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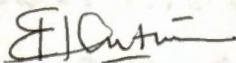
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**A PHENOLOGICAL STUDY OF SNAP BEAN (PHASEOLUS VULGARIS L.)
FOR PREDICTING HARVEST**

**A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville**

**Entin Daningsih
August 1991**

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ACKNOWLEDGMENTS

The author wishes to express her appreciation to the following persons:

Dr. David L. Coffey (major professor), for his guidance in conducting this research, for his advice and assistance in preparing the thesis, and for his support and encouragement throughout the course of this study.

Dr. Joanne Logan, for her guidance and suggestions in conducting and preparing this research and thesis, and for friendship while serving on my committee.

Dr. Charles Mullins for his encouragement and advice, for his assistance while conducting this research, and for his help while preparing this thesis.

Dr. John Foss and the entire Department of Plant and Soil Science for providing the opportunity for study.

Personnel at the Plant Science Field Laboratory, Knoxville and at the Plateau Experiment Station, Crossville who contributed their time and facilities to my research.

My friends who helped me in their kindness.

ABSTRACT

Field studies were conducted in 1989 and 1990 at Knoxville and in 1990 at Crossville, Tennessee to observe the phenology of snap bean (Phaseolus vulgaris L.) and to develop heat unit models for the cultivars 'Eagle' and 'Provider'. The best models were selected to predict bean plant development, especially the time to harvest maturity.

The experimental design was a randomized complete block with sub treatments in a split plot arrangement. The main treatments were cultivars 'Eagle' and 'Provider'. Sub plot treatments consisted of 10 planting dates at Knoxville and 6 planting dates at Crossville. Phenological observations were taken on a weekly basis and analyzed using ten methods of heat unit summation. Data on pod yield, pod distribution, and fiber content were recorded.

Since none of the ten methods of heat unit summation utilized resulted in consistently low coefficients of variation (c.v.), a model of growing degree days using the conventional method in which daily mean temperatures minus the base temperature 10°C (50°F) were summed was performed for snap bean in this study. A greater number of heat units was required at Knoxville than at Crossville to obtain harvest maturity for both cultivars. Results from multivariate regression analysis indicated the highest R^2 was obtained in 1989 at Knoxville and in 1990 at Crossville for the model including five variables; growing degree days (GDD), solar radiation (RAD), air relative humidity (ARH), wind speed (WSP), and

precipitation (PPT). Solar radiation (RAD) resulted in a greater R^2 than growing degree days in 1990 at Knoxville and Crossville when canopy height temperature and height relative humidity, and soil temperatures at 2.5 cm and 10.2 cm (1 and 4 inch) depth were added to the regression models.

Pod yield was significantly influenced by planting date over all experiments although it was not influenced by cultivars. Pod fiber content was greatest from plants at the latest planting date in 1989 at Knoxville. The pod fiber content, however, was affected only by pod size in 1990 at Knoxville and at Crossville.

Results of these experiments in arriving at the best heat accumulation models for predicting the time of harvest maturity suggested that further research is needed since the best model was different for each experiment. A more precise description of each phenological stage and more frequent observations would improve the model. Other possibilities might include using base temperatures other than 10°C (50°F) and using different base temperatures for vegetative stages and reproductive stages although this approach would change the current assumption of heat unit summation.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
II. LITERATURE REVIEW	4
A. Snap bean	4
B. Plant phenology	6
C. Heat unit system	9
III. MATERIALS AND METHODS	13
A. Field Experiments	13
A. 1. Knoxville	13
A. 2. Crossville	15
B. Weather data collection	16
C. Phenological observations.....	16
D. Yield	17
E. Heat unit summations.....	19
F. Statistical analysis	20
IV. RESULTS AND DISCUSSION	22
A. Pod yield	22
B. Pod distribution	32
C. Fiber content	38
D. Heat unit summations	40
E. Multivariate regression	60
V. CONCLUSIONS	69
LIST OF REFERENCES	71
APPENDIX	78
VITA	96

LIST OF TABLES

TABLE	PAGE
1. Planting and harvest data of snap bean at Knoxville in the 1989 and 1990 growing seasons	14
2. Planting and harvest data of snap bean at Crossville in 1990.....	16
3. Stages of snap bean development.....	17
4. Sieve size and corresponding range in diameter of whole, raw snap bean pods	18
5. Effects of cultivar and planting date on pod yield of snap bean at Knoxville, 1989	23
6. Effects of cultivar and planting date on pod yield of snap bean at Knoxville, 1990	24
7. Effects of cultivar and planting date on pod yield of snap bean over 2 years, 1989 and 1990 at Knoxville.....	25
8. Effects of cultivar and planting date on pod yield of snap bean at Crossville, 1990	27
9. Effect of pod size on distribution of snap bean pods by weight and by number at Knoxville, 1989	33
10. Effect of pod size on distribution of snap bean pods by weight and by number at Knoxville, 1990	34
11. Effects of cultivar and planting date on pod distribution of snap bean by weight and by number to determine mean weight of the total sieve size at Knoxville, 1989 and 1990	35
12. Effect of pod size on distribution of snap bean pods by weight and by number at Crossville, 1990	36
13. Effects of cultivar and planting date on pod distribution of snap bean by weight and by number to determine mean weight of the total sieve size at Crossville, 1990	37

TABLE	PAGE
14. Crude fiber content of snap bean pod tissue in 1989 at Knoxville.....	38
15. Crude fiber content of snap bean pod tissue in 1990 at Knoxville and Crossville	39
16. Regression of heat unit summations and stage of snap bean development using 10 methods of calculation based on ten planting dates at Knoxville, 1989	42
17. Regression of heat unit summations and stage of snap bean development using 10 methods of calculation based on ten planting date at Knoxville, 1990	43
18. Regression of heat unit summations and stage of snap bean development using 10 methods of calculation based on ten planting dates with data pooled for two years, 1989 and 1990 at Knoxville.	44
19. Regression of heat unit summations and stage of snap bean development using ten methods of calculation based on five planting dates at Crossville, 1990	45
20. Heat unit requirements (method 1*) for phenological stages for 2 snap bean cultivars at Knoxville (35.53°N) based on two-year data	47
21. Heat unit requirements (method 1*) for phenological stages for 2 snap bean cultivars at Crossville (33°N) in 1990	48
22. Effects of cultivar and planting date on estimated harvest time using method 1* of heat unit summation at Knoxville and Crossville	50
23. Multivariate regression with five variables for two snap bean cultivars at Knoxville in 1989.....	62
24. Multivariate regression with five variables for two snap bean cultivars at Knoxville in 1990	64
25. Multivariate regression with seven variables for two snap bean cultivars at Knoxville in 1990	65

26.	Multivariate regression with five variables for two snap bean cultivars at Crossville in 1990	67
27.	Multivariate regression with nine variables for two snap bean cultivars at Crossville in 1990	68
A1.	Climatic variables for snap bean development of cultivars 'Eagle' and 'Provider' at Knoxville, 1989 based on 10 planting dates	79
A2.	Climatic variables for snap bean development of cultivar 'Eagle' at Knoxville, 1990 based on 10 planting dates	80
A3.	Climatic variables for snap bean development of cultivar 'Provider' at Knoxville, 1990 based on 10 planting dates	81
A4.	Climatic variables for snap bean development of cultivar 'Eagle' at Crossville, 1990 based on 6 planting dates	82
A5.	Climatic variables for snap bean development of cultivar 'Provider' at Crossville, 1990 based on 6 planting dates	83
A6.	Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with five variables in 1989 at Knoxville	84
A7.	Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with five variables at Knoxville, 1990	86
A8.	Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with seven variables at Knoxville, 1990	88
A9.	Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with five variables at Crossville, 1990	94

LIST OF FIGURES

FIGURE	PAGE
1. Relationship between growing degree days and developmental stages of snap bean cultivars 'Provider' and 'Eagle' at Knoxville based on 2 year study, 1989 and 1990 (0=V0; 2=V1; 4=V3; 6=R5; 8=R7)	52
2. Relationship between growing degree days and development stages of snap bean cultivars 'Provider' and 'Eagle' at Crossville, in 1990 (0=V0; 2=V1; 4=V3; 6=R5; 8=R7)	53

CHAPTER I

INTRODUCTION

Snap bean (Phaseolus vulgaris L.) ranks fifth in per capita consumption among all vegetables in the United States (Peirce, 1987). In Tennessee, the value of commercial production of snap bean is estimated at 8 to 17 million dollars annually (Tomkins et al., 1979). Snap beans are also grown extensively in home gardens. One of the leading states for fresh market production is Tennessee (Hartmann et al., 1981; USDA Statistics, in Peirce, 1987). Production ranges from 7,290 to 9,720 ha (18,000 to 24,000 acres) and contributes 10 to 14 million dollars annually to the economy of Tennessee (Rutledge, 1982).

