first flower. Because growing season temperatures influence crop development, the time interval between harvests may vary from year to year.

Growth Curve

Changes in plant height, leaf area, and dry matter accumulation during a regrowth cycle are shown in Figure 2. The alfalfa growth curve is sigmoidal with the most rapid growth occurring before one-tenth flower. Growth curves under optimal conditions can be expressed as:

$$Y = Y_m/[1 + \exp(5.3 - 6.7\ t^{0.5})] \qquad [1]$$

where Y is dry matter yield (T/A) at some time t, which represents the normalized development time in growing degree days so that t equals 1.0 at one-tenth flower; and Y_m is the maximum yield (23). Under conditions conducive to extensive leaf disease, leaf loss from lower portions of the canopy may reduce yield as the crop matures beyond the one-tenth flower stage. The maximum yield will vary among harvests, but it generally declines after the spring harvest. As indicated in Table 1, average yield decreases about 0.4 T/A between harvests based on 24 years of Vernal variety yield data at Rosemount (24). The largest yield for each of the three successive harvests during a year amounted to 3.3, 2.2, and 2.0 T/A. Annual total yield decreased an average of 0.3T/A/yr as stands aged.

Table 1. Average yields in the first three production years of Vernal alfalfa grown under a three-harvest management system at Rosemount, MN, 1960-1983.

	Yield at Harvest			
Age of Stand	Spring	Early Summer	Late Summer	Annual
Years	Tons/Acre			
One	2.1	1.6	1.3	5.0
Two	2.0	1.5	1.2	4.7
Three	1.9	1.4	1.1	4.4

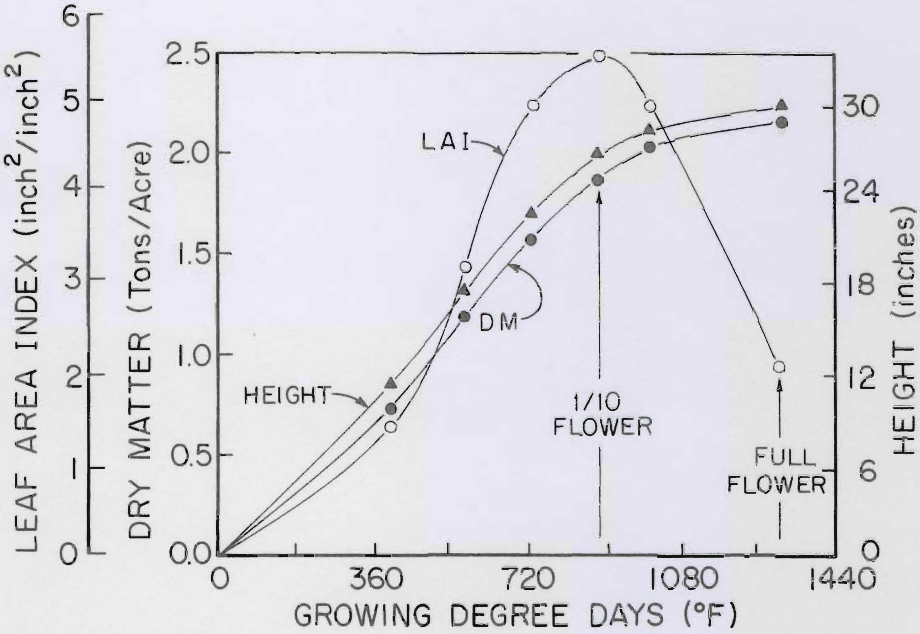

Figure 2. Changes in leaf area index, dry matter production, and plant height associated with growing degree days (GDD) at St. Paul.

Leaf Area

Leaves are nutritionally the most important part of the herbage because they contain the highest nutrient concentration of any plant part. Their growth is characterized by a sigmoidal pattern; this pattern is typified by the change in leaf area index (LAI is leaf surface area, one side only, per unit ground surface area) as shown in Figure 2. The LAI of well-developed canopies ranges from 4 to 8 and decreases with each subsequent growth period. LAI's as high as 6.5 are common during the spring growth period at St. Paul.

Changes in leaf area and leaf dry matter are highly correlated. From studies at Minnesota and other locations (25), it has been determined that alfalfa leaf area during the growing season can be estimated from either leaf or plant dry matter. However, the latter is somewhat less precise in estimating leaf area (25). Equations expressing the relationship between leaf area (LA) and leaf dry matter (LDM) and plant dry matter (PDM) are (when LDM and PDM are expressed in tons/acre):

$$LA = 6.42\ LDM^{0.993} \qquad [2]$$

and $$LA = 2.40\ PDM^{0.992} \qquad [3]$$

To estimate LA it is only necessary to determine the dry weight of the leaves of the plant, a time-saving technique compared to determining leaf area by area meters.

Growing Degree Days

Growing degree days (GDD) is a temperature-based measure of the time plants require to complete various developmental stages. For example, GDD can be used to monitor alfalfa development and to predict the time of harvest. Monitoring crop development by the number of calendar days has been used extensively in the past; however, GDD is generally more accurate. Growing degree days is defined as:

$$GDD = \sum_{i=1}^{n} (T - T_{base}) \qquad [4]$$

where T is the mean daily air temperature, which is the average of the maximum and minimum, T_{base} is the base temperature, and n is the number of calendar days to the developmental stage of interest (e.g., one-tenth flower). The base temperature is the temperature below which growth is assumed to be negligible. When T is higher than the T_{base}, growth proceeds; when it is lower, no growth occurs and GDD remains unchanged. Historically, a base temperature of 40°F has been used for alfalfa. However, the appropriate base temperature to use in the above equation was found to vary between the three growth periods in Minnesota; the appropriate base temperature being 36°F for the spring period and approximately 50°F for the early and late summer periods (26). These base temperatures indicate that spring air temperatures above 36°F induce a growth response in alfalfa, whereas in the early and late summer periods daily temperatures of 50°F must be exceeded for growth to occur. The fact that two base temperatures are used for different growth periods is important relative to the GDD calculations in this bulletin. Growing degree day information for a 50°F base temperature is usually readily available, as it is commonly employed by the National Weather Service and the U.S. Department of Agriculture in disseminating GDD information. In Minnesota, the number of GDD required for alfalfa to reach one-tenth flower using the 36°F base is 1035 for spring growth, while for the 50°F base temperature it is 595 and 765 for the early summer and late summer growth periods, respectively. Maps and tables of the normal accumulated GDD for selected dates and base temperatures in Minnesota are shown in Climate of Minnesota, Part XV (1).

WATER RELATIONS

Water Use and Water Use Efficiency

The amount of dry matter produced by a crop is in direct proportion to the amount of water consumed in evaporation and transpiration. The relationship between dry matter production and water use, or evapotranspiration, for irrigated alfalfa is illustrated in Figure 3. The high correlation ($r = 0.86$) between alfalfa yield and evapotranspiration in Minnesota is comparable to that for the southern deserts and Great Plains (2, 11).

