AN ABSTRACT OF THE THESIS OF

Mongi Ben-Younes for the degree of Doctor of Philosophy in Crop Science presented on January 15, 1992.

Title: Modeling the Temperature Mediated Phenological Development of Alfalfa (*Medicago sativa* L.)

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David B. Hannaway

This study was conducted to investigate the response of seedlings of nine alfalfa cultivars (belonging to three fall dormancy groups) to varying temperature regimes and relate their phenological development to accumulated growing degree days (GDD) or thermal time. Simulation algorithms were developed from controlled environment experiments and were tested in field conditions to validate the temperature-phenology relationships of alfalfa.

The percent advancement to first bloom per day (% AFB day^{-1}) method was used to relate alfalfa phenological development to temperature. The % AFB day^{-1} of alfalfa cultivars was best described by the equation: % AFB day^{-1} = 2.617 $\log_{10} T_m$ - 1.746 (R^2=0.94), where T_m is the mean daily temperature. The X intercept (when the % AFB day^{-1} is zero) indicated

that 4.6 °C was an appropriate base temperature for alfalfa cultivars.

Alfalfa development stage and temperature treatments had significant effects on dry matter yield, time to maturity stages, accumulated GDD_0, GDD_5, and $\log_{10} GDD_{4.6}$. Growth and development of alfalfa cultivars was hastened by warmer temperature treatments. A transformation of the GDD method using the $\log_{10} GDD_{4.6}$ resulted in less variability than GDD_0 and GDD_5 in predicting alfalfa development. The equation relating alfalfa stages of development (Y) to $\log_{10} GDD_{4.6}$ was: $Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$ (R^2=0.94).

Field studies indicated that growth stage and year had significant effects on yield and percent advancement to maturity stages per day. Little difference in MSC, MSW, and $\log_{10} GDD_{4.6}$ was observed due to year or cultivar. The observed relationship between alfalfa growth stage (Y) and accumulated $GDD_{4.6}$ was best described by the regression: $Y = 18.288 \log_{10} (GDD_{4.6}) - 48.888$ (R^2=0.96), and was not different from the growth chamber prediction equation. The non significant year effect suggests that $\log_{10}$ of accumulated $GDD_{4.6}$ would be independent of the season.

Modeling the Temperature-Mediated Phenological Development of Alfalfa (*Medicago sativa* L.)

by

Mongi Ben-Younes

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INTRODUCTION

Alfalfa (*Medicago sativa* L.) is widely cultivated throughout the U.S. and the world (Smith, 1981; Barnes and Sheaffer, 1985; and Marble, 1989). Alfalfa, often called the "Queen of the Forages", is thought by many to be the most important cultivated forage crop in the world. It also is recognized as one of the most widely adapted forage legumes and is the forage species to which all others are compared for herbage dry matter yield, palatability, and quality.

Phenology, which is defined as the study of periodical (i.e. recurring) plant growth and development, is influenced by plant genetic factors and several environmental factors including temperature, photoperiod, available moisture, solar radiation, and soil conditions. Of these, temperature and photoperiod are the most critical environment variables affecting alfalfa's growth and phenological development. Temperature, in particular, affects the rate of plant photosynthesis and respiration, thus conditioning the growth rate and timing of phasic development.

Alfalfa yield and forage quality are directly related to its stage of growth (Kalu and Fick, 1983). Alfalfa's phenological development is influenced mainly by changes in temperature (Boldocchi et al., 1981). How alfalfa responds to variations in temperature is an important question in predicting plant growth, yield, and selecting suitable cultivars for particular environments.

Crop models have been developed to simulate crop growth and development and to predict yields in specific environments. The accurate prediction of crop development can assist growers and farm managers to better schedule management operations such as planting, harvesting, fertilizing, and irrigating. In recent years, crop models have become useful tools for management and decision making in crop production systems. These models also have improved our understanding of crop development and growth processes.

Temperature is a variable that drives many crop growth models (Gepts, 1987; Hodges, 1991). It is the primary determinant of alfalfa growth, development, yield, and quality (Vough and Marten, 1971; Sharratt et al., 1986).

The concept of accumulated thermal time or growing degree days (GDD) has been advanced to describe the rate of plant development through various phenological stages. Accurate prediction of the occurrence and duration of alfalfa growth stages is essential to the accurate prediction of physiological responses and resultant forage quality under varying field conditions. Understanding phasic development of alfalfa cultivars in response to thermal time will assist in the appropriate management of alfalfa for maximum quantities of high quality harvested forage.

The primary focus of this study was to investigate the response of nine alfalfa cultivars (belonging to three fall dormancy groups) to varying temperature regimes and relating their phenological development to accumulated thermal time or heat units. Simulation algorithms were tested in field experiments.

REVIEW OF LITERATURE

IMPORTANCE AND USE OF ALFALFA

Alfalfa (*Medicago sativa* L.) is one of the most important forage plants in the U.S. where it is grown on more than 12 million hectares (Barnes et al., 1988; Marble, 1989). Of all field crops grown in Oregon, alfalfa hay ranks second in value to wheat. Alfalfa is planted on about 400,000 acres with commercial sales of over $60,000,000 and a farm-gate value of about $150,000,000 (Oregon Department of Agriculture, 1990).

Alfalfa has the highest feeding value of all conserved feeds and is used for livestock of all classes (Hanson and Barnes, 1988; Marble, 1989). Alfalfa produces more protein per hectare than any other crop for livestock (Marble, 1989). Alfalfa also is high in mineral content and contains more than 10 different vitamins (Marten et al., 1988; Conrad and Klopfenstein, 1988). It is a palatable and high yielding perennial legume which can be grown alone or in combination with other grasses/or legume species. It usually is harvested several times a year and can be fed as green chop, silage, hay, pellets, or cubes. Alfalfa also can be grown for pasture grazing or seed production.

Alfalfa gained its reputation as "Queen of the Forages" because of its high yield and superior palatability. It also is an effective source of biological nitrogen fixation for other rotational crops. Alfalfa consistently fixes more nitrogen (N) than other legume species on a seasonal basis (Vance et al., 1988). It fixes 100 to 400 kg of N ha^{-1} yr^{-1} (depending on *Rhizobium spp.,* management practices, and location), with an average of 200 kg of N fixed ha^{-1} yr^{-1} (Vance et al., 1988).

In a seven-year study at the University of Missouri (Jacobs, 1987), alfalfa ranked second only to soybeans in terms of net return per hectare, but when net return included components of soil erosion losses from the two crops, alfalfa proved to protect the soil 8 times more than soybeans. When grown for green manure in rotation with a variety of other crops, alfalfa increases soil N and organic matter and the yield of the following crops. Alfalfa can supply enough N for maximum economic corn yield the first and second year after being used as a green manure crop (Certified Alfalfa Seed Council, 1988).

The outstanding nutritional value of alfalfa, its adaptation to a wide range of environmental conditions, its palatability and high yields, and the soil improvement benefits of alfalfa, besides its ability to provide several harvests every year, have made this excellent forage legume valuable to growers and resulted in widespread use of alfalfa all over the world (Marble, 1989).

PHENOLOGICAL DEVELOPMENT OF ALFALFA

Plant phenology is defined as the study of periodical plant development, differentiation, and the initiation of organs (Hodges, 1991). Gepts (1987) defined plant phenology as the study of periodical (i.e. recurring) plant growth and development phenomena, as influenced by genotype and the total environment. Plant phenology refers to the study of how the environment controls the rate and course of plant growth and development (Gepts, 1987). Plant phenology also can be characterized in morphological terms through the use of growth and development scales. Morphological growth stages are correlated with physiological changes and characteristics of cultivated crop species.

Plant growth stages have important agronomic consequences. For example, Darwinkel (1983) found that N influenced yield components of winter wheat differently, depending on the growth stage at which N was applied. Kalu and Fick (1984) found that variation in the nutritive value of alfalfa herbage was affected by the environmental and physiological history of the crop.

The nutritional quality of alfalfa hay is greatly affected by maturity stage at cutting and the environmental conditions prior to and during harvest (Sharratt et al., 1986; Sheaffer et al., 1988). Of these factors, growth stage or maturity has the greatest influence on alfalfa yield and quality (Kalu and Fick, 1981, 1983).

Understanding alfalfa phenology has led to a better understanding of many physiological concepts, including critical nodulation periods, root carbohydrate reserves, and selecting cultivars that are better adapted to specific agricultural regions. The relationship between morphological characteristics and physiological response also is important for planning appropriate management strategies based on specific growth stages.

Alfalfa phenology relates plant morphological development to seasonal environmental changes. During the intermittent growth cycles of an established alfalfa stand, plants go through two main phases of growth and development; vegetative and reproductive. The vegetative period particularly interests forage producers. This phase starts from seeding or regrowth of alfalfa plants after grazing or cutting until the initiation of reproductive structures and flowering. The reproductive phase is of prime interest to alfalfa seed producers.

Nelson (1925) and Albert (1927) identified and classified five stages of alfalfa growth from seedling to seed pod. Albert (1927) used plant height to characterize the vegetative part of the five stages of alfalfa growth. In 1950, Dotzenko and Ahlgren used a seven-stage system where they considered two stages based on plant height for the vegetative period. These authors also subdivided the bud stage into prebud and bud, and introduced the 10%, 50%, full bloom, and seed pod stages. Winch et al. (1970) subdivided the bud stage into 3 different stages; early, medium, and late. In 1972, Gengenbach and Miller used a four-stage system to describe alfalfa growth. This system was based on the frequency distribution of alfalfa shoots in different stages. Fick and Holthausen (1975), and Fick and Liu (1976), used a scale of 1 to 4 to rate the growth and development of alfalfa from vegetative to seed pod stages. These stage classification systems lacked uniformity and accurate description, and omitted consideration of several transitional changes and proportions of stems and leaves during alfalfa phenological development.

In 1981, Kalu and Fick reported a 10-stage classification system for alfalfa development in which two procedures were used to determine stages. Table 1 displays Kalu and Fick's ten-stage classification system for defining alfalfa's morphological development stages. This system considers ontogeny, phasic development of alfalfa plant shoots, plant height, and initiation of reproductive structures. It has been used successfully in recent years by several researchers to predict alfalfa yield and quality (Kalu and Fick, 1983; Muller and Fick, 1989; Sanderson et al., 1989; Vodraska, 1990; and Fick and Janson, 1990). The mean stage by count (MSC) procedure estimates the mean stage as the average of observed stages weighted for the number of

Table 1. Names and definitions of 10 alfalfa morphological development stages (Kalu and Fick, 1981).

Stage no.	Stage name	Stage definition
0	Early vegetative	Stems ≤ 15 cm; no buds, flowers, or seed pods.
1	Mid-vegetative	Stems 16 to 30 cm; no buds, flowers, or seed pods.
2	Late vegetative	Stems ≥ 30 cm; no buds, flowers, or seed pods.
3	Early bud	One or two nodes with visible buds; no flowers or seed pods.
4	Late bud	≥ three nodes with buds; no flowers, or seed pods.
5	Early flower	One node with one open flower (standard open); no seed pods.
6	Late flower	≥ two nodes with open flowers; no seed pods.
7	Early seed pod	One to three nodes with green seed pods.
8	Late seed pod	≥ four nodes with green seed pods.
9	Ripe seed pod	Nodes with mostly brown and mature seed pods.

shoots in each stage. The MSC has provided a quick way of estimating alfalfa hay quality in a growing stand of alfalfa. The mean stage by weight (MSW) procedure estimates the average of the observed stages weighted for the dry matter of shoots in each stage (Kalu and Fick, 1981, 1983; Mueller and Fick, 1989). The MSW also can be predicted using MSC values. It is a quick and inexpensive way of predicting alfalfa's stage of development and quality (Sanderson et al., 1989; Vodraska, 1990).

Kalu and Fick (1981) defined MSC and MSW for a particular alfalfa morphological stage as follows:

$$MSC = \Sigma\ S*N/C$$

$$MSW = \Sigma\ S*D/W$$

where S = morphological stage number; 0 to 9,

N = number of shoots in stage S,

C = total number of all shoots in a forage sample,

D = dry weight of shoots in stage S,

W = total dry weight of all shoots in a forge sample.

The MSW can be estimated accurately from MSC by the equation MSW = 0.456 + 1.153*MSC (R^2=0.98) (Mueller and Fick, 1989).

TEMPERATURE EFFECTS ON ALFALFA GROWTH AND DEVELOPMENT

Variation of alfalfa response to different environmental factors has been investigated by many researchers (Ku and Hunt, 1973; Christian, 1977; Sharratt et al., 1987; Ta and Faris, 1988). Alfalfa phenological development is influenced by temperature, photoperiod, available moisture, solar radiation, and soil condition (Jung and Larson, 1972; Fick, 1988). Temperature is the most important variable influencing alfalfa growth and development (Smith and Struckmeyer, 1974; Boldocchi et al., 1981).