Production of snap beans in a northern latitude is restricted to a specific season due to the snap beans's temperature requirements. Seeds will not germinate if the temperatures are too cool. Snap beans respond differently to changing climatic regimes. Planting must be scheduled for growth and development which correspond closely to the season most favorable for optimum yield and quality.

Heat unit systems are used primarily by commercial vegetable growers, processors and packers. It is very important that the timing of production be coordinated closely with favorable growing season and temperature. For example, the time when the freeze-free period begins and ends is especially critical to planting and harvesting operations.

The use of a heat unit system began with Reaumur's concept in 1735 in which time-temperature indexing was used as a method for predicting plant growth (Brooker and Gray, 1987). Heat unit summations using temperature only for snap beans have not been very successful due to snap bean's vulnerability to varying growth rates in portions of the growing season (Kish and Ogle, 1980).

Phenology is defined as plant development related to climatological factors (Wang, 1963). Each stage of plant development corresponds to the changing of size, morphology, chemical composition, hormonal composition, etc. (Gepts, 1987). In addition, each stage requires a specific heat unit requirement for development. By doing phenological studies, a heat unit summation required for each stage of development can be more accurately defined.

This research was conducted to develop a model of heat unit summation using phenological observations that might be suitable for predicting harvest maturity of snap beans in Tennessee. The experiments were conducted in 1989 and 1990 at the University of Tennessee, Knoxville, Plant Science Field Laboratory, Knoxville and in 1990 at the Plateau Experiment Station, Crossville.

The objectives of the research were (1) to observe the phenological stages of two commonly grown cultivars of snap bean, 'Eagle' and 'Provider', (2) to predict the maturity time of snap bean using ten methods of heat unit summations, (3) to find a heat unit model that might be best for snap bean development, and (4) to quantify the effects of other climatological factors such as solar radiation, relative humidity, wind speed, precipitation, soil

SOUTH FORTH CO. U.S.A.
temperature, canopy height temperature, and canopy height
relative humidity as they may also influence the development
of snap bean.

CHAPTER II

LITERATURE REVIEW

A. Snap bean

Common bean (Phaseolus vulgaris L.) originated in Central America (Shwartz and Pastor-Corrales, 1989; Evans, 1976). Evidence of snap bean dating to 5000 BC has been found in Peru and in Mexico (Peirce, 1987). The crop migrated to the north and south along primitive trade routes. The settlers in North America found Indians interplanting snap beans with maize as staples in their diet.

Snap bean belongs to the family Leguminosae. It is also known as common bean or kidney bean. Snap bean refers to the condition of bean pods harvested for fresh use or for processing such as canning (Herklots, 1972). Snap bean differs from other beans due to earliness (Work and Carew, 1955) or because it is harvested immature (Hartmann et al., 1981). Many cultivars of snap beans have been developed, depending on their use. Each cultivar is developed through a breeding program which resulted in desired plant and pod characteristics. 'Provider' and 'Eagle' are examples of cultivars with different characteristics. 'Provider' is used either for processing or fresh market and is resistant to bean mosaic and some rusts (Hartmann et al., 1981). It produces large pods, dark seeds, and has high yields. 'Eagle' is good for freezing. Pods of 'Eagle' are tender, but they break easily.

Snap bean (Phaseolus vulgaris L.) is a tender, warm

season, annual dicotyledonous plant with an epigeal germination (Peirce, 1987; Herklots, 1972).

Peirce (1987) divided the plant growth habit of snap bean into three major types ; dwarf (bush or determinate), tall (pole or indeterminate) or semi-vining. Singh (1989) suggested that there are four principal growth habits; type I, type II, type III, and type IV. Type I has a determinate growth habit with vegetative terminal buds on main stems and branches. In addition, limited or no further node and leaf production occurs after flowering commences in type I. Type II has an indeterminate growth habit with vegetative terminal buds on main stems and branches. Node and leaf production occur after flowering commences. Main stems and branches are strong and upright. Type III has an indeterminate growth habit with branches which are relatively weak and open, semi-prostrate, or twinning. Pod load is largely concentrated in the basal part of the plant. The maximum yield from this type is realized in monoculture. Type IV has an indeterminate growth habit with stems and branches that are very weak and excessively long with a strong climbing ability. Each type has been subdivided into one additional sub-type grown in Latin America. Lebaron (1974) also divided the developmental stages of the common bean plant. His divisions were similar to those by Fernandez et al. (1986) who divided the stages into vegetative and reproductive. Lebaron determined the vegetative stages by counting the number of nodes on the main stem including the primary leaf node. He also suggested that, in addition to nodes, pod and seed characteristics must be described to observe stages. Evans

(1976) identified 5 different races of beans and suggested how to evaluate their growth patterns. He presented the range of variation for each of the race characteristics such as habit of plant growth, internode length, number of internodes, leaf size, pod length, seed number for pod, seed size, and pod texture. According to Hartmann et al. (1981), both climbing and bush types of snap bean have pods with thicker walls than dry field beans (navy, pinto, kidney). In addition, snap beans have thick walled pods that are free from strings in the early stages of development (Ware and McCollum, 1959).

The bean is the most important food legume in the developing world and in North America. Over three quarters of the annual world production of 8.5 million metric tons is produced in tropical, low-income countries (Schwartz and Pastor-Corrales, 1989). World bean production is divided into major regions of which Brazil, Mexico, and the Eastern African Highland together produce half of the world's total production. Beans are a major staple food in these regions. In the United States yields of snap bean reach about 1.5 ton/ha (FAO in Schwartz and Pastor-Corrales, 1989).

In the United States, snap bean is used fresh, frozen and canned. Approximately 204,410 acres (82,786 ha) are devoted for processing and 83,038 acres (33,630 ha) for fresh market in the United States (Peirce, 1987).

B. Plant phenology

Plant phenology is defined in general terms as the study of periodical plant growth and development phenomena as influenced by genotype and the total environment (Gepts,

1987). Plant phenology is characterized in morphological terms through the use of growth and development scales. According to Wang (1963), phenology is the study of periodic biological phenomena related to weather and climate. Phenology is the science of the relationship between climate and periodic biological phenomena such as flowering and fruiting of plants (Newman and Beard, 1962).

The rates of development and growth have to be carefully matched for optimal crop yield in different environments. Angus et al. (1981) stated that the distinction between development and growth is a useful one for crop simulation. In addition, they stated that although commonly linked to growth, development can proceed in some circumstances without substantially increased crop biomass and in other circumstances growth can proceed without development.

Dating back to ancient Chinese civilizations, observations of phenological events have been used to determine the time table of seasonal changes. Phenological studies in the modern sense began shortly after Reaumur's studies in 1735 (Newman and Beard, 1962). He assumed that plant growth increased directly with a time-temperature summation index. Therefore, for over the past two centuries, data have been recorded for emergence, leafing, and flowering of specific plants.