Regression analysis indicates that yields of alfalfa harvested at one-tenth flower increased by 0.4 T/A for each 1 inch of water consumed in Minnesota. Water use efficiency (WUE), the mass of dry matter per unit land area for each inch of water, however, will be smaller than 0.4 T/A/inch when averaged over both the vegetative and flowering growth periods. This is because alfalfa stands become more efficient in water use as the stand matures. Thus, growing period water use efficiency values of 0.25 T/A/inch are common at St. Paul and in other areas of the north-central region (2).

Daily water use during growing periods generally increases with the advancement in the growing season due to greater evaporative demand imposed upon the plant in high temperature and radiation intensity environments. The former condition also results in smaller plant leaves, which can offset the increased water use in the latter part of the season. For example, in the period 1981 to 1983, the average amount of water consumed at St. Paul in the spring, early summer, and late summer growth periods was 0.15, 0.25, and 0.20 inch/day, respectively. Water use efficiency also decreases with the progression of the season because alfalfa stomates do not completely close under high moisture stress conditions. This results in continued transpiration and little growth benefit (6, 7). Thus, the water use efficiency decreased at St. Paul from 0.30 T/A/inch in spring to 0.25 T/A/inch in early summer and to 0.20 T/A/inch in the late summer period.

Soil Water Extraction

A water extraction pattern from the soil by irrigated alfalfa at St. Paul is illustrated in Figure 4. Approximately 60 percent of the total soil water use for a given growing period is drawn from the top one-fifth of the root zone. Water extraction from each subsequent one-fifth of the root zone corresponds to about 20, 10, 5, and 5 percent of the total. These percentages are nearly the same as those found for alfalfa in Nevada (13) and Arizona (8). For example, in Nevada, water extracted from each subsequent one-fifth of the root zone corresponded to 45, 25, 10, 10, and 10 percent of the total water extracted from the root zone. The Arizona study indicated that 45, 25, 20, and 10 percent of the total soil water extracted had come from the top and subsequent quarters of the root zone.

Potential Evapotranspiration

The amount of water consumed by a crop under nonlimiting growth conditions is referred to as potential evapotranspiration (PE). Equations relating PE to meteorological factors such as temperature and solar radiation are numerous and consist of one, two, or a combination of meteorological factors in the equation (14). The equations and their product, PE, can be used for irrigation scheduling, which requires a knowledge of potential water use by a crop.

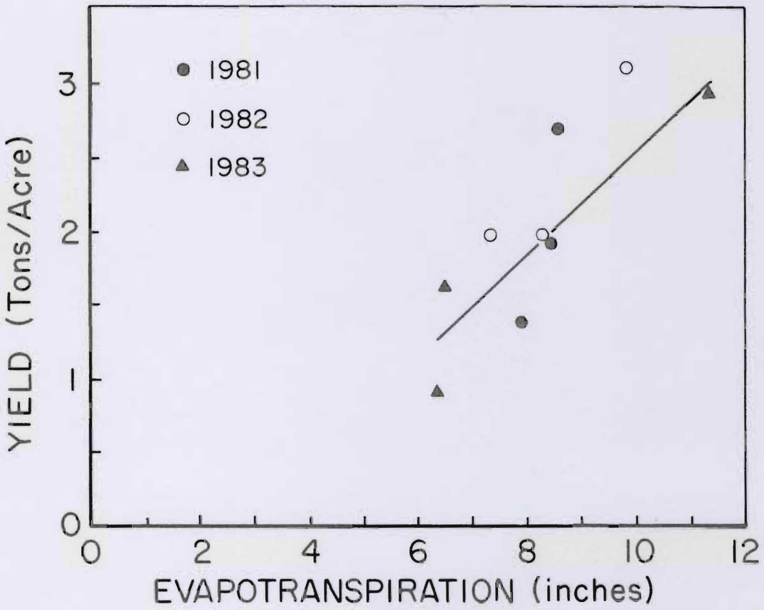

Figure 3. Relationship between the yield of alfalfa and measured evapotranspiration at St. Paul, 1981-1983.

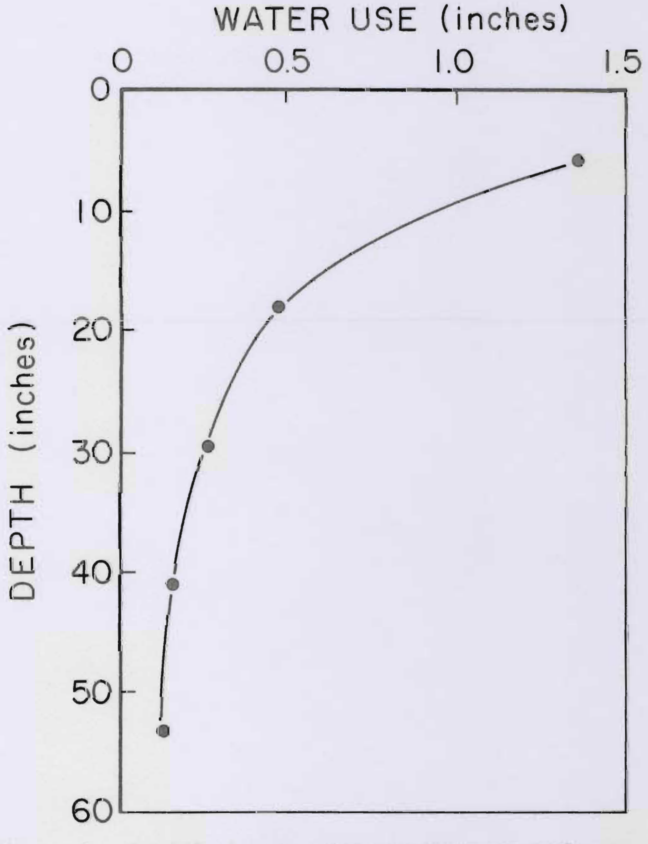

Figure 4. A typical extraction pattern of soil water for irrigated alfalfa at St. Paul.

Eighteen years of alfalfa water use data from Ohio indicated that of the PE equations which employ only a temperature factor, the Blaney-Criddle equation performed the best (18). The best PE equation for alfalfa under field conditions employing both temperature and solar radiation was that of Jensen-Haise (18). These two equations were also superior to other ET equations estimating alfalfa PE in the seeding year in Minnesota (16).

The Blaney Criddle equation (BC) is defined as:

$$BC\ PE = (0.0173 \times T - 0.314) \times KC \times T \times (DL/TDL) \quad [5]$$

where T is the average daily temperature (°F), KC is the crop coefficient, DL is daylength, and TDL is the yearly total daylight hours. PE is in inches of water.