Temperature affects the rate of both plant photosynthesis and respiration. Since it is the balance between photosynthesis and respiration which controls the rate of dry matter accumulation, temperature controls the growth rate and timing of phasic development of all plants (Fick et al., 1988).

Boldocchi et al. (1981) reported that alfalfa phenological development is influenced mainly by changes in temperature. Smith (1969) found that alfalfa exposed to a warm temperature regime (32/24 °C) flowered earlier (21 days versus 37 days) than under cooler conditions (18/10 °C). Similarly, in 1969, Nelson found that a warm temperature regime (32/24 °C) hastened alfalfa flowering. Ueno and Smith (1970) found that alfalfa maturity was delayed by cool temperatures (21/15 °C). A similar conclusion also was reported by Nelson and Smith (1969) who found that a warm temperature regime (32/24 °C) hastened alfalfa flowering. The growth of new alfalfa seedlings also was greater between 21 and 27 °C than at 16 °C (Heichel et al., 1988). As alfalfa seedlings advanced in age and growth stage, Pearson and Hunt (1972b), and Cameron (1973), found that the optimum growth temperature declined from 30/25 °C to 20/15 °C.

Several researchers have reported the effect of temperature on total nonstructural carbohydrates, crude protein, crude fiber content, and yield for alfalfa cultivars (Shih et al., 1967; Smith, 1969; Ueno and Smith, 1970; Arbi et al., 1979; and Boller and Nosberger, 1983). Alfalfa grown under cool temperatures (18/10 °C) was higher in total digestible nutrients and nonstructural carbohydrates but lower in protein and most nutrient elements except Ca and Mg (Griffith, 1974). Decreased yield (up to 50%) under high temperatures has been reported by several authors (Smith, 1969; Vough and Marten, 1971). Chemical changes also occurred, with digestible dry matter, nonstructural carbohydrates, Ca, and Mg increasing under cool temperature regimes. Crude protein, ether extract, total ash, P, K, Al, Fe, B, Ca, Mg, Cu, Zn, and Mn increased under warm temperatures.

Biological nitrogen fixation by alfalfa plants is particularly sensitive to temperature variations (Barta, 1978; Harding and Sheehy, 1980). Root temperatures of 30 °C decreased apparent nitrogen fixation as measured by acetylene reduction by as much as 50% when compared to alfalfa maintained at 16 °C (Barta, 1978). Duke and Doehlert (1981), also found that cool temperatures (5 to 10 °C) decreased acetylene reduction by more than 75% relative to warm temperatures (20 to 25 °C).

Thus, temperature has profound effects on the growth and development of alfalfa including net photosynthesis, phenological development, structural and nonstructural carbohydrates, nutrient composition, and biological nitrogen fixation.

The concept of growing degree days (GDD), sometimes called heat units, effective heat units, thermal time, or growth units, has been advanced to quantitatively describe plant growth and development (Hodges, 1991). The GDD value is an arithmetic accumulation of daily mean temperatures above a certain threshold temperature which is considered the base temperature. The GDD concept is a useful method of predicting crop growth and development. Researchers have used GDD to relate plant growth, development, and maturation to air temperature (Gilmore and Rogers, 1958; Arnold, 1959; Russelle et al., 1984). Different plant species have different base or threshold temperatures. For modeling phenological development with GDD, the base temperature should result in no advancement of phenological development. At temperatures above this base temperature, phenological development is proportional to accumulated heat units or thermal time (Davidson and Campbell, 1983; and Morrison et al., 1989).

Over the last decade many researchers have investigated the GDD concept and verified its close relationship with growth and phenological development of several crops. Russelle et al. (1984) indicated that for most field crops, simple models based on temperature alone (GDD calculation using an appropriate base temperature) often can explain over 95% of the variability in phenological development.

COMPUTER MODELING OF ALFALFA GROWTH AND DEVELOPMENT

Crop growth models are mathematical descriptions of the growth and development of the crop production systems that they represent. They are dynamic computer programs designed to simulate the response of the major plant physiological processes to environmental factors and to each other (Hodges, 1991). Crop growth models can be used to simulate complex features of the real system by using simplified designs and concept (Jones, 1970; Charles-Edwards, 1986).

Crop growth models often are used to predict changes in the crop with time (Fick, 1988). They have been developed to simulate crop growth and development and to predict yields in specific environments. Numerous models have been developed to describe the phenological development of plant species as a function of environmental variables (Daughtry et al., 1984). Most crop growth models are driven by daily weather data such as temperature, solar radiation, and moisture. Inputs for these models frequently include the soil type and pest conditions (i.e weeds, pathogens, and symbionts) (Hesketh and Dale, 1987; and Loomis and Rabbinge, 1987).

To develop these models, some crop growth modelers have used extensive information on soil, weather, and phenology. Other authors have used only one or relatively few environmental factors to predict plant growth and development

(Neild and Seeley, 1975; Davidson and Campbell, 1983 and Russelle et al., 1984).

Warrington and Kanemasu (1983) indicated that crop growth models were developed to overcome the inadequacies of calendar day systems for predicting crop growth and development. Models can be useful tools for management and decision making in crop production systems attempting to schedule critical growth stages during the most favorable environmental conditions (Charles-Edwards et al., 1986). Computer simulation models provide a means of predicting and studying the influence of management strategies and environmental variables on crop growth and development without actually conducting costly field experiments (Barnes et al., 1988). These models also have helped improve the understanding of crop growth and development processes, the response of plant metabolism to environmental factors, and the interrelationships of physiological processes (Gepts, 1987).

Temperature is a primary factor considered by many crop growth simulation models (Bourgeois et al., 1990; Ritchie and Smith, 1990). It has a direct influence on all plant metabolism processes and determines the rate of crop growth and development (Russelle et al., 1984). Plant growth and development is the result of the integrated effects of temperature on the many individual physiological processes involved. Temperature is a primary determinant affecting alfalfa growth, development, yield, and quality (Ueno and Smith, 1970; Sharratt et al., 1986; and Al-Hamdani and Todd, 1990). Several authors also indicated that alfalfa growth and development can be predicted from knowledge of alfalfa's response to environmental variables (Holt et al., 1975; Fick, 1977; and Denison et al., 1984.)

In recent years, several growth models have been developed to simulate the growth and development of a few alfalfa cultivars in the U.S. and Canada (Fick et al., 1988). Several of these models have been used successfully to simulate the growth and development of alfalfa cultivars and relate cutting management to yield and quality (Fick and Onstad, 1981; and Bourgeois et al., 1990). Alfalfa growth models are relatively recent compared to corn, wheat, soybean, and cotton models (G.W. Fick, personal communication, 1990).

A chronological listing of simulated alfalfa growth models is provided in Table 2. The earliest alfalfa model which was an explanatory one dates back to 1974 (Fields, 1974). Other models such as ALSIM 1 (LEVEL 1) (Fick, 1975), ALSIM 1 (LEVEL 2) (Fick 1981), ALSIM 1 (LEVEL 0) (Fick and Onstad, 1983); ALSIM 1 (LEVEL 0) (Fick, 1984), and SIMED (Holt et al., 1975; 1978) have been used to predict growth stage development of alfalfa. These models were originally used in alfalfa weevil protection studies (Onstad and Shoemaker, 1984). ALSIM 1 (LEVEL 2) (Fick, 1981), and DAFOSYM

Table 2. Chronological listing of alfalfa growth simulation models.

Model	Author(s) and year
The Field model	Field, 1974
ALSIM 1 (LEVEL 1)	Fick, 1975
SIMED	Holt et al., 1975
The California model I	Gutierrez et al., 1976
The California model II	Regev et al., 1976
SIMED 2	Dougherty, 1977
REGROW	Fick, 1977
SIMFOY	Selirio and Brown, 1979
The Canberra model	Christian and Milthorpe, 1981
ALSIM 1 (LEVEL 2)	Fick, 1981
DAFOSYM	Parsh, 1982
YIELD	Hayes et al., 1982
ALFAMOD	Gao and Hannaway, 1983
ALSIM 1 (LEVEL 0)	Fick and Onstad, 1983
GROWIT	Smith and Loewer, 1983
ALFALFA	Denison et al., 1984
ALSIM 1 (LEVEL ZERO)	Fick, 1984
The Gosse model	Gosse et al., 1984
ALFMAN	Onstad and Shoemaker, 1984
ALFSYM	Rotz et al., 1986
ALF2LP	Bourgeois et al., 1990

(Parsch, 1982; Savoie et al., 1985) models were later adapted and incorporated into a dairy farm simulation model. The DAFOSYM and ALF2LP models were versions derived from ALSIM 1 (LEVEL 2) (Fick, 1981; Bourgeois, 1985; and Parsch, 1982). All of these models were dynamic computer simulation models of alfalfa phenological growth written in FORTRAN.

Input data needed to run many of these alfalfa models often included the yield of leaves, stems, basal buds, total nonstructural carbohydrate reserves, soil moisture, dates of harvest, site location, and daily weather data for solar radiation, mean daily temperature, and precipitation. Although these models were limited to a few alfalfa cultivars, they were reasonable predictions of alfalfa hay quality. Two particular alfalfa models; ALSIM 1 (LEVEL ZERO) and ALFSYM, were good examples of preliminary models in which alfalfa growth rate was dependent on temperature (GDD) and soil moisture holding capacity, while regrowth of alfalfa plants was a function of GDD accumulated between harvest periods (Fick, 1984). The ALFSYM alfalfa growth model, developed by Rotz et al. in 1986 at Michigan State University, is a recent dynamic computer simulation of alfalfa growth and management model based on the 1975 Fick model.

Several of these models have been used successfully to simulate the growth and development of some alfalfa cultivars in the U.S. and Canada (Bourgeois et al., 1990). However, in several cases these models were only approximate in their prediction of alfalfa growth and yield and would need further development and validation before being adopted. It is known that temperature, photoperiod, and water supply interact with each other in determining alfalfa response. Genetic variability of alfalfa is another component to be resolved before these models can be used widely.

Alfalfa growth models can be used to better understanding certain aspects of alfalfa physical and biological processes since they are simplified mathematical expressions of these processes. When these models are developed further to be sufficiently accurate, they will be used to improve alfalfa production practices, predicting the effect of various combinations of management practices. Advancing computer technology will further enable more efficient data processing, analysis, and model building for these purposes.

MANUSCRIPT I

Evaluation of Alfalfa's Base Temperature

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ABSTRACT

Most phenological development models use a computation of growing degree days (GDD) to predict plant response to temperature. Computation is based on mean temperature minus the base temperature. Base temperature is the temperature at which plant development ceases. Several base temperatures have been proposed for alfalfa. Some investigators have used more than one base temperature to predict alfalfa (*Medicago sativa* L.) phenological development.

The objective of this study was to evaluate alfalfa's base temperature for use in computer simulation models which predict alfalfa phenological growth stages using the GDD concept.

Nine alfalfa cultivars (belonging to three fall dormancy groups) were used in a series of growth chamber experiments. Day/night temperature regimes of 11/6, 20/10, and 30/20 ± 0.5 °C were used with 18 hours of daylength and a light intensity of 350 μmol $m^{-2}s^{-2}$. Plants were grown in tubes of 4 cm diameter and 100 cm depth. The growth media was prepared by mixing soil (Woodburn silt loam; fine silty, mixed, mesic Aquultic Argixoll) and sand in a 2:1 ratio. Seeds were inoculated, and lime and fertilizer were applied based on soil test results.

Alfalfa's base temperature was evaluated using the percent advancement to first bloom per day (% AFB day^{-1})

method. The % AFB day^{-1} of all alfalfa cultivars was best described by the relationship of % AFB day^{-1} versus the log_{10} of the mean temperature. The X intercept (when the % AFB day^{-1} was zero) indicated 4.6 °C was the appropriate base temperature for this group of alfalfa cultivars.

Additional Index Words : *Medicago sativa* L.; Growing Degree Days (GDD); Heat units; Thermal time; Percent advancement per day; Phenology.

INTRODUCTION

Temperature is a primary factor in all crop growth models, due to its importance in controlling crop growth and development (Hodges, 1991). Temperature affects the rate of photosynthesis and respiration, thus controlling the growth rate and conditioning the timing of phasic development of plants (Smith, 1969; and Boldocchi et al., 1981). Physiological changes of alfalfa (*Medicago sativa* L.) with variation in temperature have been reported by several authors (Smith, 1969; Smith and Struckmeyer, 1974; and Boldocchi et al., 1981) including its close relationship to changes in phenology (McKenzie and McLean, 1980).

In recent years growing degree days (also called heat units, effective heat units, and thermal time), have found widespread use in crop growth models for predicting plant development and the date of harvest of many cultivated crop species (Neild and Seeley, 1975; Angus et al., 1981; and Ritchie and Otter, 1984). The mathematical notation for thermal time or growing degree days (GDD) required in each growth stage is calculated as follows:

$$GDD = \Sigma\ [(T_{max} + T_{min})/2] - T_b$$

where T_{max} and T_{min} represent the daily maximum and minimum temperatures used to calculate the unweighted average of daily temperature, and T_b is the minimum or threshold temperature at which alfalfa phenological development ceases (base temperature). Determining an appropriate base temperature is essential for using GDD based models.