The purpose of phenological observations in agriculture is to determine meaningful relationships between the meteorological variables in the natural environment and the associated biological responses. The main applications are as follows : 1) forecasting seasonal production

conditions, 2) forecasting seasonal operations, 3) management decisions, 4) selection of production sites, and 5) improvement of production practices (Newman and Beard, 1962).

Phenological records were kept in Europe during the last decade of the nineteenth century and the early decade of the twentieth century. The best example of a continuous record of organized phenological observations is found in The Annual Phenological Reports of the Royal Meteorological Society (Newman and Beard, 1962).

The first extensive use of phenological observations and climatic data in studies of crop growth was summarized by Abbe (1905). Magoon and Culpepper (1932) used much more intensive phenological observations in sweet corn response to varying temperatures. Wang (1959) developed procedures to use phenological observation for three major commercial canning vegetables : sweet corn, cucumber, and peas.

There are four methods in phenological observations as follows: 1) morphological or physical changes, 2) mass or rate of growth change in organisms, 3) activity changes, and 4) biochemical changes. Activity changes are more applicable to animals, such as bird migration, than to plants while morphological changes are more easily observed in plants than in animals (Newman and Beard, 1962).

Phenological observations record events of growth and development of a single species or even a single plant in considerable detail. Observations are usually taken on a daily, bi-weekly, or weekly basis (Neild and Greig, 1972). The life cycle of a plant can be subdivided into several stages of growth and development. In addition, each of

these morphological stages can be divided into several substages of growth and development to increase the precision of phenological events in the life cycle of plants (Van-Schoonhaven and Pastor-Corrales, 1987). These types of observations can be very useful in crop research studies.

Several standard evaluation scales are used to evaluate bean germplasm. One of the standards utilized for the evaluation of snap bean is provided by Centro Internacional de Agricultura Tropical (CIAT) within a scale from 1 to 9 with no decimals. This standardized system was developed to facilitate comparisons of overall plant development, damage caused by insects and diseases, and the effect of adverse soil or climatic factors (Gepts, 1987).

The snap bean has two stages of development which are vegetative and reproductive. Furthermore, each stage is subdivided into detailed substages such as emergence, first primordia leaf, first trifoliate, budding, flowering, and pod formation (Gepts, 1987). The development from one substage to the next substage depends primarily on temperature and genotype. Using the scale of stages, phenological data can be related to other observations such as phytogenesis, entomology, and climatology.

C. Heat unit system

Temperature is a critical factor in plant growth and development. Whereas light directly affects the above ground or photosynthesizing reaction, the whole plant is influenced by temperature. The effect of temperature on physical or chemical processes is quantified as the Q_{10} of the reaction. A Q_{10} of 2 indicates that the rate of

reaction doubles for each 10°C increase in temperature (Ting, 1982). Every plant species responds to changing temperature. A base temperature and a ceiling temperature are often used when considering the rate of some processes as a function of temperature. Below the base temperature, the process does not appear to occur; while above the base temperature, the process occurs at a rate corresponding to the actual temperature. As temperature increases, the rate of the process increases. Above the optimum temperature, the rate decreases. The point above the base temperature at which the rate of plant growth decreases is called ceiling temperature (Logan et al., 1983). There are three cardinal temperatures related to plant growth as follows: 1) the optimum at which a plant functions best, 2) the minimum below which a plant cannot grow, and 3) the maximum above which the plant cannot grow (Fitter and Hay, 1987).

Of all environmental factors, temperature and photoperiod are the most critical variables influencing plant growth and development of snap bean (Coyne, 1966; Gepts, 1987). Gepts (1987) stated that common bean cultivars growing at an annual average temperature of 24°C flowered at 31-41 days after planting. On the other hand, cultivars growing at an annual average temperature of 18°C flowered later at 44 to 59 days after planting.

Growing seasons using phenological and temperature normals in an agroclimatic procedure were determined to estimate earliest and latest planting and harvest dates for green vegetables (Neild and Greig, 1972). According to Neild and Greig, when grown for fresh market, time of harvest is of primary interest and earliness in harvest is

directly related to price. For vegetables grown for processing, length of harvest season is of major economic importance.

Researchers have attempted to correlate crop development with temperature. If this is possible, one could not only predict the maturation date but could also schedule successive plantings to give continuous harvest of vegetables.

The most widely used method of temperature summation is the growing degree-day (GDD). Each crop needs a certain number of growing degree days to reach maturity. A base temperature is established for each crop, below which growth and development are minimal (Gould, 1950).

The appropriate base temperature giving the smallest coefficient of variation (c.v.) is most reliable to calculate heat units from planting to harvesting to predict the first harvesting day (Arnold, 1959). An accurate determination of the base temperature in heat unit accumulation models is extremely important if the models are to be used for predictive purposes (Gbur et al., 1979).

Perry et al. (1987) used ten heat unit systems for different lengths of postbloom period in 'Golden Delicious' and 'Delicious' apples to predict harvest date. The prediction missed the actual harvest date on average of 1.0 day for 'Delicious' and 8.25 days for 'Golden Delicious'.

Perry et al. (1986) calculated heat unit summation for cucumber. They used 14 methods with daily maximum and minimum air temperature for growing seasons over 5 years. They reported that one of the 14 methods resulted in the lowest c.v. of 3% compared to 10% using the standard method

of number of days from planting to harvest.

Dufault et al. (1989) calculated heat units from planting to harvest for collard (Brassica oleraceae L. var. acephala) using 8 methods with daily maximum and minimum air temperatures from 1985 through 1987 growing seasons in the three states. The most reliable method produced a c.v. of 9.1% compared to 11.4% for the standard method and 13.4% for counting days between planting and harvest.

Kish et al. (1972) found that growing degree hours method was unreliable in predicting the maturity for three plantings of 'Tender Crop' snap bean unless other environmental factors were included. They integrated soil moisture into the degree hour method. The formula gave the smallest coefficient of variation when daily heat unit multiplied by a ratio of the daily available soil moisture to a constant soil moisture value.

Multivariate analysis combining the phenological and meteorological data were performed by Castonguay and Dube (1985) to verify phenoclimatic regionalization of the agricultural territory that reflects climate differences. This study confirms the complimentary assumption between climate and phenology and illustrates the usefulness of phenological information to characterize the bioclimate potential of a territory.

CHAPTER III

MATERIALS AND METHODS

A. Field experiments

A. 1. Knoxville

Research studies were conducted during the 1989 and 1990 growing seasons at the University of Tennessee, Plant Science Field Laboratory, Knoxville. The sites for each year were different. The first site (1989) was an Etowah Silt Loam with 2-5 % slope, and part of the area was slightly eroded with a 5-12 % slope while the second site (1990) was a Huntington Loam. Each site was plowed in the fall and tilled in the spring before planting.

A randomized complete block design with four replications and a split plot factorial arrangement of treatments was utilized. The main treatments were cultivars of snap bean which were 'Eagle' (C1) and 'Provider' (C2). The split plot treatments consisted of ten planting dates (PD) in each year. Each plot consisted of four 304 cm (10 feet) rows spaced 96 cm apart. In 1989, the planting dates ranged from April 17 through July 27, approximately 15 days apart. In 1990, the planting dates ranged from April 24 through June 27, approximately one week apart. Planting and harvest data are shown in Table 1.

Table 1. Planting and harvest data of snap bean at Knoxville in the 1989 and 1990 growing seasons.