The Jensen-Haise equation (JH) is defined as:

$$JH\ PE = (0.014 \times T - 0.37) \times SR \quad [6]$$

where T is the average air temperature (°F) and SR is the solar radiation expressed as an equivalent amount of water evaporated (inch). PE is in inches of water.

The weighing lysimeter, a precision weighing device, and the microclimate facility at St. Paul were used to test the accuracy of the two PE equations over the 3-year period 1981-1983. Alfalfa was grown under nonlimiting soil water conditions in the lysimeter and a surrounding plot. Comparisons of lysimeter PE and that estimated by both equations for the 3 years are shown in Figure 5. The average daily differences between lysimeter PE and that estimated by the BC and JH equations were each 0.09 inch. The range in the daily differences between lysimeter PE and BC PE was -0.13 to 0.26 inch; and between lysimeter and JH PE the difference range was -0.04 to 0.28 inch. These comparisons indicate that the JH PE is a better estimate of the lysimeter PE under Minnesota conditions.

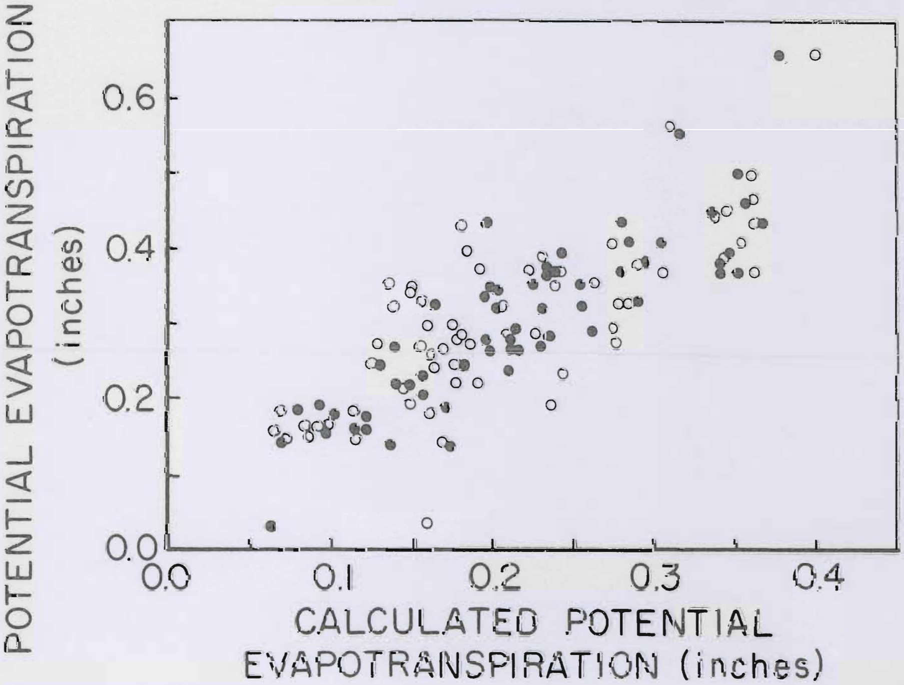

Figure 5. Comparison between lysimeter measured potential evapotranspiration at St. Paul and potential evapotranspiration calculated by the Blaney-Criddle (open circles) and Jensen-Haise (dark circles) methods.

The JH equation was developed based upon the hypothesis that the ratio of the amount of water used in evapotranspiration to the potential amount evaporated from a water surface by solar radiation is correlated with air temperature. The equation was modified for better agreement with the St. Paul lysimeter data (24). The relationship between the ratio of lysimeter PE to daily solar radiation and the average daily air temperature is plotted in Figure 6.

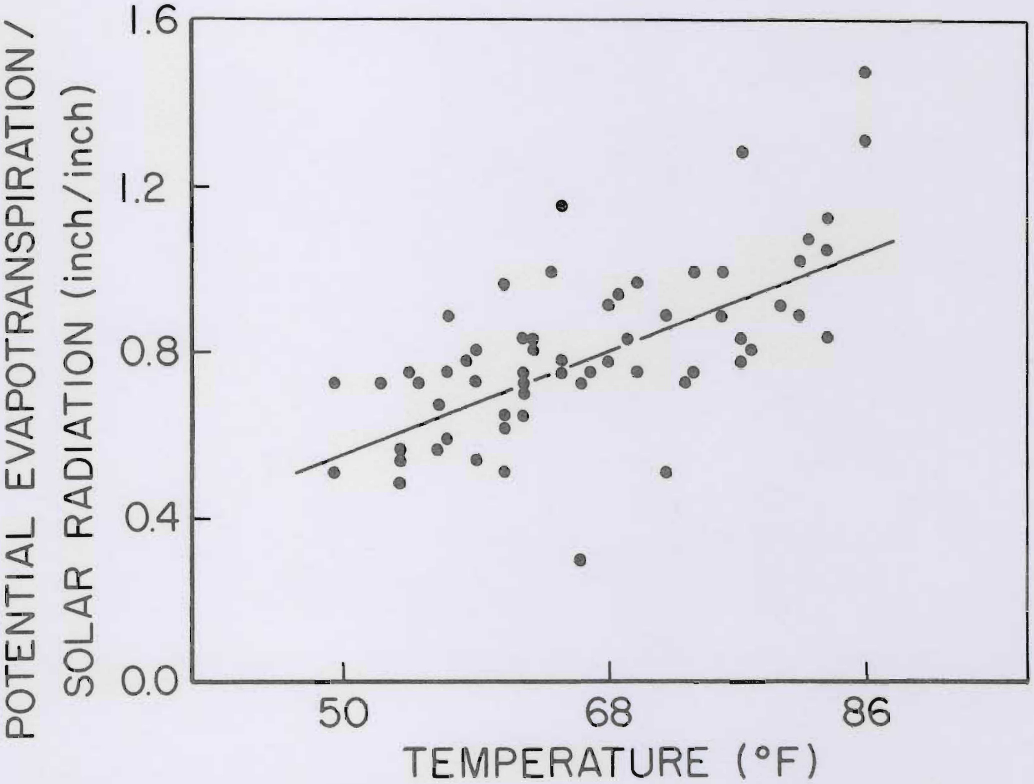

Figure 6. Relationship between the ratio of lysimeter potential evapotranspiration (PE) to daily solar radiation (expressed in its evaporation equivalent) and daily temperatures (T) at St. Paul.

The modified form of the JH equation (MJH) derived from this relationship is:

MJH PE = (0.014 x T - 0.13) x SR [7]

PE is in inches of water.

The modified and original forms of the JH equation only differ in the value of the intercept. This difference indicates that the amount of solar energy used by alfalfa in evapotranspiration at the same temperature is higher in the north-central region than in the western United States, where Jensen and Haise developed their equation. The greater utilization of solar radiation in alfalfa water use may be related to the more humid conditions and lower solar radiation reception in the north-central than the western region of the United States. The equality of the slope estimates suggests that the air temperature effect on solar energy utilization during evapotranspiration is the same for both regions.