Arnold (1959) and Morrison et al. (1989) noted that when the correct base temperature is used, the number of GDD required for a plant species to reach a particular growth stage is the same regardless of the variation in mean temperatures. Morrison et al. (1989) also indicated that the accuracy with which a GDD model can predict crop development is dependent upon the accuracy of the determination of the base temperature.

Most alfalfa growth models have used 5 °C as the base temperature for accumulated GDD computations during all growth stages (Onstad and Fick, 1983; and Fick et al., 1988). This base temperature was extrapolated from growth chamber studies where 5 °C was the threshold temperature for alfalfa leaf growth (Wolf and Blaser, 1971; and Sharratt et al., 1989). Other researchers (Jeney, 1972, and Fick, personal communication, 1990) have recommended the use of 0 °C as the base temperature for alfalfa.

The use of a constant base temperature, however, is a controversial issue since alfalfa plants respond differently to the same temperature depending on the growth stage reached when plants are exposed to this temperature (Sharratt et al., 1986, 1987). Sharratt et al. (1989) indicated that the base temperature for alfalfa changes with time and recommended using 3.5 °C, 7.5 °C, and 10.0 °C as base temperatures for spring, early summer, and late summer growth periods. However, McKenzie and McLean (1980, 1982) grew alfalfa at temperatures below those suggested by Sharratt et al. (1989) and found -2.8 °C as the minimum temperature where alfalfa growth commences. Thus, the issue of selecting an accurate base temperature for alfalfa remains unsolved.

The objective of this study was to determine an appropriate base temperature for computations in GDD models for accurate prediction of alfalfa phenological development under field conditions.

MATERIALS AND METHODS

The alfalfa cultivars used in these experiments and their associated winter hardiness characteristics are presented in Table I-1. Experiments were conducted in controlled environment rooms at the Oregon State University Crop Science research facility at Corvallis, Oregon.

Three controlled environment rooms were used, with day/night temperature regimes of 11/6, 20/10, and 30/20 ± 0.5 °C. Each temperature regime was replicated twice. Seedlings of alfalfa cultivars were grown in PVC tubes similar to those described by Hickey and Engelke (1983). Growth tubes were 100 cm long and 4 cm in diameter with free-draining plastic liners to prevent waterlogging. The growth media was prepared by mixing soil and sand in a 2:1 ratio. The soil was a Woodburn silt loam (fine, silty, mixed, mesic Aquultic Argixoll). Lime and fertilizer applications were based on soil test results and current recommendations for alfalfa production (Barnes and Sheaffer, 1985). Seeds were pelleted with $CaCO_3$ and *Rhizobium meliloti* commercial inoculant (Nitragin company, Milwaukee, WI).

Alfalfa plants were checked daily and irrigated whenever necessary, as judged from the appearance and feel of the surface soil, to maintain an adequate water supply. Each week, 1.5 g l^{-1} of fertilizer solution ($MgSO_4$, K_2HPO_4, and K_2SO_4) was provided to each experiment.

Table I-1. Alfalfa cultivars used in controlled environment experiments and their fall dormancy classifications.

Cultivars	Fall dormancy classification§
Maverick	Very dormant
Spredor 2	Very dormant
Vernal	Very dormant
Apollo II	Moderately dormant
WL-320	Moderately dormant
Vernema	Moderately dormant
Florida 77	Non dormant
WL-605	Non dormant
Madera	Non dormant

§ Fall dormancy classifications as published by the Certified Alfalfa Seed Council (1990).

The photoperiod was constant and equal to 18 hours of daylight with a light intensity of 350 μmol $m^{-2}s^{-2}$ (measured at plant height with a Li-Cor LI-188B quantum sensor, Li-Cor Inc., Lincoln, NE) provided by cool-white fluorescent lamps supplemented with incandescent lamps (400-700 nm). The relative humidity was approximately 65%. Twenty four plants from each alfalfa cultivar were grown in groups of 6 tubes and placed in a randomized block design with 4 replications in each temperature treatment. Daily observations were taken for phenological development. The number of days for each phenological stage was recorded when approximately 50% of the plants in a replication reached that growth stage. For herbage analysis, individual plants were severed from the root system 3 cm above the crown and placed in a morphological stage class according to the staging and classification system developed by Kalu and Fick (1983). Individual plant samples were dried to constant weight at 65 °C in a forced air oven.

The mean daily temperature was calculated as follows:

$$T_m = (T_{max} + T_{min})/2$$

where T_{max} and T_{min} represent the daily maximum and minimum temperatures. The number of days from seeding to each alfalfa growth stage was determined for each temperature regime. The percent advancement to first bloom per day (% AFB day^{-1}) was calculated using the following equation:

% AFB day^{-1} = 100/number of days to first bloom.

The regression equation was derived to express %AFB day^{-1} as a function of the mean growth chamber temperature. The X intercept was alfalfa's base temperature; when % AFB day^{-1} was zero, as reported by Morrison et al. (1989).

RESULTS AND DISCUSSION

The growth chamber day/night temperature treatments; 11/6 °C, 20/10 °C, and 30/20 °C, had daily mean temperatures of 8.5 °C, 15 °C, and 25 °C respectively. Combined analysis of variance indicated that temperature had a highly significant effect on % AFB day^{-1} (Table I-2). Alfalfa dormancy groups and cultivars within dormancy groups had no significant effect on % AFB day^{-1} ($P < 0.05$).

As the mean temperature increased from 8.5 to 25 °C, the % AFB day^{-1} increased. The number of days required to reach each alfalfa growth stage decreased by 2 to 3 times depending on the temperature treatment (Table I-3).

Using regression analysis, it was determined that the % AFB day^{-1} of alfalfa was best described by the relationship of % AFB day^{-1} versus the $\log_{10}$ of mean temperature according to the following equation:

$$\%\ \text{AFB day}^{-1} = 2.617 \log_{10} T_m - 1.746$$

where T_m is the mean daily temperature (Fig. I-1). Katz (1952), Brown (1960), and Morrison et al. (1989) also indicated that legume development was best described by a $\log_{10}$ linear relationship.

A base temperature for the three alfalfa fall dormancy groups was calculated by solving the resulting equation for temperature when % AFB day^{-1} equaled 0 (Arnold, 1959; and Morrison et al., 1989). A base temperature of 4.6 °C (the

Table I-2. Combined analysis of variance table of percent advancement to first bloom per day (% AFB day^{-1}) of three alfalfa fall dormancy groups grown in three temperature regimes.

Source of variation	df	Mean squares
Total	215	
Temperature	2	28.7471**
Replication (Temperature)	3	0.1171**
Block*Replication (Temperature)	18	0.0079
Dormancy	2	0.0396
Cultivar (Dormancy)	6	0.0102
Dormancy*Temperature	4	0.0102
Replication*Dormancy (Temperature)	6	0.0051
Replication*Cultivar*Dormancy (Temperature)	30	0.0074
Error	144	0.0049

** Significant at the 0.01 probability level.

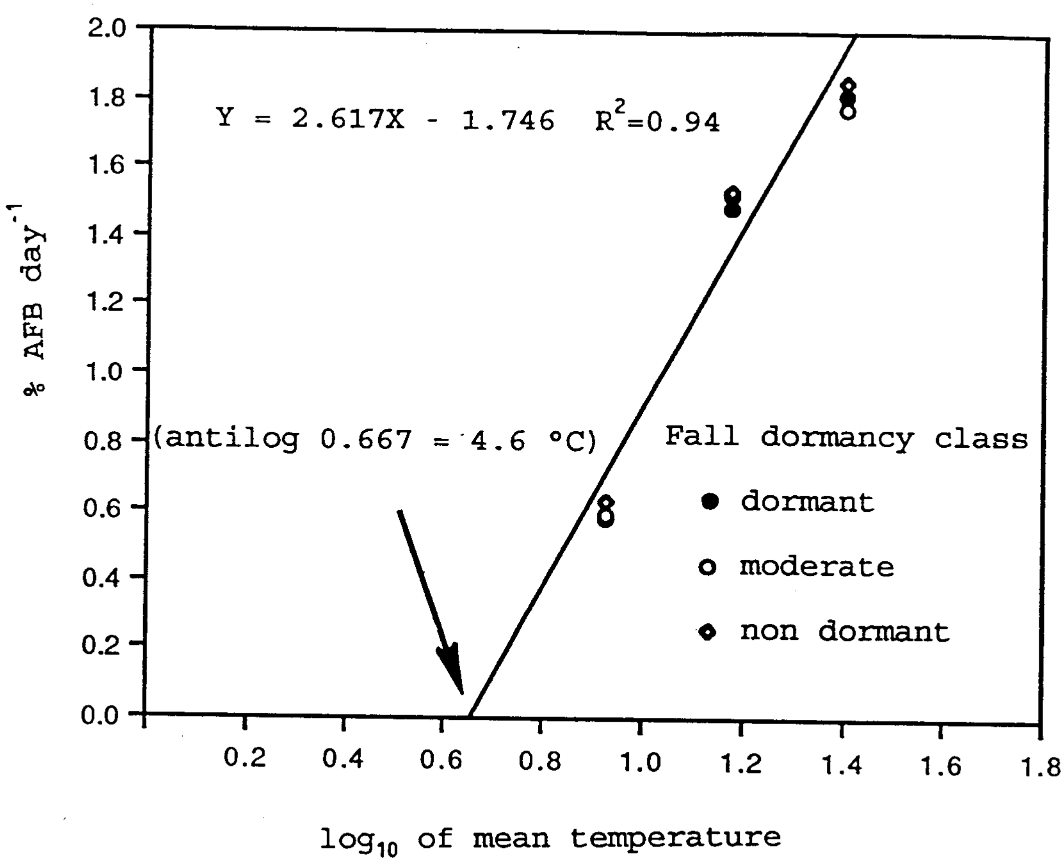
Table I-3. Percent advancement to first bloom per day (% AFB day^{-1}) of three alfalfa fall dormancy groups grown in three day/night temperature regimes.

	Day/night mean temperature (°C)		
Fall dormancy group	8.5	15	25
	% AFB day^{-1}		
Very dormant	0.58b* §	1.49b	1.82ab
Moderately dormant	0.59b	1.52ab	1.78b
Non dormant	0.63a	1.53a	1.85a

* Temperature means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa cultivars in each fall dormancy group.

Fig. I-1 Percent advancement to first bloom per day (% AFB day^{-1}) of three alfalfa fall dormancy groups as a function of the $\log_{10}$ of mean temperature.



antilog of 0.667) was the result (Fig. I-1).

Alfalfa base temperature values reported in the literature are different from the current study. This is not surprising since the method of determining T_b in this study used a $\log_{10}$ transformation rather than a linear relationship. In addition, this study used a wide range of fall dormancy types. Early reports of alfalfa base temperature were established for specific cultivars. These reports indicated base temperatures ranging from -2.8 to 10 °C, depending on the season (Sharratt et al. 1989).

The most commonly used base temperature for alfalfa has been 5 °C. This baseline temperature was determined from alfalfa growth chamber studies (Wolf and Blaser, 1971) where extrapolation was made from leaf dry matter accumulation and temperature relationship. These studies defined base temperature as the threshold for alfalfa growth. The 5° C value was obtained from simple extrapolation of the dry matter accumulation and temperature relationships.

Recent research reports have indicated the existence of misunderstanding of the threshold temperature for alfalfa growth (an increase in weight or height) and that of alfalfa development which refers to the advancement in stages of maturation (Sharratt et al. 1989). These two different alfalfa processes are often mistaken for the same phenomenon, although they are physiologically distinct.

Jeney (1972) used 0 °C as the base temperature for calculation of accumulated thermal time to alfalfa flowering. This temperature was assumed to be the freezing temperature at which alfalfa growth processes would be halted.

Sharratt et al. (1989) reported 3.5 °C, 7.5 °C, and 10 °C as the base temperature for spring, early summer, and late summer alfalfa growth periods to minimize variability of alfalfa thermal time requirements. These base temperatures were derived from field established alfalfa stands and used simple linear regression rather than using an appropriate log transformation. This resulted in underestimation of alfalfa's base temperature during the spring season and overestimation for the early and late summer growth periods.

Several methods have been used to estimate base temperature for plants and insects (Arnold, 1960, Baker et al. 1984, Strand, 1987, Sharratt et al. 1989, and Davidson and Campbell, 1983). The least variability, the X-intercept, and the regression coefficient methods have been used to estimate base temperatures for field use of GDD models (Arnold, 1960; and Sharratt et al. 1989).

In 1959, Arnold used regression analysis to determine the base temperature for field corn, using a series of planting dates to obtain variation in mean daily temperature and mean daily development rate. Such field experiments however, are expensive and lengthy. Arnold (1960) indicated that these methods were cumbersome because thermal time summations must be calculated on a series of base temperatures to find the correct one.