Number	1989				1990	
	Planting date	Harvest (DAP) *		Planting date	Harvest (DAP)	
		C1 ¹	C2		C1	C2
1.	17 April	67	62	24 April	65	57
2.	24 April	73	60	1 May	65	54
3.	4 May	76	63	8 May	58	51
4.	17 May	64	56	15 May	62	56
5.	25 May	64	55	22 May	69	50
6.	31 May	66	52	31 May	67	63
7.	25 June	67	51	6 June	-	61
8.	10 July	63	49	13 June	75	69
9.	18 July	62	55	20 June	68	69
10.	27 July	69	-	27 June	64	61

* DAP = days after planting ¹ C1 = Eagle C2 = Provider - = no available data.

After the plants reached stage V2 or V3 (Table 3) for each planting date, they were fertilized with ammonium nitrate (43-0-0) at a rate of 33.6 kg per ha or 30 lbs per acre. The rows were kept weed-free by hoeing. Sevin (carbaryl insecticide) was used to control insects. Manzeb fungicide was used in the second experiment to control plant diseases. The experiment in 1990 was irrigated twice at fourth and fifth planting dates .

A. 2. Crossville

A study like the one at Knoxville was conducted in 1990 at Crossville. A randomized complete block design with four replications and a split plot factorial arrangement of treatments was also utilized. Instead of 10 planting dates as in Knoxville, six planting dates were evaluated at the Plateau Experiment Station (Table 2). The site was a Lily sandav loam soil with 3-4% slope. The soil depth ranges from 46 to 61 cm (18 to 24 inches). The site was planted to a winter wheat cover crop and green residue was turned under plowed in the spring. The plants were fertilized with 10-10-10 at a rate of 560 Kg per ha or 500 lbs per acre. Due to a severe hail storm on August 29, only four plantings were harvested. The first three harvests were for both cultivars but the fourth harvest was only for cultivar 'Provider'.

Table 2. Planting and harvest data of snap bean at Crossville in 1990.

Number	Planting date	Harvest (DAP) *	
		C1 ¹	C2
1.	25 May	67	54
2.	7 June	64	58
3.	20 June	65	56
4.	7 July	-	53
5.	20 July	-	-
6.	30 July	-	-

* DAP = days after planting ¹ C1 = Eagle C2 = Provider - = no available data

B. Weather data collection

An automated weather station (Campbell CR10, Logan, Utah), was used to collect meteorological data. Hourly average, maximum, and minimum air temperature, relative humidity, soil temperature at 2.5 and 10.2 cm (1 and 4 inches) in depth, canopy height relative humidity and canopy height temperature (45.7 cm or 18 inches above sod) were recorded. The hourly total wind speed, precipitation, and solar radiation were also recorded.

C. Phenological observations

Phenological observations were taken once a week. CIAT's scale of snap bean development was used (Table 3) with development divided into 2 stages, each with five substages (Fernandez et al., 1986)

Table 3. Stages of snap bean development.

Growth Stage	Characteristics
Vegetative	
V0	Germination
V1	Emergence: cotyledons of 50% of plants have reached soil level
V2	Primary leaves : primary leaves of 50% of plants are unfolded
V3	First trifoliate leave : first trifoliate leaf of 50% of plants is unfolded
V4	Third trifoliate: third trifoliate leaf of 50% of plants is unfolded
Reproductive	
R5	Preflowering: first raceme on flower buds have appeared in 50% of plants
R6	Flowering: first flower has opened in 50% of plants
R7	Pod wall growth: first pod has appeared in 50% of plants
R8	Pod filling: first pod in 50% of plants has reached its maximum size and seed contained in pod have started to grow
R9	Maturation: first pod in 50% of plants has changed color.

From Fernandez, F., P. Gepts, and M. Lopez. 1986. Etapas de Desarrollo de la Planta de Frijol Comun, Ser. 04SB-09, CIAT, Cali, Columbia (cited in Gepts, 1987).

D. Yield

Two 1.52 m (5-foot) long rows were hand harvested at Knoxville while two 6.08 m (20-foot) long rows were harvested by machine at Crossville. Pod yields were determined for each cultivar at each harvest. After weighing the total harvest of each replication, 908 grams (two lbs) of sample were separated into six sieve sizes. Sieve size is determined by passing pods through sieve perforations according to those diameter listed in Table 4. Each size represents the development of pod. A pod size

less than 5 is desired for fresh snap bean (Rutledge, 1982). Usual harvest is 20% to 50% of pod size number 5. The same pod size from each replication in each planting date were combined for fiber analysis.

Table 4. Sieve size and corresponding range in diameter of whole, raw snap bean pods.

Sieve size	Pod diameter
	--- mm ---
No. 1	4.8 to 5.7
No. 2	5.8 to 7.3
No. 3	7.4 to 8.3
No. 4	8.4 to 9.5
No. 5	9.6 to 10.9
No. 6	11.0 +

Fiber content of pod sizes 3, 4, 5, and 6 was determined from three (early, middle, and late) of the ten planting dates. One hundred grams of pod tissue from each size was deseeded and crushed. After adding 175 ml of water, the crushed pod tissue was brought to a boil. A 25 ml aliquot of 50% NaOH solution was added to the pod tissue and let boil for 5 minutes. The pod mixture was placed in a malted milk stirrer and stirred for 5 minutes. The blended material was, then, transferred to a previously weighed metal screen (monel metal screen) and washed with warm water until the fiber was clear and free of alkali. Finally, the screen and fibrous material were dried in the oven at 70°C before dry weights were recorded. The fiber percentage was

calculated using the formula as follows:

$$\text{Fiber(\%)} = \frac{(\text{weighed screen} + \text{dry fiber}) - \text{weighed screen}}{\text{weight of pod sample tissue}} \times 100\%$$

(USDA, 1961).

In 1989, pod samples for fiber content were frozen before being analyzed and in 1990, they were analyzed in fresh condition soon after harvest and grading.

E. Heat unit summations

Ten methods for heat unit summation were used in this study. Seven methods were based on daily maximum, minimum, and average temperatures; three methods were based on hourly data. The methods for growing degree days and degree hours are as described by Perry et al. (1987) with modifications in methods 9 and 10. Method 9 calculated the hourly temperatures during the day time only. Method 10 included day length.

A base temperature of 10°C (50°F) was used for all calculations of growing degree days and growing degree hours. In addition, ceiling temperature was 29.4°C (85°F).

Methods for Heat Unit Summation:

1. $GDD = \Sigma (\text{mean daily temperature} - \text{base})$
 $\text{mean} = \frac{(\text{daily maximum} + \text{daily minimum})}{2}$
2. $GDD = \Sigma (\text{maximum daily temperature} - \text{base})$
3. $GDD = \Sigma (\text{mean daily temperature} - \text{base})$
 if $t_{\text{max}} > \text{ceiling}$
 $t_{\text{max}} = \text{ceiling}$
4. $GDD = \Sigma (\text{maximum daily temperature} - \text{base})$
 if $t_{\text{max}} > \text{ceiling}$
 $t_{\text{max}} = \text{ceiling}$

5. $GDD = \sum (\text{mean daily temperature} - \text{base})$
 if $t_{\text{max}} > \text{ceiling}$
 $t_{\text{max}} = \text{ceiling} - (t_{\text{max}} - \text{ceiling})$
6. $GDD = \sum (\text{maximum daily temperature} - \text{base})$
 if $t_{\text{max}} > \text{ceiling}$
 $t_{\text{max}} = \text{ceiling} - (t_{\text{max}} - \text{ceiling})$
7. $GDD = \sum (\text{maximum daily temperature} - \text{base})$
 if $t_{\text{max}} > \text{ceiling}$
 $t_{\text{max}} = \text{daily mean} - (\text{maximum} - \text{ceiling})$
8. Growing Degree Hours
 $GDH = \sum (\text{mean hourly temperature} - \text{base})$
9. GDH accumulated during daytime only
10. Daily GDH multiplied by daylength

F. Statistical analysis

Statistical Analysis System (SAS) procedures were used to analyze the data. Ten methods for heat unit summation were regressed on the stage of snap bean development using linear regression. Results of 1989 and 1990 experiments using the conventional method (Method 1) at Knoxville were pooled. The pod yield and fiber content were analyzed using SAS GLM and SAS Anova, respectively, with a split plot model. Pod sieve size distribution was analyzed using SAS GLM with a split split plot model. The stages of snap bean development were regressed on air temperature, solar radiation, precipitation, air relative humidity, and wind speed. In addition, growing degree days based on soil temperature at 2.5 and 10.2 cm (1 and 4 inches) in depth were included in 1990 at Knoxville. Canopy height relative humidity and growing degree days based on canopy height temperature were also added in 1990 at Crossville. Variation inflation factors (VIF) were used to detect the multicollinearity among the independent variables.