The concept of PE is only applicable to crops having well developed canopies which cover the underlying surface and to soils with a readily available water supply. In the early stages of alfalfa development, an adjustment, called a crop factor (CF), must be applied to the PE estimate to compensate for reduced water use when the crop does not completely cover the underlying surface. Potential evapotranspiration at any developmental time can be estimated by the modified JH equation and accounting for the CF as follows:

PE = CF * MJH PE [8]

For application in Minnesota the CF was determined by comparing the ratio of the lysimeter to MJH PE over a range of development as defined by GDD (24). This procedure permits a determination of the crop factor as a function of GDD as illustrated in Figure 7. A curvilinear expression describes the St. Paul data well, with the CF having an upper threshold value of 1.0 after which it remains constant as GDD increases.

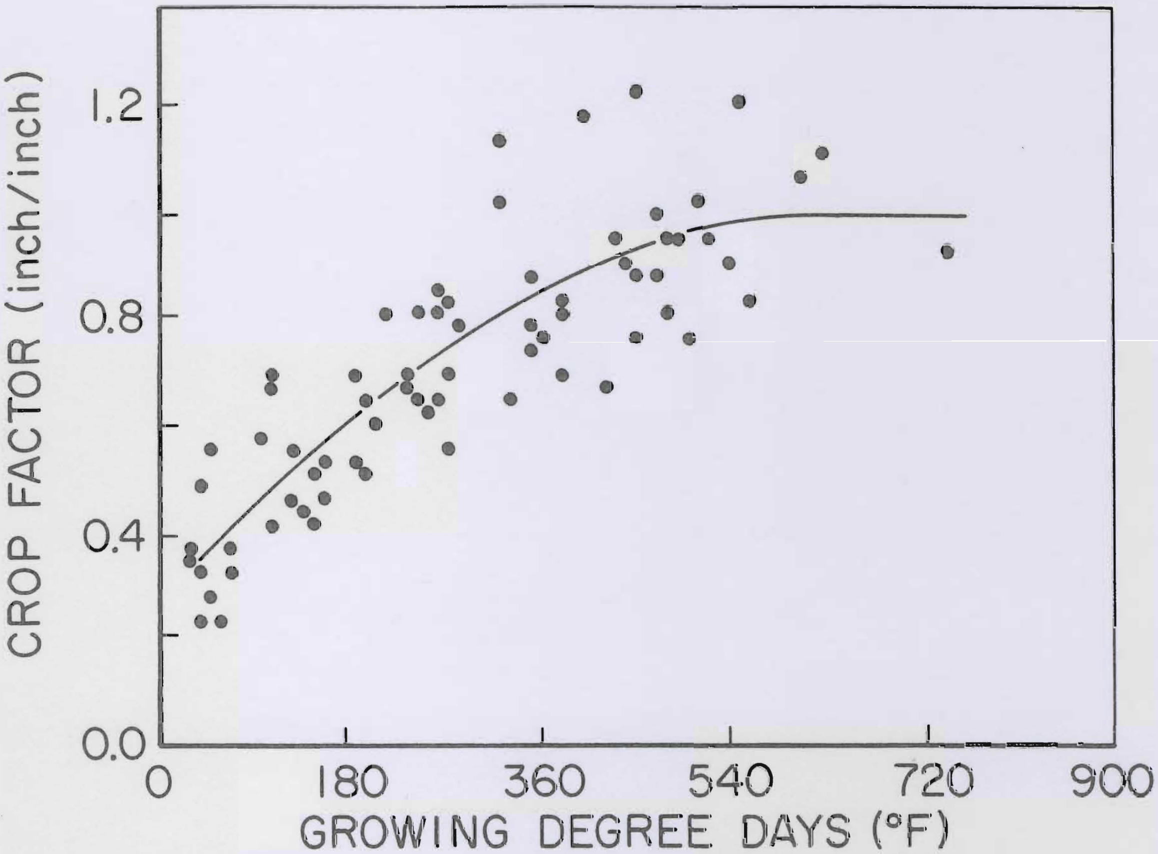

Figure 7. Change in the crop factor shown as a function of growing degree days. The crop factor is an adjustment applied to evapotranspiration estimates until the development of a full canopy. The growing degree days serve as a measure of time.

The appropriate CF for use with the MJH equation in estimating alfalfa PE under conditions of incomplete vegetative cover can be derived as follows:

$$CF = 0.26 + (2.24 \times 10^{-3} \times GDD) - (1.66 \times 10^{-6} \times GDD^2) \qquad [9]$$

This expression indicates that CF = 1.0 when GDD in °F equals 580 using the appropriate base temperature as noted in the section on GDD. Above 580 GDD the CF can be assumed to remain constant throughout the remainder of the growth period.

Daily potential evapotranspiration calculated using the modified JH equation increases with subsequent growth periods (24). Accounting for the increasing CF in the early stages of development, alfalfa under nonlimiting soil water conditions can be expected to consume about 0.15, 0.30, and 0.25 inch/day of water for each successive growth period. These estimates, however, will vary due particularly to differences in the climate, and also to soil and plant factors.

Pan Evaporation

Pan evaporation can be a useful measure of crop water use. It is generally a rapid and simple method to estimate water use and integrates all climatic factors into a single value, the amount of evaporation. Pan evaporation can be measured directly or estimated from meteorological data. Seven years of daily data from St. Paul were used to derive empirical relationships between pan evaporation and climatic factors (24). Monthly correlations between pan evaporation and selected factors were derived using the daily data for each of the seven months in the growing season (April to October) and are presented in Table 2. The correlations between evaporation and each factor change from month to month.

Table 2. Statistical monthly correlations between pan evaporation and climatic factors at St. Paul, MN, 1972-1978.

Climatic Factor	Monthly Correlation[1]						
	April	May	June	July	August	September	October
Solar Radiation	.59	.64	.52	.54	.58	.54	.45
Temperature							
Maximum	.68	.62	.58	.58	.57	.56	.60
Minimum	.35	.28	.37	.37	.28	.26	.30
Mean	.56	.49	.51	.51	.45	.46	ND
Wind Speed	0	.01	.35	.45	.42	.41	.50
Relative Humidity							
Maximum	ND[2]	ND	-.26	-.39	-.39	-.59	-.53
Minimum	ND	ND	-.42	-.39	-.53	-.46	-.48
Mean	ND	ND	-.41	-.47	-.58	-.59	-.60

[1] Based upon daily climatic data.
[2] ND indicates that insufficient data were collected.