Morrison et al. (1989) indicated that the series of planting dates procedure is not practical, especially in regions with a short growing season. They also indicated that most of these methods assumed that the accumulated thermal time required for a particular species to reach a specific stage is the same, regardless of the mean temperature during the course of the species development. The finding of significant differences in accumulated thermal time for the same species when grown under different ambient temperatures suggested that another approach was needed for a better understanding of threshold temperature (Russelle et al. 1984, Davidson and Campbell, 1983, and Morrison et al. 1989).

Davidson and Campbell (1983) presented a more comprehensive way of relating species growth rates and advancement towards maturity stages with daily mean temperature. This method (% AFB day^{-1}) has the advantage of relating alfalfa phenological development to mean temperature. The use of the base 10 logarithm of the mean temperature is considered an appropriate transformation in relating plant species phenological development to ambient temperature (Morrison et al., 1989). The logarithmic relationship best describes plant metabolism and development processes (Katz, 1952; Brown, 1960; Arnold, 1960 and Morrison et al. 1989). The %

AFB day^{-1} also best describes the phenological changes independent from growth; a source of error in several early methods of estimating base temperature for plant and insect species (Sharratt et al. 1989).

Sharratt et al. (1989) suggested that other factors, such as photoperiod, may be important to consider in alfalfa GDD models. This supports the suggestion of Arnold (1959) who indicated that development was influenced by both temperature and photoperiod.

SUMMARY AND CONCLUSIONS

There has been little agreement in the literature concerning the base temperature for alfalfa growth and phenological development. Suggested base temperatures ranged from -2.8 °C to 10 °C. This was due, in part, to mistaking alfalfa growth and phenological development as the same phenomenon. Research reports also focused on the constant thermal time required for alfalfa to reach its flowering stage, regardless of variation in ambient temperature during the season and specific growth periods. The reported diversity of suggested base temperatures has resulted in under or overestimating alfalfa thermal time to flowering stage. Most of the early research reports used untransformed data to derive a linear relationship of alfalfa growth to accumulated thermal time.

The current study was conducted to determine an appropriate base temperature for the phenological development of nine alfalfa cultivars (belonging to three fall dormancy groups) grown in three day/night temperature regimes. The percent advancement to first bloom per day (% AFB day^{-1}) method was used to relate alfalfa phenological development to temperature. This method assesses the maturation stage rather than the growth process of plant species.

The % AFB day^{-1} of alfalfa was best described in this study by the relationship of % AFB day^{-1} versus the log_{10} of mean air temperature. The following equation resulted in minimum variation:

$$\% \text{ AFB day}^{-1} = 2.617 \log_{10} T_m - 1.746$$

where T_m is the mean daily temperature. Solving the resulting equation for temperature when % AFB day^{-1} is equal to 0 suggested a base temperature of 4.6 °C for alfalfa cultivars of the three fall dormancy groups. This base temperature is not much different from the 5 °C values often used by crop models. However, in a cumulative thermal time scale it would give a more accurate timing of alfalfa development and is based on a more appropriate rationale.

The use of the % AFB day^{-1} method is preferred for estimating alfalfa's base temperature. It uses a normalized time scale (% AFB day^{-1}). This allows results from a variety of environmental conditions to be compared on a normalized time basis. This technique also can be used for other field crops without requiring the expensive series of field plantings used in other methods. The current base temperature will be evaluated in GDD growth stage models to determine how it compares with previously reported values.

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MANUSCRIPT II

Prediction of Alfalfa Growth Stage Based on Growing Degree Days

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ABSTRACT

A consistently reliable method for predicting alfalfa *(Medicago sativa* L.) phenological growth stages is needed. Accurate prediction of alfalfa development stages is an important question when maximum yield of high quality forage is the objective.

The use of thermal time [(cumulative growing degree days (GDD)] as a nondestructive method of predicting the phenological growth stages and dry matter yield of nine alfalfa cultivars (belonging to three fall dormancy groups) was investigated using controlled environments. Temperature regimes of 11/6 °C, 20/10 °C, and 30/20 ± 0.5 °C were used for the day/night temperatures with 18 hours of daylength. Light intensity at plant height was 350 μmol $m^{-2}s^{-2}$ (400-700 nm). Single plants were grown in tubes of 4 cm diameter and 100 cm depth. The growth media was prepared by mixing soil (Woodburn silt loam; fine silty, mixed, mesic Aquultic Argixoll) and sand in a 2:1 ratio. Seeds were inoculated and lime and fertilizer were applied based on soil test results.

Temperature had significant effects on accumulated dry matter, time to maturity stages, percent advancement per day, and the $\log_{10}$ of accumulated $GDD_{4.6}$. Temperature and growth stage also displayed significant interaction. Little difference was observed due to cultivar or fall dormancy

group. At 11/6 °C, alfalfa cultivars accumulated 3 to 4 times more dry weight than at 30/20 °C. Warm and hot temperature treatments (20/10 °C, and 30/20 °C) hastened alfalfa maturity.

A transformation of the GDD method using the $\log_{10}$ of accumulated $GDD_{4.6}$ was used to relate phenological stage to $\log_{10}$ $GDD_{4.6}$. This method was compared to conventional computed GDD using 0 °C and 5 °C as base temperatures. The $\log_{10}$ $GDD_{4.6}$ method resulted in less variability in predicting alfalfa development. The equation relating seedling year alfalfa development stages to $\log_{10}$ $GDD_{4.6}$ was:

$$Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114.$$

This equation may be of practical importance to alfalfa growers and researchers, since it is a nondestructive method of predicting alfalfa growth stages.

Additional Index Words : *Medicago sativa* L.; Heat units; Thermal time; Phenology; Base temperature.

INTRODUCTION

Phenology is the study of the periodical (i.e. recurring) differentiation and development of plant organs as influenced by genotype and the total environment (Gepts, 1987; Hodges, 1991). Alfalfa phenological development is influenced by changes in temperature, photoperiod, available moisture, solar radiation, soil conditions, and genotype (Leach, 1971; Stout, 1980; Fick, 1988).

Temperature has been reported to be the most important variable influencing alfalfa growth and development (Leach, 1971; and Boldocchi et al., 1981). Since forage scientists have developed alfalfa cultivars for particular environmental conditions based on their variation in response to temperature (Bula, 1972; Barnes and Sheaffer, 1985), phenological development may vary according to fall dormancy classification.

Understanding the relationship between temperature and phenology of alfalfa cultivars is important in predicting plant growth, yield, and selecting suitable cultivars for particular environments. Accurate prediction of the timing of alfalfa growth stages is essential to the prediction of physiological responses under varying environmental conditions. Sharratt et al. (1986, 1987) reported that each stage of alfalfa growth responded differently to temperature, precipitation, and solar radiation. These environmental factors also affected the regrowth, persistence, and yield of alfalfa in subsequent growth stages and seasons (Mckenzie and McLean, 1982; and Stout, 1980).

Accurate prediction of alfalfa growth stages is important in scheduling management practices such as planting dates, pesticide applications, irrigation periods, and frequency of cutting or grazing. Timely management can greatly increase the quantity and quality of harvested alfalfa (Sanderson et al., 1989).

The concept of accumulated growing degree days (GDD) (also called thermal time, heat units, and effective heat units), has been advanced to describe the effect of temperature on the rate of plant growth and maturity for crop species (Hodges, 1991). The heat unit system has found widespread use for several cultivated crop species, including wheat, cotton, and corn (Neild and Seeley, 1975; Davidson and Campbell, 1983; Russelle, 1984; and Allen and O'brien, 1986). Neild and Seeley (1975), and Russelle et al. (1984) indicated that temperature indices (growing degree days) can explain more than 95% of the variability for corn and sorghum development. Therefore, a phenological prediction model or index based on meteorological parameters that accurately describes the phasic development of alfalfa may be helpful to growers and researcher scientists.

The objective of this study was to investigate the response of nine alfalfa cultivars belonging to three fall dormancy groups to varying temperature regimes and to develop an algorithm to predict alfalfa phenological development for each fall dormancy group.

MATERIALS AND METHODS

Certified alfalfa cultivars used in this experiment and their fall dormancy characteristics are presented in Table II-1. Experiments were conducted in controlled environment rooms at the Oregon State University Crop Science research facility at Corvallis, Oregon.

Three controlled environment rooms were used, with day/night temperature regimes of 11/6 °C, 20/10 °C, and 30/20 ± 0.5 °C. Each temperature regime treatment was replicated twice. Individual plants were grown in tubes of 4 cm diameter and 100 cm depth with free-draining plastic liners to prevent waterlogging (Hickey and Angelke, 1983). The growth media was prepared by mixing soil and sand in a 2:1 ratio. The soil was a Woodburn silt loam (fine, silty, mixed, mesic Aquultic Argixeroll). Fertilizer and lime applications were based on soil test results and current recommendations for alfalfa production (Barnes and Sheaffer, 1985). Seeds were pelleted with $CaCO_3$ and *Rhizobium meliloti* commercial inoculant (Nitragin company, Milwaukee, WI) and planted immediately.

Plants were checked daily and irrigated whenever necessary, as judged from the appearance and feel of the soil surface, to maintain an adequate water supply. Each week, 1.5 g l^{-1} of fertilizer solution (10% $MgSO_4$, 15% K_2HPO_4, and 5% K_2SO_4) was provided to each experiment.

Table II-1. Alfalfa cultivars used in controlled environment experiments and their fall dormancy classifications.

Cultivars	Fall dormancy classifications§
Maverick	Very dormant
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Vernal	Very dormant
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WL-320	Moderately dormant
Vernema	Moderately dormant
Florida 77	Non dormant
WL-605	Non dormant
Madera	Non dormant

§ Fall dormancy classifications as published by the Certified Alfalfa Seed Council (1990).

The photoperiod was constant and equal to 18 hours of daylight with light intensity at plant height of 350 μmol $m^{-2}s^{-2}$ (measured with a Li-Cor LI-188B quantum sensor, Li-Cor Inc., Lincoln, NE) provided by cool-white fluorescent lamps supplemented with incandescent lamps (400-700 nm). The relative humidity was approximately 65%. Twenty four plants from each alfalfa cultivar were arranged in groups of 6 tubes and placed in a randomized block design with 4 replications for each temperature treatment. Daily observations were taken for phenological development. The number of days required to reach each phenological stage was recorded when approximately 50% of the plants in a replication reached that phenological stage. For herbage analysis, individual plants were severed from the root system 3 cm above the crown and assigned to a morphological stage class according to the staging and classification system developed by Kalu and Fick (1981, 1989). Individual plant samples were dried to constant weight at 65 °C in a forced air oven.

The mathematical notation for growing degree-days (GDD) required to reach each growth stage was calculated for each cultivar as follows:

$$GDD = \Sigma\ [(T_{max} + T_{min})/2 - T_b]$$

where T_{max} and T_{min} represent the maximum and minimum daily temperatures and T_b is the base temperature. For alfalfa, T_b has been defined as 4.6 °C (Ben-Younes et al., 1992).

A transformation of the GDD formula also was used:

$$\log_{10} GDD = \log_{10} \Sigma [(T_{max} + T_{min})/2 - T_b]$$

This transformation was performed in accordance with the linear relationship of plant species development to the $\log_{10}$ of mean temperature as shown by Katz (1952), Brown (1960), Morrison et al. (1989), and Ben-Younes et al. (1992). The GDD values were accumulated for each alfalfa phenological stage from planting to first flower. This method was compared to the traditional GDD computation method using base temperatures of 0 and 5 °C. A best fit algorithm was developed to predict alfalfa phenological stages.

Statistical Analysis

Data were analyzed using the SAS microcomputer software system (SAS, 1990). The PROC ANOVA and PROC GLM procedures were used to examine the differences between temperature treatments, alfalfa fall dormancy groups for phenological development, accumulated GDD, and dry weight. The least squares method was used to determine the best fitting linear regression relating alfalfa phenological stages and the $\log_{10}$ of accumulated $GDD_{4.6}$. All statistical tests were calculated with $\alpha = 0.05$.

RESULTS AND DISCUSSION

Combined analysis of variance of the growth chamber experiments indicated that temperature, alfalfa growth stage, and temperature X growth stage interaction had significant effects on dry matter yield, percent advancement per day, time to alfalfa maturity stages and accumulated $GDD_{4.6}$ (Tables II-2 and II-3). Temperature and growth stage effects were more important than cultivar effects. Dry matter yield per plant declined from 7.1 g to 1.6 g as temperature increased from 11/6 °C to 30/20 °C (Table II-4). The decline in dry matter is possibly a consequence of increased respiration relative to photosynthesis when alfalfa cultivars were exposed to hot temperature (Fick et al., 1988). The largest dry matter yield per plant was observed at 11/6 °C when alfalfa cultivars accumulated 3 to 4 times more dry matter during alfalfa six growth stages compared to the hot temperature regime (Table II-4). At 20/10 °C and 30/20 °C, alfalfa dry matter yield per plant was not significantly different, although the accumulated dry weight under the former temperature treatment was slightly higher. These findings confirm the yield decrease at higher temperatures reported by Ueno and Smith (1970), Vough and Marten (1971), Smith and Struckmeyer (1974), and AL-Hamdani and Todd (1990).