Multicollinearity is data where some of the independent variables generally indicate fairly high correlations among independent variables (Steel and Torrie, 1980). The variation inflation factor is defined as $1/(1-R^2)$. Stepwise and R^2 procedures were used to select variables that contributed significantly to the multiple regression equation.

CHAPTER IV

RESULTS AND DISCUSSION

Two snap bean cultivars 'Eagle' and 'Provider' were evaluated at Knoxville in 1989 and 1990 and at Crossville in 1990. The results of pod yield, pod distribution by weight and number, pod fiber content, and heat unit summation will be discussed.

A. Pod yield

In 1989, pod yield decreased with later planting dates (Table 5). Pod yield was sharply reduced in the tenth planting date (27 July) with $451 \text{ kg} \cdot \text{ha}^{-1}$. Average pod yield over 10 planting dates in 1989 at Knoxville (Table 5) was significantly higher for 'Provider' ($7,086 \text{ kg} \cdot \text{ha}^{-1}$) than for 'Eagle' ($5,901 \text{ kg} \cdot \text{ha}^{-1}$). Average pod yields of both cultivars were almost identical in 1990 at Knoxville (Table 6). Pod yields of snap bean cultivars 'Eagle' and 'Provider' for both years at Knoxville (Table 7) showed no statistical differences between main treatments (cultivars). Pod yields were significantly affected by planting date both in 1989 and in 1990 at Knoxville. The highest pod yield occurred with the first planting date in both years. Pod yields in 1990 with a c.v. of 37.3% was higher than in 1989 with a c.v. of 29.0%. However, the stability of the average pod yield of cultivar for each planting date in 1990 was relatively higher than those recorded in 1989 (Table 7). Table 7 showed that the maximum and the minimum pod yields of 1990 were $9,475 \text{ kg} \cdot \text{ha}^{-1}$ and $3,722 \text{ kg} \cdot \text{ha}^{-1}$, respectively

Table 5. Effects of cultivar and planting date on pod yield of snap bean at Knoxville, 1989.

Planting date		Cultivar	
Number	Date	Eagle	Provider
kg · ha ⁻¹			
1	17 April	12,980	14,906
2	24 April	6,432	6,286
3	4 May	-	5,392
4	17 May	7,588	5,508
5	25 May	5,739	7,511
6	31 May	9,398	6,644
7	25 June	7,780	7,048
8	10 July	1,348	4,583
9	18 July	1,390	5,046
10	27 July	451	-
Means		~ 5,901 ^a	7,086 ^a
Interaction (Cultivar X Planting date)		NS	NS
Cultivar		NS	NS
Planting date		***	***

***, NS significant at 0.01 % probability level or not significant, respectively.
 ~ Mean separation within row by SNK, 5 % level.
 Means with the same letter are not significantly different.

Table 6. Effects of cultivar and planting date on pod yield of snap bean at Knoxville, 1990.

Planting date		Cultivar	
Number	date	Eagle	Provider
		kg · ha ⁻¹	
1	24 April	9,090	9,860
2	1 May	6,586	8,705
3	8 May	6,760	7,280
4	15 May	5,970	4,892
5	22 May	3,640	4,237
6	31 May	7,934	5,269
7	6 June	-	7,164
8	13 June	7,357	6,760
9	20 June	6,682	6,825
10	27 June	3,325	4,210
Means		~ 6,362 ^a	6,520 ^a
Interaction (Cultivar X Planting date)		NS	NS
Cultivar		NS	NS
Planting date		***	***

***, NS Significant at 0.1 % probability level or not significant, respectively.
 ~ Mean separation within row by SNK, 5 % level.
 Means with the same letter are not significantly different.

Table 7. Effects of cultivar and planting date on pod yield of snap bean over 2 years, 1989 and 1990, at Knoxville.

Factor	Pod yield	
	1989	1990
	kg · ha ⁻¹	
<u>Cultivar</u>		
Eagle	∞ 5,906 ^b	6,362 ^a
Provider	~ 7,086 ^a	6,520 ^a
Means	~ 6,496 ^a	6,441 ^a
<u>Planting date</u>		
1	∞ 13,943 ^a	9,475 ^a
2	6,359 ^b	7,646 ^{ab}
3	5,392 ^{bc}	7,020 ^{ab}
4	6,548 ^b	5,430 ^b
5	6,625 ^b	3,938 ^b
6	8,021 ^b	6,602 ^{ab}
7	7,414 ^b	7,164 ^{ab}
8	2,966 ^c	7,058 ^{ab}
9	3,218 ^c	6,754 ^{ab}
10	451 ^d	3,722 ^b
<u>Interaction</u>		
(Cultivar X	NS	NS
Planting date)		
Cultivar	NS	NS
Planting date	***	***
c.v.	29.0%	37.3%

***, NS significant at 0.1 % probability level or not significant, respectively.

∞ Mean separation of the combined yield for two years within column by SNK, 5 % level. Means with the same letter are not significantly different.

~ Mean separation within row by SNK, 5 % level. Means with the same letter are not significantly different.

whereas the maximum and the minimum pod yields of 1989 were 13,943 kg · ha⁻¹ and 451 kg · ha⁻¹, respectively. In 1990 at Knoxville, the fourth and fifth planting dates also resulted in low pod yields.

Planting date also affected pod yield at Crossville in 1990 (Table 8) although there was no significant difference in pod yield between snap bean cultivars. Contrary to the results obtained at Knoxville, the first planting date at Crossville resulted in the lowest pod yield of 3,091 kg · ha⁻¹ and 1,367 kg · ha⁻¹ for 'Eagle' and 'Provider', respectively. The highest pod yield was at the third planting date although there was no statistical differences between the pod yield from the second and the third planting dates.

The average yield for both years at Knoxville (Table 7) were lower than the average yields at Crossville (Table 8). Snap beans are a warm season vegetable, adapted in temperate conditions (equivalent to temperature at altitude 500-1500 meters in the tropical region) (Evans, 1976). Because plants are not able to regulate the temperature effectively, their distribution is strongly influenced by ambient temperature. The world's climatic zone is determined by latitude and altitude. Laing et al. (1984) reported that beans in Latin American countries are grown in microregions in which most of the production is from areas where temperatures are approximately 21°C (equivalent to temperature at an altitude of 1250 meters in the tropics). In Latin America, beans are grown throughout the continent from the northern states of Mexico (30°N) down to regions as far south as Chile (43°S) (Schwartz and Pastor-Corrales,

Table 8. Effects of cultivar and planting date on pod yield of snap bean at Crossville, 1990.

Planting date	Cultivar	
	Eagle	Provider
	kg · ha ⁻¹	
25 May	2,091	1,367
7 June	10,206	9,567
20 June	13,227	11,289
7 July	-	5,040
Means	~ 8,508 ^a	6,815 ^a
Interaction (Cultivar X Planting date)	NS	NS
Cultivar	NS	NS
Planting date	***	***

***, NS significant at 0.1 % probability level or not significantly, respectively.
 ~ Mean separation within row by SNK, 5 % level.
 Means with the same letter are not significantly different.