Maximum air temperature is most highly correlated with evaporation over the entire season, accounting for about 35 percent of the variability in pan evaporation. Empirical pan evaporation equations which best estimate pan evaporation in each month are listed in Table 3. Generally, 70 percent of the pan evaporation variability is accounted for by climatic factors.

Table 3. Empirical equations relating pan evaporation to climatic factors for the growing season months at St. Paul, MN.

Month	Equation[1]	R^2
April	$\mathrm{Epan} = -0.30 + 2.7 \times 10^{-4}\ \mathrm{SR} + 4.8 \times 10^{-3}\ \mathrm{TX} + 4.5 \times 10^{-4}\ \mathrm{WD}$	0.72
May	$\mathrm{Epan} = -0.34 + 3.0 \times 10^{-4}\ \mathrm{SR} + 5.0 \times 10^{-3}\ \mathrm{TX} + 6.0 \times 10^{-4}\ \mathrm{WD}$	0.72
June	$\mathrm{Epan} = -0.33 + 2.6 \times 10^{-4}\ \mathrm{SR} + 8.2 \times 10^{-4}\ \mathrm{WD} - 2 \times 10^{-3}\ \mathrm{RHN} + 6.7 \times 10^{-3}\ \mathrm{TA}$	0.63
July	$\mathrm{Epan} = -0.30 + 2.1 \times 10^{-4}\ \mathrm{SR} + 5.3 \times 10^{-3}\ \mathrm{TX} + 1.1 \times 10^{-3}\ \mathrm{WD} - 1.6 \times 10^{-3}\ \mathrm{RHN}$	0.70
Aug.	$\mathrm{Epan} = -0.16 + 1.7 \times 10^{-4}\ \mathrm{SR} + 4.3 \times 10^{-3}\ \mathrm{TX} + 1.0 \times 10^{-3}\ \mathrm{WD} - 2.4 \times 10^{-3}\ \mathrm{RHN}$	0.66
Sept.	$\mathrm{Epan} = 0.02 + 2.1 \times 10^{-4}\ \mathrm{SR} + 7.7 \times 10^{-4}\ \mathrm{WD} + 3.4 \times 10^{-3}\ \mathrm{TA} - 3.0 \times 10^{-3}\ \mathrm{RHA}$	0.74
Oct.	$\mathrm{Epan} = 1.3 \times 10^{-4}\ \mathrm{SR} + 2.6 \times 10^{-3}\ \mathrm{TX} + 5.2 \times 10^{-4}\ \mathrm{WD} - 1.9 \times 10^{-3}\ \mathrm{RHA}$	0.74

[1] Epan = pan evaporation (inch/day);
SR = solar radiation (cal/cm^2 day);
TX = maximum air temperature (°F);
WD = wind speed (miles/day);
RHN = minimum relative humidity (%);
TA = average air temperature (°F);
RHA = average relative humidity.

Pan evaporation can also be used to estimate alfalfa PE by applying a pan factor (PF) to the pan evaporation. The relationship is expressed as:

$$PE = PF \times Epan \qquad [10]$$

where Epan is pan evaporation. This relationship assumes a crop with complete cover; however, PF can be varied depending on the stage of crop development. To derive PF, the relationship between lysimeter PE and pan evaporation was evaluated during the growing periods with time measured by GDD, Figure 8.

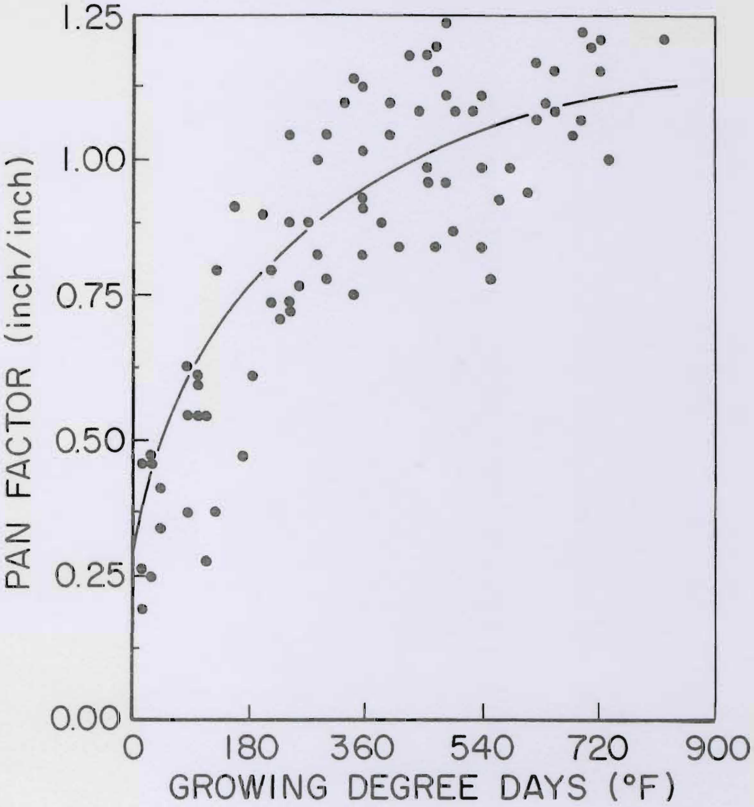

Figure 8. Relationship between the pan factor and growing degree days.

The relationship obtained in the Minnesota study (24) is:

$$PF = 0.29 + (4.89 \times 10^{-3} \times GDD) - (7.43 \times 10^{-6} \times GDD^2) \qquad [11]$$

This expression indicates that pan evaporation and alfalfa PE are equal (PF = 1.0) at 365 GDD using the appropriate base temperature. Thereafter, alfalfa PE exceeds pan evaporation. Typical PF values during the growing season at St. Paul are shown in Figure 9. Values range from 0.5 following a harvest to 1.1 at one-tenth flower. An average PF for each growing period from regrowth to harvest was determined from total pan evaporation and lysimeter PE data for each of the three growing periods. Based upon experimental results the PF values of 0.85, 0.95, and 0.85 can be expected in the spring, early summer, and late summer periods, respectively (24).

GROWTH-CLIMATE RELATIONS

Plants use both solar radiation and moisture in the photosynthetic process of fixing carbon. A portion of the fixed carbon is stored for use during dormancy and for regrowth in spring and following each harvest. The thermal environment influences this process through its effect on enzymatic reactions which can positively or negatively influence growth. Three environmental factors affecting plant growth are the focus of this section: temperature, solar radiation, and moisture.