Table II-2. Combined analysis of variance table of dry matter (DM) yield, number of days to development stages, and percent advancement per day (% Adv. day^{-1}) to maturity of nine alfalfa cultivars grown in three day/night temperature regimes.

Source of variation	df	Mean squares		
		DM Yield	Days to maturity	% Adv. day^{-1}
Total	1295			
Temperature	2	528.5**	696953.9**	347.041**
Replication(Temperature)	3	15.8**	426.1**	1.510**
Block*Replication(Temperature)	18	0.3*	68.1**	0.036**
Cultivar	8	0.2	194.6**	0.108*
Cultivar*Temperature	16	0.3	80.5**	0.018
Cultivar*Replication(Temperature)	24	0.2	51.6**	0.037
Cultivar*Block*Replication(Temperature)	144	0.2	24.8**	0.018**
Stage	5	352.3**	121125.7**	136.030**
Stage*Temperature	10	81.0*	24512.1**	10.458**
Stage*Replication(Temperature)	15	3.6**	1360.9**	1.244**
Stage*Block*Replication(Temperature)	90	0.3**	15.1**	0.013**
Stage*Cultivar	40	0.1	27.3**	0.019
Stage*Cultivar*Temperature	80	0.1	24.4**	0.012
Stage*Cultivar*Replication(Temperature)	120	0.2	12.2*	0.013**
Error	720	0.1	9.4	0.007

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

Table II-3. Combined analysis of variance table of accumulated growing degree days (GDD) and $\log_{10}$ $GDD_{4.6}$ of nine alfalfa cultivars grown in three day/night temperature regimes.

Source of variation	df	Mean squares		
		GDD_0	GDD_5	$\log_{10}$ $GDD_{4.6}$
Total	1295			
Temperature	2	7702736.7**	18803232.1**	8.4047**
Replication(Temperature)	3	385175.1**	85917.8**	0.0584**
Block*Replication(Temperature)	18	9023.6**	3519.9**	0.0019**
Cultivar	8	27956.8**	9980.1**	0.0065**
Cultivar*Temperature	16	6984.8	2487.9	0.0013
Cultivar*Replication(Temperature)	24	5894.6**	2066.0**	0.0017**
Cultivar*Block*Replication(Temperature)	144	4057.6**	1798.7**	0.0008**
Stage	5	19941500.7**	7430725.9**	5.6915**
Stage*Temperature	10	814183.5**	470916.9**	0.1522**
Stage*Replication(Temperature)	15	135726.5**	39786.9**	0.0450**
Stage*Block*Replication(Temperature)	90	2146.6**	893.6**	0.0004**
Stage*Cultivar	40	3538.2**	1316.3**	0.0007
Stage*Cultivar*Temperature	80	2882.1**	1076.0*	0.0006
Stage*Cultivar*Replication(Temperature)	120	1761.6*	736.3	0.0005**
Error	720	1405.5	602.9	0.0003

*, **, Significant at the 0.05 and 0.01 probability levels, repectively.

Table II-4. Dry matter yield at six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

	Day/night temperature (°C)		
Growth stage	11/6	20/10	30/20
	—— g plant^{-1} ——		
Early vegetative	0.3a* §	0.2a	0.1a
Mid-vegetative	0.6a	0.5a	0.2a
Late vegetative	2.0a	0.8ab	0.4b
Early bud	2.9a	1.3b	0.9b
Late bud	3.9a	1.6b	1.2b
First bloom	7.1a	2.3b	1.6b

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

The interactive effect of alfalfa growth stage and temperature is an important factor affecting dry matter accumulation and phenological development (Fagerberg, 1988; and Sharratt et al., 1989). The significant temperature and growth stage interaction (Table II-2, and Table II-3) indicates this is also true for accumulated thermal time.

Figure II-1 displays the mean of the accumulated dry weight per plant at six alfalfa numerical growth stages for the three alfalfa fall dormancy groups. The graph indicates that rapid dry matter accumulation started when alfalfa plants entered the early bud stage (stage 3). Maximum dry weight was reached at the first bloom stage (stage 5).

The percent advancement per day (% Adv. day^{-1}) to six alfalfa growth stages increased 2 to 3 times as temperature increased from 11/6 °C to 30/20 °C (Table II-5). For each alfalfa growth stage, the % Adv. day^{-1} was significantly different under the three temperature regimes. The higher % Adv. day^{-1} indicated that the increase in temperature hastened the phenological development of alfalfa cultivars within the three alfalfa fall dormancy groups. Pearson et al. (1972a), Faix (1974), Arbi et al. (1979), and Heichel al. (1981) also reported that alfalfa flowered earlier when exposed to warmer temperatures.

The number of days after planting to six alfalfa growth stages declined 2 to 3 times depending on the stages as temperature increased from 11/6 °C to 30/20 °C (Table II-6).

Fig. II-1. Dry matter yield at six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

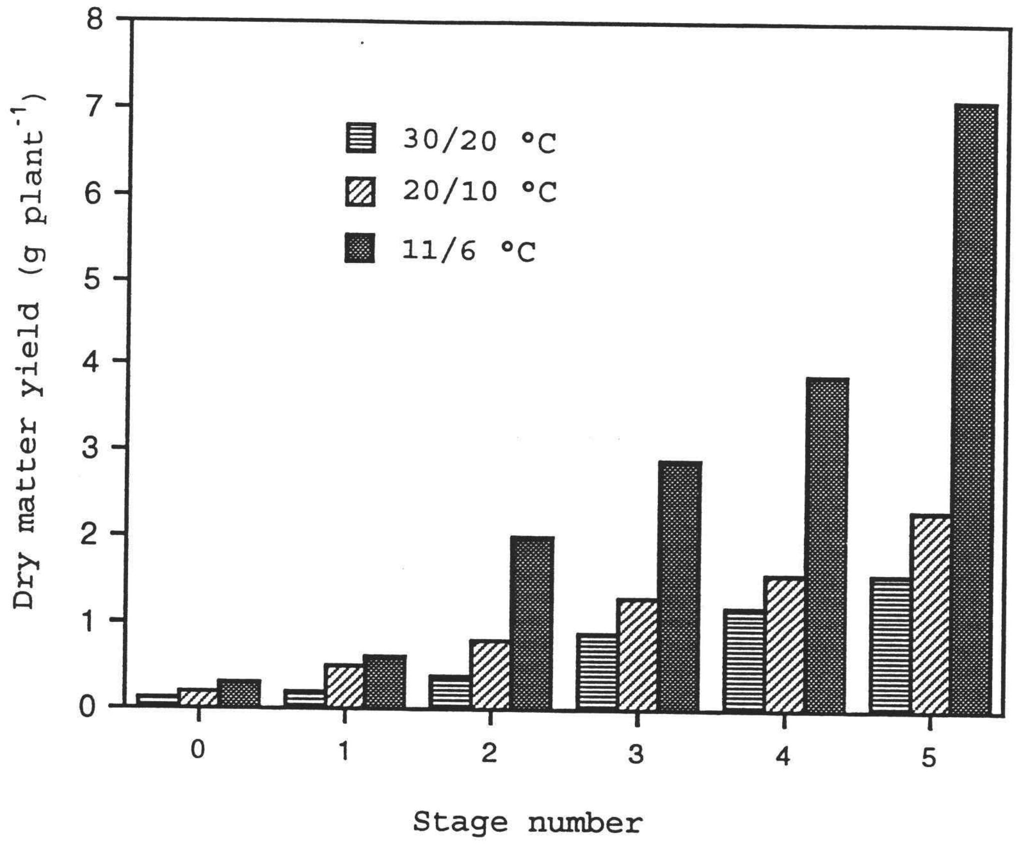


Table II-5. Percent advancement per day (% Adv. day^{-1}) to six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

	Day/night temperature (°C)		
Growth stage	11/6	20/10	30/20
	% Adv. day^{-1}		
Early vegetative	2.07b* §	3.14b	5.01a
Mid-vegetative	1.31c	2.37b	3.47a
Late vegetative	0.93c	2.15b	2.65a
Early bud	0.71c	1.80b	2.14a
Late bud	0.69c	1.67b	1.92a
First bloom	0.60c	1.51b	1.81a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

Table II-6. Days after planting (DAP) to reach six growth stages for three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

	Day/night temperature (°C)		
Growth stage	11/6	20/10	30/20
	DAP		
Early vegetative	49.5a* §	31.8b	20.0b
Mid-vegetative	76.3a	42.8b	28.8c
Late vegetative	107.3a	46.7b	37.6b
Early bud	140.3a	55.4b	46.8b
Late bud	146.0a	59.8b	52.0b
First bloom	166.3a	66.3b	55.0b

* Stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

At 20/10 °C and 30/20 °C, the number of days after planting to alfalfa phenological development stages was not significantly different except for the mid-vegetative stage (Table II-6). However, alfalfa cultivars developed an average of 10 days earlier under the 30/20 °C temperature treatment. Slowest development was observed for the 11/6 °C temperature treatment when alfalfa cultivars flowered 166 days after planting. Under this temperature treatment it took alfalfa cultivars 2 to 3 times more time (days) to reach the six phenological growth stages compared to 20/10 °C and 30/20 °C treatment. These findings confirm the results of Sato (1971a), Smith and Struckmeyer (1974), and Heichel et al. (1981) who indicated slow development of alfalfa cultivars under cool temperature regimes.

The effects of temperature and alfalfa growth stage were significant and more important then the cultivar effects on accumulated thermal time from planting to growth stage regardless of the base temperature used in thermal time computations (Table II-2).

When a base temperature of 0 °C was used to calculate GDD, 11/6 °C and 30/20 °C treatments were not significantly different and had higher values than the 20/10 °C treatment (Table II-6). The 0 °C base temperature used by Jeney (1972) and suggested by Strand (1987) is too low for alfalfa and results in excessive thermal time requirements for alfalfa phenological development Arnold (1959).

Table II-7. Accumulated thermal time $(GDD_0)^{\#}$ to six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

Growth stage	Day/night temperature (°C) 11/6	20/10	30/20
	GDD_0		
Early vegetative	420.6a* §	477.5a	501.7a
Mid-vegetative	648.5a	642.3a	721.5a
Late vegetative	912.3a	700.8b	941.6a
Early bud	1192.8a	831.6b	1171.2a
Late bud	1240.3a	896.8b	1302.1a
First bloom	1414.1a	995.4b	1378.5a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

\# GDD_0 is the cumulative growing degree days with a base temperature of 0 °C.

Alfalfa growth and development also may be halted before a freezing temperature of 0 °C is reached (Sharratt et al., 1989; Morrison et al., 1989). A base temperature of 0 °C would be too low and would result in overestimated thermal time requirement (Arnold, 1959; and Morrison et al. 1989).

When a base temperatures of 5 °C was used for the computation of accumulated GDD, temperature treatments 11/6 °C and 20/10 °C had similar GDD values but significantly lower than those of the 30/20 °C temperature regime (Table II-8). At 30/20 °C, alfalfa cultivars accumulated nearly 2 times the GDD accumulated under the 11/6 °C (Tables II-8). Accumulated thermal time to alfalfa first bloom stage using 0 °C and 5 °C base temperatures varied from 582 GDD to 1124 GDD, respectively. The latter GDD value is higher than those reported by Holt et al. (1975) and Sharratt et al. (1989) (who used 5 °C as the base temperature) but comparable to those reported by Kephart and Twidwell (1990) for regrowth of alfalfa in South Dakota. These differences may be attributed to seedling growth and development being slower than regrowth from established alfalfa plants (Fick et al., 1988). During the establishment year, alfalfa seedlings lack the vigorous crown, roots, and nodule system of established alfalfa plants.

The combined analysis of variance of accumulated $\log_{10}$ $GDD_{4.6}$ also indicated significant differences due to alfalfa

Table II-8. Accumulated growing degree days (GDD_5)[#] to six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

Growth stage	Day/night temperature (°C)		
	11/6	20/10	30/20
	GDD_5		
Early vegetative	173.2b* §	318.3a	401.4a
Mid-vegetative	267.0c	428.2b	577.2a
Late vegetative	375.6b	467.2b	753.3a
Early bud	491.1b	554.4b	937.0a
Late bud	510.7b	598.0b	1041.6a
First bloom	582.3b	663.6b	1102.8a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

\# GDD_5 is the cumulative growing degree days with a base temperature of 5 °C.

growth stages (Table II-3). The growth stages effect was more important than temperature treatment effects (Table II-3).

The $\log_{10}$ $GDD_{4.6}$ method resulted in less variability of the transformed GDD values required for alfalfa development over the three temperature treatments (Table II-9). Sharratt et al. (1989) reported that when an appropriate method of base temperature is used it results in the lowest coefficient of variation of alfalfa thermal time to flowering.