1989). Knoxville lies at 271 meters or 890 feet (Kurian, 1983) above sea level while Crossville lies at 549 meters or 1,800 feet above sea level. Knoxville does not lie within the ranges, while Crossville does lie within the range of altitude to successfully grow snap bean described by Laing et al. The differences in altitude between the two locations resulted in different temperatures which probably affected the yields of snap beans.

The average yields of 6,131 kg $\cdot$ ha⁻¹ and 6,780 kg $\cdot$ ha⁻¹ in 1989 and 1990, respectively at Knoxville were nearly identical (Table 7). The yield of commercially grown snap beans is not usually very high; average yields are usually less than 1.4 ton $\cdot$ ha⁻¹ in most developed countries (Laing et al., 1984). However, under experimental conditions snap beans in pure stands can yield more than 5 ton $\cdot$ ha⁻¹ (Graham, 1978). For instance, in the Dominican Republic, snap beans can yield 4.0 - 5.0 ton $\cdot$ ha⁻¹ and even when associated with a high density of maize can yield 2 ton $\cdot$ ha⁻¹ (Francis, 1978). The yields from the first two plantings at Knoxville were higher than those listed in the above reference. Hand harvest at Knoxville reduced the pod breakage encountered with mechanical harvest at Crossville. Furthermore, all pod yields at Knoxville were harvested and there was very little chance to lose small pod when hand harvested. The yield, however, varied from a maximum of 13,943 kg $\cdot$ ha⁻¹ to a minimum of 451 kg $\cdot$ ha⁻¹ from the first planting to the last planting at Knoxville in 1989. On the third planting, the yield was low (Table 7). The average temperature from 4 May 1989 through 17 May 1989 was 13°C. The total precipitation was 41 mm (1.61 inches) and 104 mm

(4.26 inches) on 4 May 1989 and 17 May 1989, respectively (data not shown). Snap bean seeds require at least 16°C soil temperature to germinate (Adams et al, 1985). Austin and Maclean (1972) suggested that low temperatures during the growing season was a major factor limiting yields of dwarf French beans (Phaseolus vulgaris L.) in Great Britain. Low temperatures and high precipitation during early stages of the third planting date reduced the germination rate which resulted in low pod yield production. Germination was as low as 43% for both cultivars (data not shown). In later developmental stages, some plants showed wilted leaves and lesions on the basal stems and roots were probably caused by fungal root rot due to *Rhizoctonia* or *Phytophthora*. The total precipitation in May 1989 was 192 mm (7.57 inches), and the total precipitations in June and July 1989 were 946 mm (9.70 inches) and 178 mm (7.02 inches), respectively. High total precipitation (381 mm and 427 mm for 'Provider' and 'Eagle', respectively) during growing seasons of the third planting and disease problems were probably responsible for failure of seed germination and the decrease in the rate of snap bean development. Therefore, these conditions resulted in low pod yield production of the third planting in 1989 (Table 5). After the third planting date, tillage and weed removal were difficult due to heavy rains and wet soils. While the temperature increased in the later part of the season, relative humidity remained high at approximately above 80% (data not shown). Conditions were favorable for insect attack especially from Mexican Bean Beetles (MBB). These climatic conditions also accounted for increasing competitions from weeds during the snap bean development.

In 1990, the weather conditions were different from those during the 1989 growing season. Less precipitation and higher temperatures resulted in slight drought stress in 1990.

The average snap bean yields in 1990 at Knoxville were rather stable from one planting to another. Nevertheless, pod maturity took a longer time resulting in later harvest dates compared to those in 1989. The basic assumption is that abscission of blossoms and subsequent poor set is associated with high temperature and low humidity. The yield from the May 22 planting was very low (Table 6). The average temperature at Knoxville in June and July 1990 was over 25°C (data not shown). The total precipitation in June 1990 was only 38 mm (1.48 inches), and the total precipitation was 99 mm (3.88 inches) in July 1990. Lambeth (1950) showed a significant relationship between the percentage set of pods and the mean daily temperature. It appears that when the mean temperature for the 24-hour period following anthesis was above 25.6°C or 78°F, pod set was reduced. There was no significant correlation between pod set and mean daily relative humidity. Relative humidity during this period was in the favorable range (70-91%) and was probably in no case limiting to pod set. The average relative humidity during the fourth planting date was approximately 57%. Total precipitation was 259 mm (10.22 inches).

Contrary to the yields obtained from the first planting at Knoxville, the yields from the first planting date at Crossville were the lowest compared to those from the three other planting dates. Wet soil and low

100% COTTON FIBER

temperatures retarded the growth of snap bean for both cultivars. In addition, no disease pressure was encountered at Crossville. During the days before the first planting (23 May 1990), the precipitation was 125 mm (4.92 inches) in May. As temperatures became more favorable, the yield increased from 2,091 kg · ha⁻¹ to 13,227 kg · ha⁻¹ and 1,367 kg · ha⁻¹ to 11,289 kg · ha⁻¹ for 'Eagle' and 'Provider', respectively (Table 8.). The increase in temperature at Crossville caused a 'split set', which resulted from flower abortion due to high temperature and moisture stress causing delayed pod formation. Beans require a warm, frost free climate, but the plants drop their blossoms or pods during excessively hot or rainy weather (Ware and McCollum, 1959). Monterroso and Wien (1990) found that 82% of heat stressed structures of the pods abscised as small pods (less than 2 cm length), when the stress was applied at various flower bud stages of snap beans. Low humidity of 54% (data not shown) at reproductive stages probably contributed to reduced pod set, thus, resulting in the lowest yield for the fourth planting date at Crossville.

The constraints on bean yield are associated with a narrow temperature tolerance. Yield reduction is related to failure of flowers to produce mature pods (Monterroso and Wien, 1990). Abscission of flowers and failure to set and fill pods are probably the greatest constraints to bean yields. Davis (1945) found that abscission increased by approximately 2% for each degree above 24°C. Phaseolus vulgaris L., although not known to be a drought-tolerant species, is nevertheless subjected in many environments to an increasing probability of water stress as the growing

season proceeds. Stress during flowering when the crop is most sensitive, reduces yield through increased flower failure and to a lesser extent, by reducing the number of seeds per pod (Monterroso and Wien, 1990).

At the other extreme, heavy rain or irrigation produces a humid crop microclimate conducive to disease problems. High precipitation and temperature at early vegetative stages caused the third planting to be exposed to root rot attack. At Crossville, the cultivar 'Provider' recovered earlier than the cultivar 'Eagle'.

B. Pod distribution

To determine the correct stage of pod harvest depends on the ratio. This ratio shows the percentage of pod sieve size distribution. The most common range of ratios used for determining the stage of maturity for harvest are 70:30, 65:35, and 60:40 (Rutledge, 1982). The larger number in each ratio is the percentage of pod sieve size number 1, 2, 3, and 4 and the smaller number in each ratio is the percentage of pos sieve size number 5 and 6 by weight.

Most processor are set up to handle more pods of sieve No. 4 (U.S. No. 1) or smaller than they are of sieve size No. 5 (U.S. No. 2) or larger (Rutledge, 1982). The most common harvesting ratio for processor in Tennessee is 70:30 (Rutledge, 1982).

The pod distribution of bean yield by number and weight at Knoxville was not affected by cultivar or planting date (data not shown). However, highly significant differences were observed in size. The cultivars interacted

with the size of pods significantly both in weight and in number of the pod bean. As the size number increased, the mean weight of the pod also increased (Table 9). Based on calculation to determine the correct stage of pod harvests, the ratios for determining the stage of maturity for harvest in 1989 at Knoxville were 496:387 and 174:57 or approximately 56:44 and 75:25 by weight and by number, respectively (Table 9).