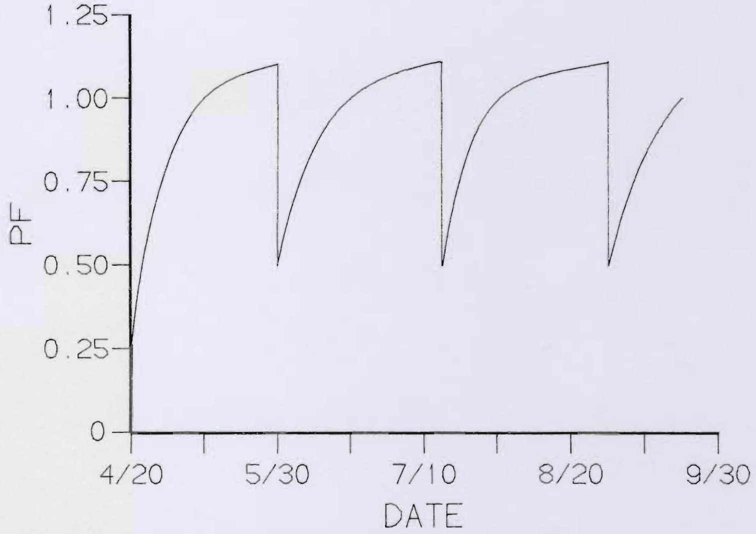

Figure 9. Pan factor (PF) values to be applied to daily pan evaporation measurements in order to approximate the evapotranspiration of irrigated alfalfa from spring regrowth through a three-cutting season.

Growing Season

Alfalfa survives in environments that have extreme climatic conditions. It grows in regions subject to air temperatures as low as -83°F and as high as 120°F. However, growth processes cease much before these temperature extremes. Two important physiological processes that affect growth and that are influenced by temperature are photosynthesis and respiration. Photosynthesis rapidly increases from a temperature of 25°F (temperature at which cellular components freeze) to 40°F; over this range the photosynthetic rate increases 25-fold (19). Temperatures between 40 and 75°F have little effect on photosynthesis, but above 75°F the photosynthetic rate decreases and becomes negligible near 120°F. Respiration proceeds both during the day and at night, but its role in growth and accumulation of dry matter is more pronounced at night. Night temperatures between 25 and 70°F have little effect on the respiration rate. However, above 70°F the rate increases (33), and thus the potential for dry matter accumulation decreases. Night temperatures below 50°F may also have a negative effect on photosynthesis the following day by reducing the translocation of fixed carbon from the chloroplasts (5). The optimum temperatures for growth encompass a daytime temperature range between 60 to 75°F and a nighttime range of 50 and 70°F (5, 19, 33). High temperature environments also cause alfalfa to rapidly mature and have small leaf areas (21). The small leaf area and rapid maturity can lead to reduced carbohydrate concentrations in the roots which affect the vigor and regrowth potential of the plant (5).

Alfalfa photosynthesis increases with solar radiation intensity up to approximately 50 percent of the maximum intensity (33). The maximum rate of photosynthesis occurs when light saturation is reached. This is at intensities near 0.8 cal/(cm^2 min) (a value reached between 8 to 9 a.m. on a clear summer day at St. Paul). Generally, higher intensities result in a larger number of stems, smaller plants (10), and more photosynthate partitioning into roots than stems (9). While the intensity of solar radiation is important, the duration of solar radiation above the light compensation point is of greater importance in dry matter accumulation, since the duration sets a limit to production (3).

Soil moisture is needed to support growth processes in the plant. Generally, the higher the moisture content of the soil is, the more favorable is the water status of the plant. However, alfalfa is prone to phytophthora root rot (Phytophthora megasperma Drechs) under saturated soil conditions (17). As a general rule, growth is best when the soil moisture content is maintained between 35 and 85 percent of the plant available water-holding capacity (32). Although moisture levels associated with optimum growth vary with the water-holding capacity of the soil, the growth is equal when soils of different capacities are at similar relative moisture contents (i.e., similar water potentials). As the soil moisture content decreases below a critical threshold level, stomatal conductance decreases and gaseous exchange is reduced (35). The numbers of buds and stems on a plant are greater under conditions of higher soil moisture content (10).

Hardening Period

The hardening period generally occurs in the fall when a relatively rapid decline occurs in daylength and in air and soil temperatures. The hardening process continues until the soil permanently freezes and the prevailing air temperatures remain below freezing. At this time the maximum level of hardiness is attained (30). At St. Paul this condition ordinarily occurs in early December. Field experiments with alfalfa at Madison, Wisconsin, indicate that although the maximum hardiness was not reached until January 1, it was very little different from the hardiness developed in mid-December (12). Hardening generally occurs over a temperature range between 25 and 60°F with an optimum at 40°F (34). Alternating day and night temperatures favor hardening, preferably with warmer temperatures during daylight and cooler temperatures at night.

Alfalfa cultivars vary in response to decreasing daylength and temperature in the fall (29). For the winter period a reduced herbage production and an increased root carbohydrate storage occurs in adapted dormant (winterhardy) cultivars. Non-dormant or non-winterhardy cultivars have little or no response to daylength and temperature and typically have greater fall herbage production than adapted cultivars. Non-dormant cultivars do not consistently overwinter in Minnesota.

Alfalfa undergoes many physiological changes during the hardening process, most notably in the crown and roots, which enable it to survive the extreme cold temperatures of winter in the northern United States. The changes occurring in the plant cells as hardening commences include: (a) a decrease in the cellular water content, (b) an increase in bound water concentration of cells, (c) structural changes in the protoplasm, and (d) an increase in solutes and transformations of carbohydrate from a stored (starch) to a mobile form (sucrose) (31).

Solar radiation is important in promoting hardening of alfalfa plants. Generally, greater intensities favor a higher photosynthetic rate, which results in increased carbohydrate storage. The positive relationship between solar radiation intensity and hardiness applies only when air temperatures are between 40 and 85°F. Below 40°F hardiness is influenced by the photoperiod or the quantity of solar radiation received. A doubling of the solar radiation results in nearly a two-fold increase in hardiness (34).

The role of soil moisture in the hardening process is not firmly established, although saturated soils are not conducive to hardening. Apparently soil moisture plays an important role in the temperature relations of the plant. Under short periods of cold temperatures, soils with a higher moisture content cool more slowly because of their increased thermal capacity. However, heaving of alfalfa is more pronounced in high moisture soils. In addition, because air is a better insulator than is water or ice, higher soil moisture levels may ultimately result in lower soil and plant temperatures.

Winter

Of the four seasons, winter may be the most important in terms of alfalfa stand maintenance and long-term production. Meteorological factors are important in winter injury sustained by alfalfa, but the relative importance of the factors appears to differ between climatic regions. Possibly the two most important factors are air temperature and snow cover (22), both of which influence soil temperature. Alfalfa stand loss is largely due to lethal soil temperatures. Other meteorologically induced conditions which influence winter survival are periods of alternating temperatures and ice sheeting. Alternating temperatures may lead to freezing and thawing of the soil and result in heaving of the plants. In addition, alfalfa regrowth may be stimulated during warm periods only to be followed by killing temperatures. Ice sheeting, which occurs largely on poorly drained soils, reduces the gaseous exchange between the soil and the atmosphere. The build-up of respiratory products in the soil is lethal to alfalfa.