Figure II-2 displays the $\log_{10}$ $GDD_{4.6}$ to six alfalfa growth stages for the three growth chamber temperature regimes. The $\log_{10}$ of accumulated $GDD_{4.6}$ to six alfalfa numerical growth stages increased as alfalfa plants advanced in maturity stages. The high coefficients of determination (R^2=0.91 to 0.95) indicated a high correlation between alfalfa phenological development and the $\log_{10}$ of accumulated $GDD_{4.6}$.

The $\log_{10}$ of $GDD_{4.6}$ increased in a linear fashion with alfalfa numerical growth stages. Figure II-2 displays the regression functions of $\log_{10}$ of accumulated $GDD_{4.6}$ for alfalfa development stage for the three temperature treatments. The 11/6 °C and 20/10 °C were similar for the last four alfalfa numerical development stage (stages 2, 3, 4, and 5). The 30/20 °C treatment consistently showed higher values of $\log_{10}$ of accumulated $GDD_{4.6}$.

Table II-9. Log_{10} of accumulated thermal time (log_{10} $GDD_{4.6}$)[#] to six growth stages of three alfalfa fall dormancy groups grown in three day/night temperature regime growth chamber experiments.

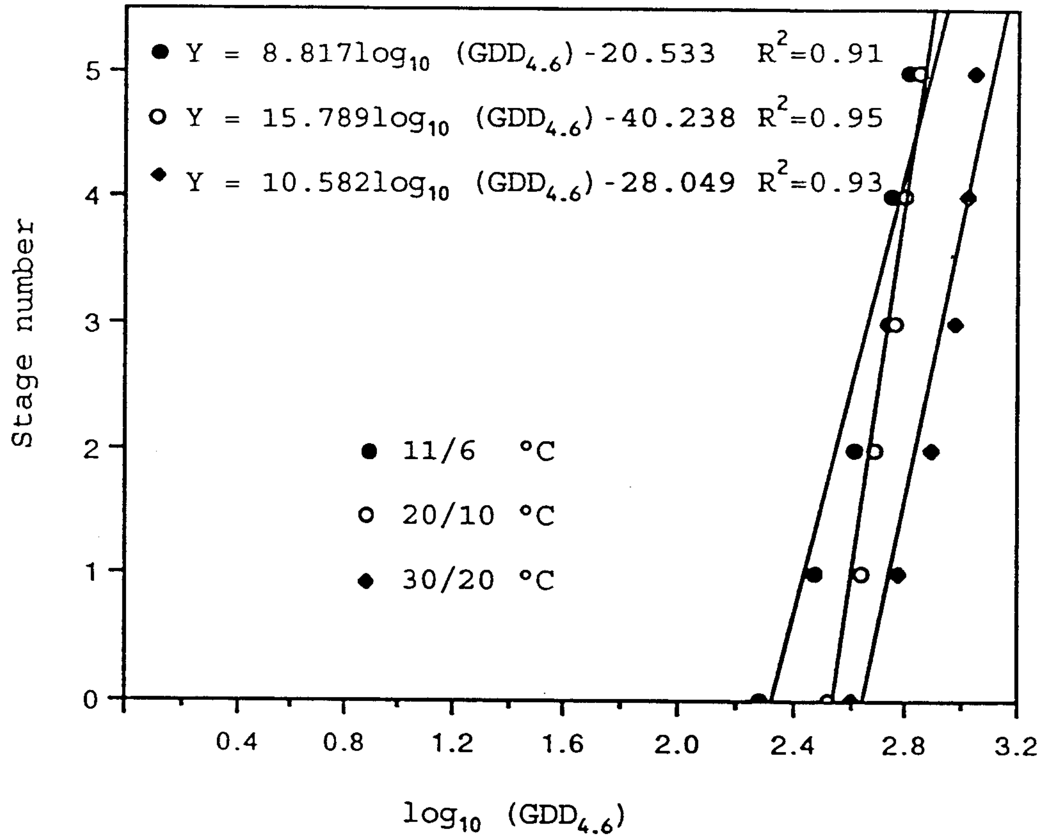
Growth stage	Day/night temperature (°C)		
	11/6	20/10	30/20
	log_{10} $GDD_{4.6}$		
Early vegetative	2.279b* §	2.519a	2.611a
Mid-vegetative	2.472b	2.645a	2.769a
Late vegetative	2.621b	2.685b	2.885a
Early bud	2.737b	2.760b	2.979a
Late bud	2.754b	2.793b	3.026a
First bloom	2.810b	2.838b	3.050a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

Log_{10} $GDD_{4.6}$ is the log_{10} of the cumulative of growing degree days using a base temperature of 4.6 °C.

Fig. II-2. Log_{10} ($GDD_{4.6}$) versus growth stage response curve for three alfalfa fall dormancy groups grown in three day/night growth chamber temperature experiments.



The 11/6 °C represents a cold temperature environment where alfalfa maturity was delayed. The 30/20 °C is a hot temperature regime which hastened the development of alfalfa cultivars but resulted in low dry matter yield probably due to increased respiration. The optimum and recommended temperature for alfalfa growth and development is between the 20/10 °C and 30/20 °C temperature regimes (Fick et al., 1988). Therefore, the model that would best predict alfalfa phenological development would be the average of the $\log_{10}$ of accumulated GDD values between 20/10 °C and 30/20 °C regression lines. Therefore, the model which would best relate the $\log_{10}$ of accumulated $GDD_{4.6}$ to alfalfa development stages would be as follows:

$$Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$$

where Y is alfalfa growth stage number as defined by Kalu and Fick (1981).

Since this regression equation was developed under growth chamber conditions, it will be tested in field experiments to determine how well it predicts alfalfa phenological development.

SUMMARY AND CONCLUSIONS

Temperature and growth stage had a significant effect on alfalfa dry matter yield, the number of days to growth stages, the percent advancement per day (% Adv. day^{-1}) to maturity, and thermal time (GDD). Temperature and growth stage effects were more important than cultivars effects.

Alfalfa grown at 11/6 °C accumulated 3 to 4 times the dry weight as when grown at 30/20 °C. The temperature regime also affected the thermal time required to reach each alfalfa growth stage. The highest thermal time to each alfalfa development stage was recorded for the 30/20 °C treatment. Thermal time recorded to the first bloom stage after seeding was higher than that reported from established stands in Indiana, Minnesota, and New York (Holt et al. 1975; Sharratt et al., 1989; and Fick, 1984). These differences may be attributed to alfalfa seedling year growth and development being slower than regrowth from established alfalfa plants. During the establishment year, alfalfa seedlings lack the vigorous crown, roots, and nodule system of established alfalfa plants. It also may be partially attributed to the controlled environment chambers having lower light intensities than typical field conditions.

The equation relating alfalfa phenological development stages to thermal time was found to be:

$$Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$$

where Y is the alfalfa growth stage number and $GDD_{4.6}$ is the accumulated growing degree days with a base temperature of 4.6 °C.

This equation may be of practical use to growers and researchers, since it should enable prediction of alfalfa development stages with greater accuracy. In the current study, little difference was observed within each temperature treatment in thermal time and top growth between cultivars belonging to different fall dormancy categories. Thus, one equation may be adequate to describe phenological development of cultivars within this range of fall dormancy classifications.

The variation in thermal time requirements under different temperature treatments suggests that other factors such as photoperiod, light intensity, water relations, and microclimate of the crop, which are not considered in a solely thermal model, may be important in the phenological development of alfalfa cultivars. If phenological development of alfalfa is influenced by both temperature and photoperiod, the current thermal time model may need to be revised to include photothermal units. Further investigation of the alfalfa response to a range of temperature and photoperiod regimes is needed to quantify the temperature and photoperiod effects on the phenological development of alfalfa cultivars.

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MANUSCRIPT III

Validation of an Alfalfa Growth Stage Model Based on Growing Degree Days

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ABSTRACT

The concept of accumulated growing degree days (GDD) or thermal time has found use in agriculture for predicting the date of harvest and management of a number of crop species. The purpose of this study was to evaluate under field conditions an alfalfa phenological development model derived from several controlled environment experiments.

Field studies were conducted during 1989 and 1990 at two sites at the Oregon State University Crop Science field laboratory. Alfalfa seeds were inoculated and seeded at 15 kg live seeds ha^{-1}. Plots were 6.1 m by 1.5 m with 15 cm between rows. The statistical design was a randomized block design with 4 replications. Daily observations were taken of phenological stages. For herbage analysis, samples of 0.1 m^2 quadrates were taken from each replication. Mean stage by count (MSC) and mean stage by weight (MSW) were calculated. Daily maximum and minimum temperatures were used to derive the daily mean temperature and to calculate thermal time for each phenological stage.

The current study indicated that growth stage and year had significant effects on yield and percent advancement to maturity stages. Little difference in MSC, MSW, and $\log_{10}$ $GDD_{4.6}$ was observed due to year or cultivar.

The observed relationship between alfalfa growth stage number and accumulated $GDD_{4.6}$ during the growth year was best

described by the regression equation:

$$Y = 18.288 \log_{10} (GDD_{4.6}) - 48.888$$

This equation was not significantly different from the predicted equation derived from growth chamber experiments. The high coefficient of determination (R^2=0.96) between the $\log_{10}$ $GDD_{4.6}$ and stage of development indicated that the growth and development of alfalfa cultivars can be predicted accurately from maximum and minimum temperatures.

This study confirms the use of 4.6 °C as an appropriate base temperature for alfalfa. It also confirms the need for a logarithmic transformation of the conventional GDD computation used for alfalfa phenological stage models.

Additional Index Words: *Medicago sativa* L., Thermal time; Phenological development; Mean stage by count (MSC); Mean stage by weight (MSW); Percent advancement per day.

INTRODUCTION

Although alfalfa models have resulted in many advances in management practices of alfalfa, they are still considered too complex for alfalfa growers. In several cases these models were only approximate in their prediction of alfalfa growth and yield and would need further development and validation before being adopted (Fick et al., 1988; and Bourgeois et al., 1990). What is needed is a simple and reliable index for quantifying maturity and predicting alfalfa forage quality. This could be a morphological or phenological index based on meteorological parameters that accurately describes alfalfa development under particular environmental conditions.

Kalu and Fick (1981, 1983) developed a 10-stage classification system for alfalfa development and used two procedures to determine mean stages. The mean stage by count (MSC) procedure estimates the mean stage as the average of observed stages weighted for the number of shoots in each stage. The mean stage by weight (MSW) procedure estimates the average of the observed stages weighted by the dry matter of shoots in each stage (Kalu and Fick, 1981, 1983; and Mueller and Fick, 1989).

The MSC has provided a quick way of estimating alfalfa hay quality in growing stands of alfalfa. The MSW also can be predicted using MSC values and is a quick and inexpensive way to predict alfalfa stages of development and quality (Sanderson et al., 1989; and Vodraska, 1990).

These methods, however, still require sampling and processing before alfalfa phenological growth stages can be estimated accurately. The objective of this study was to evaluate in field studies a computer simulation model of alfalfa phenological development based on GDD. Validation of this model would permit prediction of alfalfa phenological development based on maximum and minimum temperature data.

MATERIALS AND METHODS

Field studies were conducted during 1989 and 1990 on two different sites at the Oregon State University Hyslop Crop Science field research facility at Corvallis, Oregon. The soil was a Woodburn silt loam (fine, silty, mixed, mesic Aquultic Argixeroll). Daily maximum and minimum air temperatures measured at 1.5 m above the ground were recorded at the Oregon State University Hyslop Crop Science field research weather station located 400 m from the experiment sites. Sites were selected based on a history of non-legume culture for seven years, during which the field had been cultivated in either small grain or fallow.

Several weeks prior to planting, the field was limed with dolomitic limestone to raise the soil pH to 6.2. Additional fertilizer applications were based on soil test results and current recommendations for alfalfa production (Barnes and Sheaffer, 1985). Alfalfa cultivars used and their fall dormancy characteristics are presented in Table III-1. Seeds were inoculated with *Rhizobium meliloti* (Nitragin company, Milwaukee, WI) and pelleted with commercial grade $CaCO_3$. Seeds were planted on 12 June 1989, and 28 June 1990, at a rate of 15 kg live seeds ha^{-1} using a small plot cone-type seeder. Plots were 6.1 m by 1.5 m with 15 cm between rows. Irrigation was provided as needed. Manual weed control measures were used.

Table III-1. Alfalfa cultivars used in field experiments and their associated fall dormancy classifications.

Cultivars	Fall dormancy classifications§
Maverick	Very dormant
Spredor 2	Very dormant
Vernal	Very dormant
Apollo II	Moderately dormant
WL-320	Moderately dormant
Vernema	Moderately dormant
Florida 77	Non dormant
WL-605	Non dormant
Madera	Non dormant

§ Fall dormancy classifications as published by the Certified Alfalfa Seed Council (1990).

After emergence, daily observations were taken of phenological development stages. When approximately 50% of the plants of each cultivar in a replication were judged to have reached a particular phenological stage, that cultivar was considered to be at that stage. For herbage analysis, samples of 0.1 m^2 quadrates were taken for each growth stage. Plants were cut 3 cm above the crown. Shoots were separated into stage categories as defined by Kalu and Fick (1981, 1983). Subsamples were dried to constant weight at 65 °C in a forced air oven.