Table 9. Effect of pod size on distribution of snap bean pods by weight and by number at Knoxville, 1989.

Sieve size	Weight	Number	Mean weight
	--gram--		--gram--
No. 1	~ 52 ^c	~ 66 ^a	0.8
No. 2	46 ^c	20 ^d	2.3
No. 3	108 ^d	32 ^c	3.4
No. 4	290 ^a	57 ^b	5.1
No. 5	224 ^b	35 ^c	6.4
No. 6	163 ^c	22 ^d	7.4

~ Mean separation within column by SNK, 5% level. Means with the same letter are not significantly different.

Contrary to the result in 1989, pod distribution of the bean yield in 1990 at Knoxville was affected by cultivars, planting dates, and size (data not shown). The interaction between size and cultivars was observed as in 1989. The ratios for the stage maturity were 629:265 and 248:42 or approximately 70:30 by weight and 86:14 by number (Table 10).

Table 10. Effect of pod size on distribution of snap bean pods by weight and by number at Knoxville, 1990.

Sieve size	Weight	Number	Mean weight
	--gram--		--gram--
No. 1	77 ^d	103 ^a	0.8
No. 2	51 ^e	23 ^d	2.2
No. 3	157 ^b	48 ^c	3.3
No. 4	344 ^a	74 ^b	4.7
No. 5	166 ^b	28 ^d	5.9
No. 6	99 ^c	14 ^e	7.1

Mean separation within column by SNK, 5% level.
Means with the same letter are not significantly different.

The mean weight of total pod size of 'Provider' is larger than those of 'Eagle' (Table 11). Furthermore, the mean weight of the total pod size in 1989 was larger than in 1990 at Knoxville for 3.8 and 3.1 gram, respectively.

The response of pod distribution at Crossville in 1990 was similar to those of 1989 at Knoxville (data not shown). No significant different were observed in cultivars or planting dates. However, sieve size affected the pod distribution significantly. Unlike at Knoxville, 1989 and 1990, there was a significant interaction between pod size and planting date for both weight and number at Crossville.

The ratios for the stage maturity were 417:473 and 122:65 or approximately 47:53 and 65:35 by weight and number, respectively (Table 12).

Table 11. Effects of cultivar and planting date on pod distribution of snap bean by weight and by number to determine mean weight of the total sieve size at Knoxville, 1989 and 1990.

Factor	Weight		Number		Mean weight	
	1989	1990	1989	1990	1989	1990
--- gram ---						
<u>Cultivar</u>						
Eagle	146 ^a	150 ^a	43 ^a	53 ^a	3.4	2.8
Provider	148 ^a	149 ^a	34 ^b	45 ^b	4.4	3.3
Means	147	149.5	39	49	3.9	3.1
<u>Planting date</u>						
1	144 ^a	150 ^a	40 ^{bc}	46 ^{bcd}	3.6	3.3
2	149 ^a	151 ^a	33 ^c	49 ^{bc}	4.5	3.1
3	-	151 ^a	-	49 ^{bc}	-	3.1
4	149 ^a	151 ^a	35 ^c	51 ^b	4.3	3.0
5	149 ^a	152 ^a	37 ^c	64 ^a	4.0	2.4
6	141 ^a	147 ^a	32 ^c	45 ^{bcd}	4.4	3.3
7	148 ^a	150 ^a	32 ^c	36 ^d	4.6	4.2
8	149 ^a	150 ^a	47 ^{ab}	38 ^{cd}	3.2	3.9
9	148 ^a	151 ^a	57 ^a	46 ^{bcd}	2.6	3.3
10	-	135 ^a	-	53 ^b	-	2.6

- ~ Means separation within column by SNK, 5% level.
Means with the same letter are not significantly different.
- Data not available.

Table 12. Effect of pod size on distribution of snap bean pods by weight and by number at Crossville, 1990.

Sieve size	Weight	Number	Mean weight
	--gram--		--gram--
No. 1	38 ^d	41 ^b	0.9
No. 2	24 ^d	10 ^e	2.4
No. 3	67 ^c	18 ^d	3.7
No. 4	288 ^a	53 ^a	5.4
No. 5	272 ^a	40 ^b	6.8
No. 6	201 ^b	25 ^c	8.0

Mean separation within column by SNK, 5% level.
Means with the same letters are not significantly different.

Planting date affected the mean weight of the pod distribution (Table 13). The first and the fourth harvests resulted in smaller mean weight than from the second and the third harvests.

Since the ratio of pod distribution by weight in 1990 at Knoxville was 70:30, it was the closest to the ideal ratio for Tennessee while the ratios from the two other experiments in 1989 at Knoxville and in 1990 at Crossville were slightly over mature. Unfortunately, the ideal ratio in 1990 at Knoxville, the pods were not as good as in 1989

Table 13. Effects of cultivar and planting date on pod distribution of snap bean by weight and by number to determine mean weight of the total sieve size at Crossville, 1990.

Factor	Weight	Number	Mean weight
	--gram--		--gram--
<u>Cultivar</u>			
Eagle	~ 145 ^a	~ 28 ^b	5.2
Provider	151 ^a	34 ^a	4.4
Means	148	31	4.8
<u>Planting date</u>			
1	143 ^a	40 ^a	3.6
2	151 ^a	26 ^c	5.8
3	151 ^a	25 ^c	6.0
4	151 ^a	33 ^b	4.6

~ Mean separation within column by SNK, 5% level.
Means with the same letters are not significantly different.

were slightly over mature. Unfortunately, the ideal ratio in 1990 at Knoxville, the pods were not as good as in 1989 at Knoxville and in 1990 at Crossville. Pods in 1990 at Knoxville were very small and poor texture (not marketable after harvest on planting date 7). The correct stage of pod harvest depends on the environmental conditions under which the crop is grown. Less favorable climatic conditions resulted in reduced pod filling (Mullins and Coffey, 1990). Adams et al. (1985) showed that there is a marked tendency for growth habit and vigor to be associated with drought

tolerance.

C. Fiber content

The percentage of crude fiber content from pods of 3, 4, 5, and 6 sieve size was analyzed for three of the planting dates represented as early, middle, and late in both years at Knoxville, and from all planting dates at Crossville. No statistical differences between cultivars in fiber content or in pod size was observed in 1989 at Knoxville. Planting dates affected crude fiber content. Fiber content increased from .025 % to 0.166% from the early to the late planting date (Table 14). Crude fiber content was much less in 1990 at Knoxville (Table 15). Neither cultivar nor planting date affected crude fiber content in 1990. However, the fiber content was affected by pod size. The percentage of the crude fiber content of pod tissue was also affected by pod size in 1990 at Crossville (Table 15).

Table 14. Crude fiber content of snap bean pod tissue in 1989 at Knoxville.

Planting Dates	Fiber (%)
1st PD (Early)	0.025 ^b
4th PD (Middle)	0.068 ^b
9th PD (Late)	0.166 ^a

Means with the same letter are not significantly different when tested at P=5% , SNK

Table 15. Crude fiber content of snap bean pod tissue in 1990 at Knoxville and Crossville.

Sieve size	Fiber (%)	
	Knoxville	Crossville
3	0.00040 ^b	0.00015 ^b
4	0.00063 ^b	0.00025 ^b
5	0.00192 ^b	0.00028 ^b
6	0.00405 ^a	0.00078 ^b

Means with the same letter with the same column are not significantly different when tested at P=5%, SNK

There are three distinct pod textures found in the common bean (Evans, 1976): (a) the parchmented which is very fibrous and dehisces strongly at maturity, (b) the leathery which is less dehiscent but splits readily along the sutures, and (c) fleshy or stringless which is indehiscent and does not split readily. Lynch and Smith (1973) found that early cultivated fragments of beans from an intermountana Peruvian valley do not have heavy, inner fibrous layer characteristics of wild bean pods.