Freezing of alfalfa crown and root cellular tissue may begin at temperatures near 25°F (20). However, it is not until temperatures drop below 15°F that substantial injury occurs to this tissue; the 15°F temperature appears to be near the lethal point (31). In regions with continental climates, such as Minnesota, air temperature is the most important meteorological factor influencing alfalfa injury. Air temperature is less important in maritime climatic regions where moisture in the form of rain or snow (ice sheeting and heaving) contributes most to injury (22).

Snow insulates the soil from extreme cold air temperatures. This insulation retards and often prevents the soil from reaching temperatures which could be lethal to the alfalfa crown and roots. The amount of snow required to insulate the soil from reaching temperatures as low as 15°F is dependent on several factors, including the equivalent water content of the snow (its density), ice crystals formed in the snow, and the moisture content of the soil. One investigation found that 4 inches of snow was sufficient to completely insulate the soil (15). However, to define the insulating quality of snow at various depths, a graphic representation is provided in Figure 10 of the amount of snow required to maintain a certain soil temperature for any air temperature based upon results at St. Paul. For example, about 5 inches of snow is needed to prevent the soil temperature from dropping below the lethal temperature (15°F) when the air temperature is 0°F. A snow depth of about 6 inches is usually sufficient to maintain soil temperatures above the lethal temperature of alfalfa for the extreme air temperatures encountered in the north-central United States.

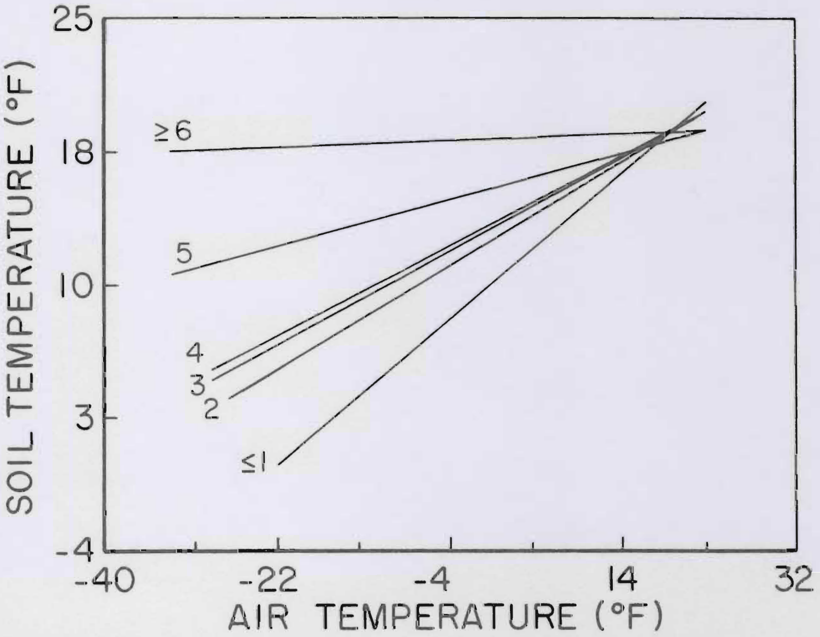

Figure 10. Average depth of snow in inches for a given air temperature that will keep the shallow soil temperature at or above the indicated temperature. Because the density of snow varies greatly, the values shown are only approximate and should be used with caution.

YIELD-CLIMATE RELATIONS

The production achieved at each harvest during the year is dependent on climate, soil, and physiological factors. Possibly the least known and studied of these factors are those related to climate (27, 28). Under high management inputs, it may be assumed that production is limited at any one harvest in the season by the climate and the yield from the previous harvest. The previous harvestable yield is related to the amount of root and crown carbohydrates stored in the tissue, which influences the regrowth potential of the plant (31). Spring production is dependent on the previous late summer yield and the climate since the late summer harvest. Similarly, early and late summer yields are dependent on the previous yield and the climate during the regrowth period. The climatic factors most important to spring, early summer, and late summer yields are listed in Table 4. Multiple regression equations are listed from which the response in yield to climatic factors can be assessed. The response in yield to these factors is not necessarily equal in all production years, given the different stand characteristics. Quantified responses referred to hereafter are based upon a 68-percent chance that an increase or decrease in the climate factor is within the specified amount.

Spring Harvest

With Minnesota based studies (24) it was determined that yields of one-year-old stands are favored by high levels of precipitation in the fall prehardening period, the time from late summer harvest to the first occurrence where the maximum air temperature is 60°F or less. Plant growth is active during this period; therefore, precipitation will promote growth at a time of the year when soils are normally low in moisture. Active growth promotes carbohydrate synthesis and storage, which is needed for wintering. Each additional inch of precipitation received during the prehardening period increases spring yields of one-year-old stands by about 0.1 T/A.

Table 4. Environmental factors most important in yields of alfalfa under a three-harvest management system and the associated relationships.

Harvest	Stand Age	Equation[1]	R^2
	Years		
Spring	One	SGYD = 1.81 + 0.078 x PHPN	0.40
	Two	SGYD = -7.41 + 0.059 x FLTX + 0.056 x SGTX + 0.053 x WRTN	0.50
	Three	SGYD = 3.08 + 0.0035 x FLSR - 0.049 x FLTN	0.45
Early Summer	One	ESYD = 1.13 - 0.0126 x ESWD + 0.0032 x ESSR	0.24
	Two	ESYD = 6.61 - 0.0897 x ESTN	0.37
	Three	ESYD = 0.46 + 0.0963 x ESPE	0.33
Late Summer	One	LSYD = 1.66 - 0.685 x ESMR	0.26
	Two	LSYD = -1.72 + 0.0525 x LSTN	0.48
	Three	LSYD = 0.62 + 0.112 x LSPN	0.61

[1] Two-letter prefix on factors indicates growth period: SG = spring, PH = prehardening, FL = fall, WR = winter, ES = early summer, LS = late summer. Factors are: YD = yield in tons/acre, PN = precipitation in inches, TX = maximum air temperature in °F, TN = minimum air temperature in °F, SR = solar radiation in cal/(cm^2 day), WD = wind speed in miles/day, PE = potential evapotranspiration in inches, MR = moisture ratio of precipitation/PE.

Fall and spring maximum air temperatures and winter minimum air temperatures positively influence spring yields of two-year-old stands. The importance of fall temperatures may be related to the positive photosynthesis response to higher daytime temperatures, especially at the time of the year when temperatures drop below the photosynthetic optimum of 50 to 75°F. Winter minimum temperatures positively influence spring yields by reducing winter injury. Generally a 2°F increase in any of the three temperature factors (fall and spring maximum and winter minimum) results in a 0.1 T/A increase in spring yield.