Mean stage by count (MSC) and mean stage by weight (MSW) were calculated using the equations of Kalu and Fick (1981):

$$MSC = \Sigma\ S*N/C$$

$$MSW = \Sigma\ S*D/W$$

where S = morphological stage number; 0 to 9,

N = number of shoots in stage S,

C = total number of all shoots in the sample,

D = dry weight of shoots in stage S, and

W = total dry weight of all shoots in the sample.

The mathematical notation for growing degree days (GDD) required to reach each growth stage was calculated for each cultivar as follows:

$$GDD = \Sigma\ [(T_{max} + T_{min})/2 - T_b]$$

where T_{max} + T_{min} are the daily maximum and minimum air temperatures, and T_b is the base temperature (the temperature at which alfalfa phenological development ceases).

The $\log_{10}$ transformation of the GDD formula suggested by Ben-Younes et al. (1992b) was used as follows:

$$\log_{10} GDD_{4.6} = \log_{10} \Sigma \left[(T_{max} + T_{min})/2 - T_b \right]$$

For alfalfa, T_b for each stage has been defined as 4.6 °C (Ben-Younes et al., 1992a). The $GDD_{4.6}$ and $\log_{10} GDD_{4.6}$ values were computed for each alfalfa growth stage from planting to first bloom. These values were used to relate alfalfa phenological development to the $\log_{10}$ of accumulated $GDD_{4.6}$. A simulation algorithm which was developed from growth chamber experiments was compared to the results observed under field conditions for validation of the temperature/phenology relationship of alfalfa grown in Corvallis, Oregon.

Statistical Analysis

Data analysis consisted of a two-way analysis of variance to determine significant differences between cultivars, fall dormancy groups, and year of planting for the $\log_{10}$ of accumulated $GDD_{4.6}$, dry weight, and mean stages. Regression analysis was conducted to determine curve functions. Curves were selected based on the error least squares method and the coefficient of determination. All statistical tests were calculated with a probability level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Combined analysis of variance of the field experiments indicated that alfalfa growth stage and year had significant effects on yield and percent advancement per day (% Adv. day^{-1}) to phenological growth stages (Table III-2). Alfalfa growth stage also had a significant effect on alfalfa MSC and MSW (Table III-3). Little difference in MSC and MSW was observed due to year effect.

The percent advancement per day (% Adv. day^{-1}) to alfalfa growth stages is presented in Table III-4. During 1990, the % Adv. day^{-1} was significantly higher than that of 1989; with alfalfa cultivars advancing to maturity stages by 20 to 30% per day more than in 1989 (Table III-4). The faster development of alfalfa cultivars may be attributed to the mean temperature conditions during the growth season of 1990 being in the optimum range for alfalfa growth and development (20.6 °C) as compared to 1989 (17.8 °C). Hesterman et al. (1981) found that the growth of recently germinated alfalfa seedlings is most rapid at 20 to 30 °C. Stock (1971), Harada (1975), and Evans and Peaden (1984) reported that alfalfa's optimum temperature under full light conditions in the field (summer season) would be higher than those reported under low light conditions.

The number of days after planting to six alfalfa growth stages is presented in Table III-5. In 1990, alfalfa culti-

Table III-2. Combined analysis of variance table of dry matter (DM) yield, number of days to development stages, and percent advancement per day to maturity (% Adv. day^{-1}) of nine alfalfa cultivars grown in field experiments at Corvallis, OR in 1989 and 1990.

Source of variation	df	Mean squares		
		DM Yield	Days to maturity	% AFB day^{-1}
Total	431			
Year	1	1885.0**	11791.7**	32.231**
Block(Year)	6	402.2**	7.9**	0.056*
Cultivar	8	281.4**	69.3**	0.228**
Cultivar*Year	8	55.2	5.3*	0.023*
Cultivar*Block(Year)	48	34.4**	2.1**	0.010**
Stage	5	9414.4**	6851.6**	21.825**
Stage*Year	5	680.8**	140.8**	0.789**
Stage*Block(Year)	30	54.6**	1.2**	0.010**
Stage*Cultivar	40	42.9**	2.3**	0.025**
Stage*Cultivar*Year	40	22.1**	2.1**	0.016**
Error	240	11.5	0.4	0.002

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

Table III-3. Combined analysis of variance table of $\log_{10}$ $GDD_{4.6}$[§], mean stage by count (MSC), and mean stage by weight (MSW) of nine alfalfa cultivars grown in field experiments at Corvallis, OR in 1989 and 1990.

		Mean squares		
Source of variation	df	Log_{10} $GDD_{4.6}$	MSC	MSW
Total	431			
Year	1	0.0034	0.64**	0.01
Block(Year)	6	0.0015**	0.47**	0.56**
Cultivar	8	0.0070**	1.04**	0.49**
Cultivar*Year	8	0.0004	0.17*	0.17
Cultivar*Block(Year)	48	0.0003**	0.07**	0.10**
Stage	5	0.7301**	54.73**	96.77**
Stage*Year	5	0.0071**	0.26**	0.39**
Stage*Block(Year)	30	0.0002**	0.05*	0.07**
Stage*Cultivar	40	0.0002**	0.10**	0.09**
Stage*Cultivar*Year	40	0.0002**	0.05*	0.06*
Error	240	0.0001	0.03	0.04

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

§ Log_{10} of accumulated growing degree days using a base temperature of 4.6 °C.

Table III-4. Percent advancement per day (% Adv. day^{-1}) to six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

Growth stage	Year 1989	Year 1990
	% Adv. day^{-1}	
Early vegetative	2.8b* §	3.7a
Mid-vegetative	2.3b	2.8a
Late vegetative	2.0b	2.6a
Early bud	1.9b	2.4a
Late bud	1.8b	2.2a
First bloom	1.5b	1.9a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

Table III-5. Days after planting (DAP) to reach six growth stages for three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

Growth stage	Year 1989	Year 1990
	DAP	
Early vegetative	35.9a* §	25.5b
Mid-vegetative	42.0a	35.4b
Late vegetative	48.7a	38.2b
Early bud	51.7a	41.9b
Late bud	56.5a	45.2b
First bloom	67.0a	51.8b

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three fall dormancy groups.

vars flowered 15 days earlier than in 1989. The hastened phenological development of alfalfa in 1990 may be attributed to more optimal temperature and solar radiation conditions which would enhance photosynthesis as suggested by Sato (1971), Hesterman et al. (1981), and Sharratt et al. (1986, 1987).

Dry matter yield during the 1990 growing season was significantly higher than 1989 during the first four alfalfa phenological development stages (Table III-6). In 1990, alfalfa dry matter yield at the late bud and first bloom stages (33.1 g and 43.0 g 0.1 m^{-2}, respectively) was higher than that of 1989 (30.9 and 36.9 g 0.1 m^{-2}) but was not statistically different (Fig. III-1). Smith (1969), Sato (1971a), and Sharratt et al. (1987) also found that alfalfa yield was higher when alfalfa plants were exposed to more optimal light and temperature conditions.

Alfalfa growth stage had significant effects on the $\log_{10}$ of accumulated $GDD_{4.6}$ (Tables III-3 and III-7). Growth stage effect was more important than cultivar and year effects.

The regression equation:

$$Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$$

relating alfalfa phenological stages and $\log_{10}$ of the accumulated $GDD_{4.6}$ (Ben-Younes et al., 1992b) was used to predict the $\log_{10}$ of accumulated thermal time for the field experiments.

Table III-6. Dry matter yield at six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

	Year	
Growth stages	1989	1990
	g $(0.1\ m)^{-2}$	
Early vegetative	6.7b* §	8.4a
Mid-vegetative	12.1b	21.7a
Late vegetative	18.0b	27.1a
Early bud	23.1b	31.7a
Late bud	30.9a	33.1a
First bloom	36.9a	43.0a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

Fig. III-1. Dry matter yield at six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

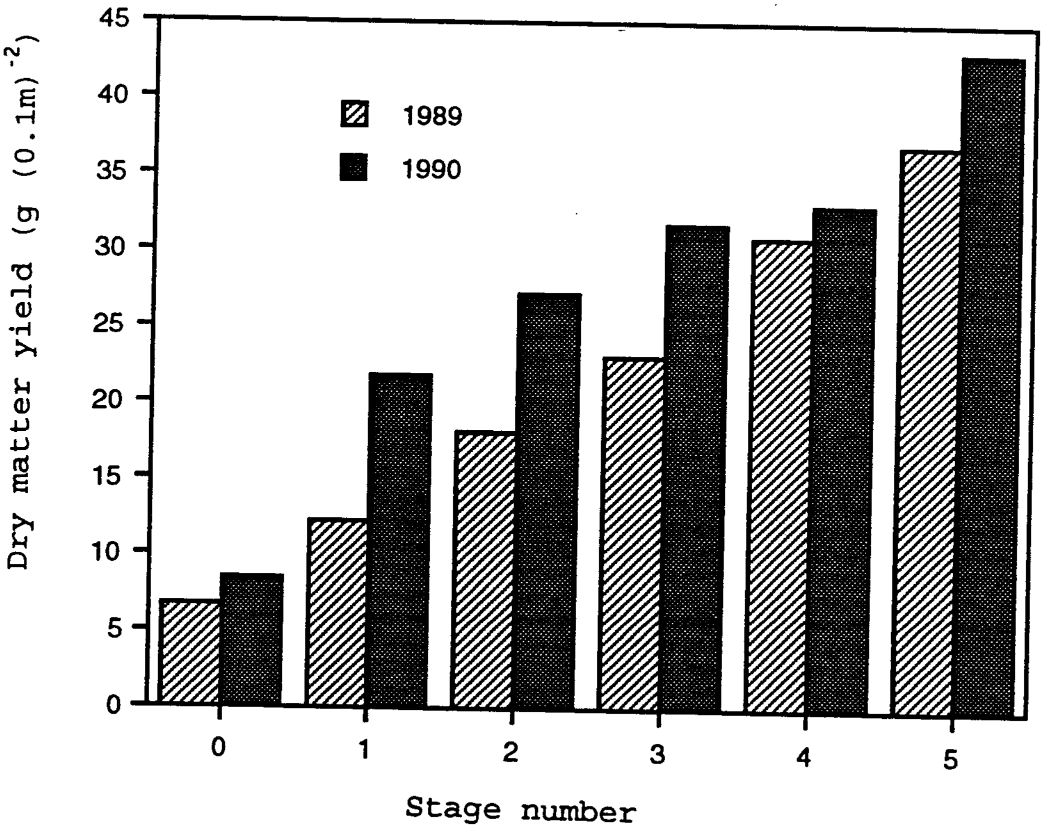


Table III-7. Log_{10} of accumulated thermal time (log_{10} $GDD_{4.6}$)# to reach six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

Growth stage	Planting year	
	1989	1990
	log_{10} $GDD_{4.6}$	
Early vegetative	2.669a* §	2.634b
Mid-vegetative	2.742b	2.761a
Late vegetative	2.807a	2.796a
Early bud	2.834a	2.842a
Late bud	2.874b	2.879a
First bloom	2.950a	2.929b

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

\# Log_{10} $GDD_{4.6}$ is the log_{10} of the cumulative of growing degree days using a base temperature of 4.6 °C.

The observed $\log_{10}$ of $GDD_{4.6}$ from field experiments had the following regression equation:

$$Y = 18.288 \log_{10} (GDD_{4.6}) - 48.888$$

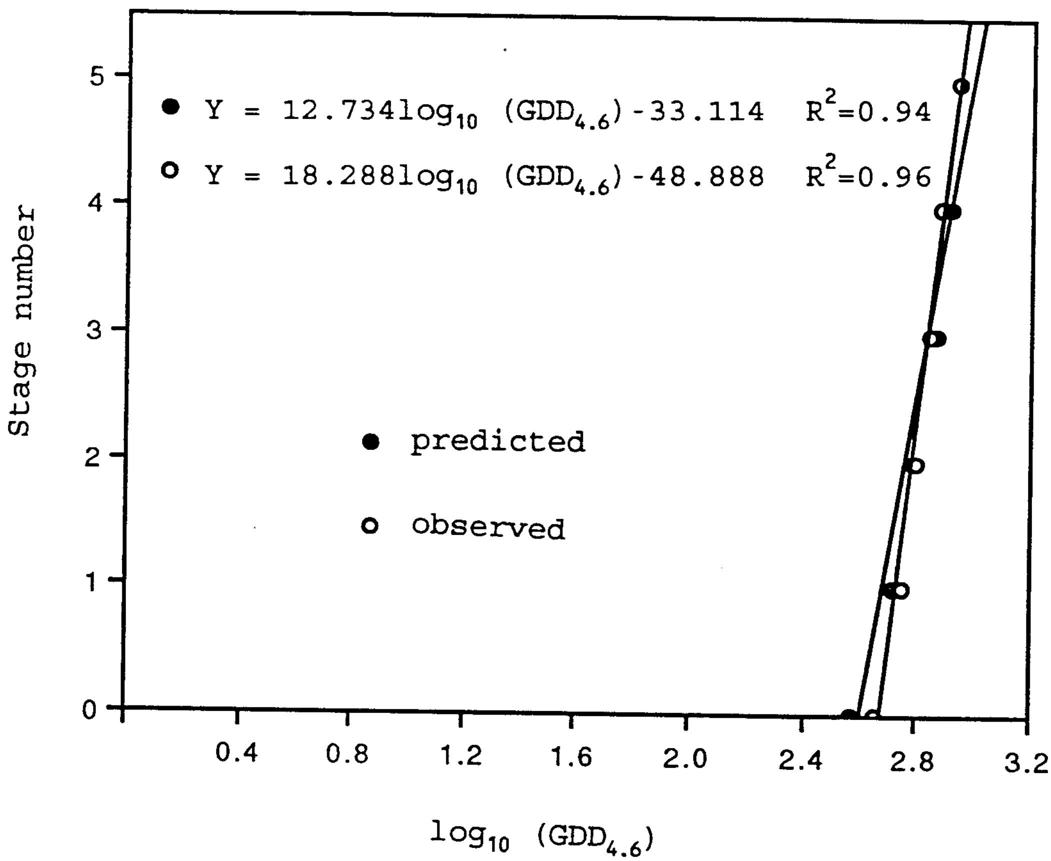
where Y refers to alfalfa growth stage number.

Figure III-2 displays the predicted and observed $\log_{10}$ of accumulated $GDD_{4.6}$ to six phenological growth stages for field grown alfalfa. The predicted and observed $\log_{10}$ of $GDD_{4.6}$ were not significantly different for the last four phenological stages ($P< 0.05$). Phenological development and response to temperature of alfalfa cultivars grown in growth chambers were similar to field grown alfalfa. The high coefficient of determination (R^2=0.96) indicated that alfalfa phenological development can be accurately predicted by the $\log_{10}$ of accumulated $GDD_{4.6}$. This confirms the findings of Boldocchi et al. (1981) who reported that alfalfa phenological development is influenced mainly by temperature.

The agreement between field and growth chamber experiments supports the use of 4.6 °C as an appropriate base temperature for field grown alfalfa and indicates that alfalfa phenological development can be predicted from $\log_{10}$ of accumulated $GDD_{4.6}$.

Growth stage effects on mean stage by count (MSC) and mean stage by weight (MSW) were significant and more important than year and cultivars effects (Table III-3). Alfalfa cultivars reached the first bloom stage when their MSC and

Fig. III-2. Predicted and observed $\log_{10}$ transformation of growing degree days (GDD4.6) versus growth stage response curves of three alfalfa fall dormancy groups.



MSW values were 2.4 and 3.2, respectively, during 1989 and 1990 (Table III-8 and III-9). This confirms the findings of Kalu and Fick (1981, and 1983), Muller and Fick (1989), and Vodraska (1990). These authors indicated that alfalfa MSC and MSW can be used to quantify alfalfa development stages and to predict its nutritive value. Muller and Fick (1989) used a linear regression equation (Y = 1.153 MSC + 0.456) to relate alfalfa MSW to the MSC from field samples (R^2=0.98).

Figure III-3 displays the relationship between MSC and MSW from the 1989 and 1990 field experiments. These data indicate that alfalfa MSW can be related to its MSC values using the following equation:

$$Y = 1.338*MSC - 0.039$$

where Y is the mean stage by weight and MSC is the mean stage by count (R^2=0.99).

The association between alfalfa growth stages and the changes in nutritive value (Kalu and Fick, 1981; 1983) makes the use of MSW important for evaluating alfalfa quality and development. However, the MSW method remains destructive in nature and requires field sampling. In contrast, the $\log_{10}$ of accumulated $GDD_{4.6}$ method is accurate and nondestructive.

Table III-8. Mean stage by count (MSC) for six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

	Year	
Growth stage	1989	1990
	MSC	
Early vegetative	0.0a* §	0.0a
Mid-vegetative	0.7b	0.9a
Late vegetative	1.1a	1.3a
Early bud	1.5a	1.7a
Late bud	2.0a	1.9b
First bloom	2.4a	2.4a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

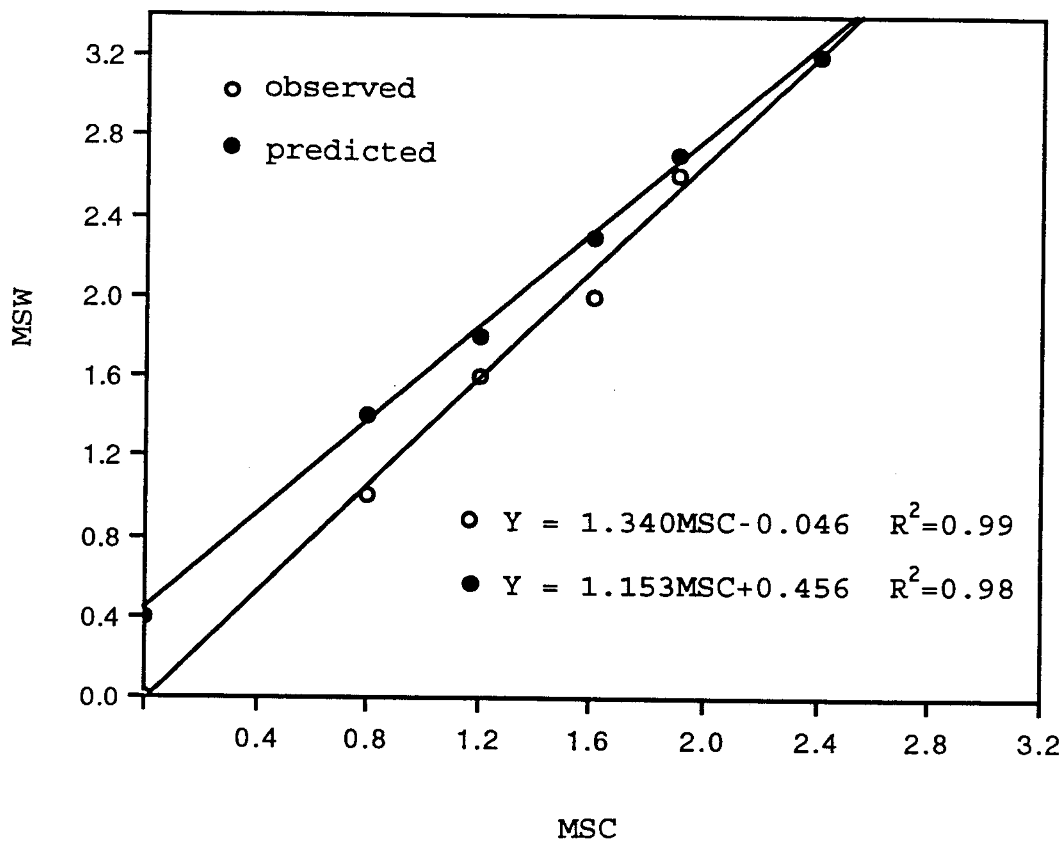
Table III-9. Mean stage by weight (MSW) for six growth stages of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.

Growth stage	Year 1989	Year 1990
	MSW	
Early vegetative	0.0a* §	0.0a
Mid-vegetative	0.9b	1.1a
Late vegetative	1.5a	1.6a
Early bud	2.1a	2.0a
Late bud	2.7a	2.5b
First bloom	3.2a	3.2a

* Growth stage means followed by different letters are significantly different at the 0.05 level as determined by the Least Significant Difference method.

§ Values are means of three alfalfa fall dormancy groups.

Fig. III-3. Predicted and observed mean stage by weight (MSW) as a function of mean stage by count (MSC) of three alfalfa fall dormancy groups grown in field experiments at Corvallis, OR in 1989 and 1990.



SUMMARY AND CONCLUSIONS

This study was conducted to evaluate a model developed from growth chamber experiments relating seedling alfalfa phenological development to accumulated growing degree days. Field experiments indicated that alfalfa growth stage and year had significant effects on yield and percent advancement per day to phenological development stages. Alfalfa growth stage and year effects were more important than cultivar effects.

The observed regression equation relating alfalfa growth stage number to the $\log_{10}$ of accumulated $GDD_{4.6}$ under field conditions was:

$$Y = 18.288 \log_{10} (GDD_{4.6}) - 48.888$$

This equation was not significantly different from the predicted equation derived from growth chamber experiments ($Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$).
The high coefficient of determination (R^2=0.96) between the $\log_{10}$ of $GDD_{4.6}$ and alfalfa development stage indicated that growth and development of alfalfa cultivars can be predicted accurately from temperature. The agreement between growth chamber and field experiments results confirms early research reports indicating that temperature is the most important environmental factor driving alfalfa growth and development processes.

The relationship between alfalfa phenology and $\log_{10}$ $GDD_{4.6}$ should be of practical use to producers and researchers since it accurately predicts the development stages for alfalfa cultivars. This simple linear model relating alfalfa phenological development to mean temperature is a useful and nondestructive method of predicting alfalfa growth stages.

The changes in nutritive value of alfalfa forage in relation to phenological development are well documented. Therefore, accurate prediction of alfalfa growth stage is a prerequisite for making appropriate agronomic recommendations for increased yield and quality of harvested alfalfa forage. The equations presented here will assist in that process.

Additional validation sites will be necessary to confirm that this relationship is not dependent on location. Experiments also are needed to investigate the correlation between alfalfa forage quality and accumulated thermal time. Additional environmental factors such as light intensity and soil conditions may help improve the prediction of alfalfa phenology and forage quality.

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GENERAL CONCLUSIONS

The current study was conducted to investigate the temperature mediated phenological development of alfalfa. Nine alfalfa cultivars (belonging to three fall dormancy groups) were used in growth chamber and field experiments to develop and validate a predictive model for alfalfa phasic development.

Growth chamber day/night temperature treatments of 11/6, 20/10, and 30/20 ± 0.5 °C were used to determine the base temperature for alfalfa phenological development. The percent advancement to first bloom per day (% AFB day^{-1}) method was used. The $\log_{10}$ transformation of the mean temperature indicated that 4.6 °C was an appropriate base temperature for the phenological development of alfalfa cultivars. Alfalfa stage of development and temperature treatments had significant effects on dry matter yield, time to maturity stages, accumulated GDD_0, GDD_5, and the $\log_{10}$ $GDD_{4.6}$. Growth stage and temperature regimes were more important than the effect of alfalfa cultivars.

The growth and development of alfalfa cultivars was hastened by warmer temperature treatments. The dry matter yield was 2 to 3 times higher under cool temperature regimes than warm or hot temperature treatments. The $\log_{10}$ $GDD_{4.6}$ method resulted in less variability than the GDD_0 and GDD_5 methods.

Growth chamber experiments were used to develop a simulation algorithm relating alfalfa phenological development to $\log_{10}$ $GDD_{4.6}$ for six alfalfa growth stages.
A simple linear model:

$$Y = 12.734 \log_{10} (GDD_{4.6}) - 33.114$$

(where Y is alfalfa growth stage number) was determined to accurately predict alfalfa phenological development from the $\log_{10}$ of accumulated $GDD_{4.6}$ (R^2=0.94).

Field experiments conducted during 1989 and 1990 validated the growth chamber stage model. Alfalfa growth stage and year had significant effects on time to harvest, dry matter yield, and percent advancement per day to maturity of alfalfa cultivars. However, years did not have significant effects on the $\log_{10}$ of accumulated $GDD_{4.6}$ to alfalfa stages of development, mean stage by count, or mean stage by weight.

The regression equation relating observed alfalfa development stages to $\log_{10}$ $GDD_{4.6}$ from field experiments was

$$Y = 18.288 \log_{10} (GDD_{4.6}) - 48.888$$

Field observed and growth chamber predicted $\log_{10}$ $GDD_{4.6}$ values were not significantly different. The agreement between field and growth chamber experiments supports the use of 4.6 °C as an appropriate base temperature for field $GDD_{4.6}$ computation for alfalfa phenological growth stages.

The current study suggests that alfalfa phenological development can be predicted accurately from a $\log_{10}$ transformation of growing degree days using a base temperature of 4.6 °C. The nonsignificant year effect suggests that $\log_{10}$ $GDD_{4.6}$ would be independent of season. Thus, $\log_{10}$ of accumulated $GDD_{4.6}$ can be used as a nondestructive method of predicting alfalfa phenological development.

The close association between alfalfa maturity stages, yield, and quality makes accurate prediction of alfalfa development stages important for alfalfa management. Further investigation of the temperature-mediated phenological development of alfalfa is needed to assure that this relationship is sufficiently robust to account for differences in years and locations. Additional environmental factors (such as solar radiation, soil type and moisture conditions) also need study to determine their effect on the growth and development of alfalfa cultivars under a variety of regions and environments.

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