The fall season appears to be the most important to spring yields in the third production year. Solar radiation positively affects and minimum air temperature negatively affects yield. Greater solar radiation may support more top growth provided the plant moisture status is favorable. Increasing top growth in the fall creates the potential to store more root carbohydrates, which influences both the winter survival and spring yield. The minimum air temperature is important in terms of plant respiration. The higher the night air temperature is, the greater is plant respiration, which results in lower dry matter accumulation. The relationships found (24) suggest that for every 1°F rise in fall minimum air temperature or 36 cal/cm^2 decrease in solar radiation, spring yields decrease by nearly 0.1 T/A.

Early Summer Harvest

In the first production year, early summer yields are positively and negatively influenced by early summer solar radiation and wind speed, respectively. The negative effect of wind speed on yields can result from two phenomena. Wind creates a response in plants called "thigmomorphogenesis," which is described as a shortening and thickening of stems caused by mechanical disruption of the plant. Shortening of plants due to stress, either mechanical or environmental, can result in reduced yields. Secondly, under conditions of adequate soil moisture, wind enhances atmospheric mixing and increases the vapor pressure deficit at the top of the canopy. Increasing the vapor deficit leads to higher evapotranspiration rates and creates the potential for water stress if the atmospheric demand is great, thus causing an imbalance in plant water status and eventually reducing growth. Early summer yields can be expected to increase by 0.15 T/A for each 40 cal/cm^2 increase in solar radiation and also to increase 0.35 T/A for each 1 mi/hr decrease in wind speed.

Minimum air temperature was the most important climatic factor influencing yields of two-year-old stands in early summer. The negative relationship between yield and minimum air temperature indicates a reduction in yield following high minimum temperatures. One explanation for this effect is the relationship between high night air temperature and reduced dry matter accumulation due to respiratory losses of carbohydrates. Early summer yields increased by 0.2 T/A for a decrease in minimum air temperatures of 2.5°F.

Early summer yields of three-year-old stands are positively related to potential evapotranspiration (PE). The relationship may be associated with the linear response of yield to evapotranspiration provided that evapotranspiration and PE are equal. This equality is generally correct during early summer when 3 inches of moisture are available (calculated by subtracting PE from precipitation for the winter, spring, and early summer periods) for plant growth at the end of the early summer period.

Late Summer Harvest

Late summer yields of one-year-old stands are negatively influenced by the early summer moisture ratio of precipitation to PE. This suggests that a dry period preceding late summer growth favored yields. A dry period preceding late summer growth may result in greater canopy heating, which offsets the effect of the shortening of the photoperiod, or it may result in greater root penetration into the soil. Greater root penetration may enable alfalfa to cope with precipitation deficits by extracting more water from deep within the soil profile.

Higher minimum air temperatures favor yields of two-year-old stands (24). This effect may be a means of offsetting the short photoperiod characteristic of the late summer period. Higher temperatures result in a growth response of alfalfa that a shortening of the photoperiod would otherwise negate. An increase in minimum air temperature of 2.5°F at St. Paul resulted in a yield increase of 0.15 T/A.

Precipitation is the most important climatic factor influencing yields of three-year-old stands (24). The positive effect of precipitation on yields in late summer results from the typical occurrence of an inadequate moisture supply in late summer. A moisture deficit of at least 2.0 inches commonly occurs at the end of late summer, suggesting that all the water needs of the crop are not met and precipitation received above the normal amount is beneficial. Yield increases of 0.25 T/A for each 2.5 inches increase in precipitation were found in Minnesota (24).

SUMMARY

The study of environmental effects on alfalfa production is a complex problem, complicated by the fact that alfalfa is a perennial crop and the environmental conditions vary from one year to the next. These responses to the varying environment are also complicated by the morphological changes of the plant such as an increase in the rooting depth or in the canopy structure as the stand ages. These types of factors influence the response of the plant to its environment, leading to microclimates within plant associations which can be quite different between years.

Information collected from a Minnesota study and from a survey of the literature illustrates the response of alfalfa growth to the environment (Table 5). The environmental factors evaluated over several growth periods include the following: (a) potential evapotranspiration, (b) temperature, including growing degree days, (c) solar radiation, (d) soil moisture content, and (e) precipitation.

Table 5. Alfalfa environmental guide depicting the central Minnesota climate, and the environmental relations and crop growth characteristics of alfalfa. Data used to generate this guide were taken from the literature and from Minnesota-based studies.

	Growth Period[a]					
Variable	Spring	Early Summer	Late Summer	Prehardening	Hardening	Winter
Days						
Range[b]	20-65	20-65	25-50	10-70	5-50	165-225
Mean[b]	45	35	40	30	20	195
GDD[c] (°F)						
Range	395-1325	395-1010	425-1045	370-1510	45-720	NA
Mean	1035	595	765	855	270	NA
PE[d] (inch)						
Range	2-12	6-18	4-14	2-6	NA	NA
Mean	8	10	10	4	NA	NA
Temperature (°F)						
Range	55-60	65-75	65-75	55-70	40-60	20-30
Mean	58	70	70	65	50	25
Yield response	Increase	Decrease	Increase	Decrease	Increase	Increase
Plant response						
Range[e]	Daytime: 40-85				25-60	15-32
Optimum[f]	Daytime: 60-75		Nighttime: 50-70		40	32
Killing[g]	25				25	15
Solar Radiation						
Range (cal/cm^2·day)	375-560	460-620	375-550	285-405	165-420	155-275
Mean (cal/cm^2·day)	465	535	490	355	260	225
Yield response	None	Increase	None	Increase	Increase	Increase
Plant response[h]						
Threshold (cal/cm^2.min)	Light compensation point: 0.08 Light saturation point: 0.80					NA
Precipitation (cm)						
Range	2-16	2-16	2-10	2-14	0-8	4-16
Mean	6	6	4	4	2	12
Yield response	Decrease	None	Increase	Increase	Decrease	None
Snow Depth						
Optimum	NA					≥ 6 in
Soil Moisture						
Optimum[i]	35-85% available				Field capacity or lower	
WUE[j] (T/A/inch)	0.30	0.25	0.20	NA		

a. Prehardening generally constitutes September, hardening October; NA = not applicable.
b. Range and mean values of days are based on 21 years of data from Rosemount, MN.
c. Growing degree days (GDD) computed at 50°F base temperature for summer periods, 36°F base temperature for all other periods.
d. PE is potential evapotranspiration.
e. After Murata et al., 1965.
f. After Bula and Massengale, 1972; Murata et al., 1965; and Thomas and Hill, 1949.
g. After Nath and Fisher, 1971; and Smith, 1978.
h. After Bula and Massengale, 1972; and Thomas and Hill, 1949.
i. After Stanberry, 1955.
j. WUE is water use efficiency.

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