Both cultivars 'Eagle' and 'Provider' are stringless and pods are expected to have very low fiber content. The first experiment in 1989 at Knoxville resulted in higher content of fiber in pods from the late planting date (the ninth) than from earlier planting dates. The percentage of fiber increased as temperatures increased. Kaldy (1966) concluded that fiber content of green snap beans appeared to be a varietal characteristic that was greatly influenced by temperature and humidity. This statement was supported by

the results of the research he conducted showing that 'Tenderlong 15' had fiber content of 0.495% at cool temperature (21°C) and increased fiber content up to 0.6963% at warm temperature (25°C) whereas 'Tendercrop' did not change the fiber content when grown under environment in those two different conditions. The results from 1989 at Knoxville (Table 14) agreed with those of Kaldy.

Contrary to 1989, pods from both experiments in 1990 at Knoxville and at Crossville had no difference in fiber content resulting from planting date or cultivars. The fiber content was significantly different due to pod size which can be explained that as pod size developed, fiber was accumulated, therefore increasing the fiber content. Another explanation for the extremely low fiber content in 1990 was probably due to different method in fiber analysis (see materials and methods p. 19).

D. Heat unit summations

The coefficient of variation (c.v.) and standard deviation are the appropriate statistics to optimize method of heat unit summation (Arnold, 1959). Heat unit summations were calculated for each of ten methods previously described in materials and methods (7 GDD and 3 GDH) for ten planting dates at Knoxville for each year in 1989 and 1990 and for five planting dates at Crossville in 1990. The coefficient of variation (c.v.) was used for discussion in arriving to whether the base temperature used for calculations was appropriate for the model of heat unit system. And R^2 was used to determine whether the regression models were fit. There was no consistency among the ten methods of

calculations resulting in the lowest coefficient of variation (c.v.) and the highest R^2 . Since there was no consistency in coefficient of variation between the two cultivars, data from 1989 and 1990 at Knoxville were pooled when the coefficient of variation was not consistent for each method.

The calculations using ten methods of heat unit summation resulted in different coefficient of variations (c.v.) for each cultivar. At Knoxville in 1989, method 9 had the lowest c.v. (21.8%) and the highest R^2 (96.7%) for the cultivar 'Eagle'. Method 9 also resulted in the lowest c.v. (16.3%) for cultivar 'Provider' and the highest R^2 (98.1%) (Table 16 on p. 42).

In 1990 at Knoxville, method 9 resulted in the lowest c.v. (26.9%) and the highest R^2 for cultivar 'Eagle' whereas method 6 and method 7 resulted in the lowest identical c.v.'s (29.6%) for 'Provider' (Table 17 on p. 43).

When the data from 1989 and 1990 at Knoxville were pooled, method 9 resulted in the lowest c.v. of 25.2% and the highest R^2 of 95.5% for 'Eagle' whereas method 3 resulted in a c.v. of 26.5% and the highest R^2 of 95.0% for 'Provider' (Table 18 on p. 44).

In 1990 at Crossville, methods 6 and 7 resulted in the lowest c.v.'s and the highest R^2 for both cultivars. 'Eagle' had a c.v. of 19.0% and a R^2 of 97.6% and 'Provider' had a c.v. of 15.8% and a R^2 of 98.4% (Table 19 on p. 45). Therefore, the results in 1990 at Crossville with the lowest c.v.'s of 15.8% using method 6 and method 7 were not the same with the results in the data pooled for two years at Knoxville.

Table 16. Regression of heat unit summations and stage of snap bean development using 10 methods of calculation based on ten planting dates at Knoxville, 1989.

Method	H.U. ¹	Eagle			Provider		
		Equation ² Y = bX	R ² %	c.v. ³ %	Equation Y = bX	R ² %	c.v. %
1	GDD ⁴	Y = 0.0125X	95.2	26.1	Y = 0.0148X	96.9	20.8
2	GDD	Y = 0.0120X	95.9	23.9	Y = 0.0144X	97.6	18.3
3	GDD	Y = 0.0124X	95.8	24.4	Y = 0.0148X	97.4	19.2
4	GDD	Y = 0.0120X	96.2	23.4	Y = 0.0143X	97.6	18.3
5	GDD	Y = 0.0123X	95.9	24.3	Y = 0.0148X	97.3	19.6
6	GDD	Y = 0.0120X	96.0	23.8	Y = 0.0143X	97.6	18.4
7	GDD	Y = 0.0120X	96.2	23.3	Y = 0.0143X	97.6	18.3
8	GDD ⁵	Y = 0.0005X	96.1	23.6	Y = 0.0006X	96.5	22.1
9	GDH	Y = 0.0007X	96.7	21.8	Y = 0.0009X	98.1	16.3
10	GDH	Y = 0.0087X	95.6	25.2	Y = 0.0014X	96.8	21.4

¹ Regression equation without intercept. ² H.U. = heat unit ³ c.v. = coefficient of variation. ⁴ GDD = growing degree days.

⁵ GDH = growing degree hour.

Table 17. Regression of heat unit summations and stage of snap bean development using 10 methods of calculation based on ten planting dates at Knoxville, 1990.

Method	H.U. ¹	Eagle			Provider		
		Equation ² Y = bX	R ² %	C.V. ³ %	Equation Y = bX	R ² %	C.V. %
1	GDD ⁴	Y = 0.0112X	94.3	28.4	Y = 0.0119X	93.4	30.4
2	GDD	Y = 0.0107X	94.4	28.1	Y = 0.0113X	93.8	29.7
3	GDD	Y = 0.0112X	94.3	28.4	Y = 0.0119X	93.4	30.4
4	GDD	Y = 0.0108X	94.4	28.2	Y = 0.0113X	93.7	29.7
5	GDD	Y = 0.0112X	94.3	28.4	Y = 0.0119X	93.4	30.4
6	GDD	Y = 0.0107X	94.5	27.8	Y = 0.0113X	93.8	29.6
7	GDD	Y = 0.0107X	94.5	27.8	Y = 0.0113X	93.8	29.6
8	GDH ⁵	Y = 0.0005X	94.7	27.5	Y = 0.0005X	93.5	30.4
9	GDH	Y = 0.0007X	94.9	26.9	Y = 0.0007X	93.8	29.7
10	GDH	Y = 0.0008X	94.1	28.9	Y = 0.0008X	93.4	30.3

¹ Regression equation without intercept. ² H.U. = heat unit ³ c.v. = coefficient of variation. ⁴ GDD = growing degree days.

⁵ GDH = growing degree hour.

Table 18. Regression of heat unit summations and stage of snap bean development using ten methods of calculation based on ten planting dates with data pooled for two years, 1989 and 1990 at Knoxville.

Method	H.U. ¹	Eagle			Provider		
		Equation ² Y = bX	R ² %	C.v. ³ %	Equation Y = bX	R ² %	C.v. %
1	GDD ⁴	Y = 0.0117X	94.6	27.6	Y = 0.0130X	94.1	28.9
2	GDD	Y = 0.0113X	94.8	27.0	Y = 0.0125X	94.3	28.4
3	GDD	Y = 0.0119X	95.1	26.4	Y = 0.0135X	95.0	26.5
4	GDD	Y = 0.0114X	95.0	25.6	Y = 0.0124X	94.3	28.3
5	GDD	Y = 0.0117X	94.9	26.9	Y = 0.0131X	94.2	28.5
6	GDD	Y = 0.0113X	94.9	26.7	Y = 0.0125X	94.3	28.3
7	GDD	Y = 0.0113X	95.1	26.4	Y = 0.0125X	94.3	28.3
8	GDH ⁵	Y = 0.0005X	95.4	25.6	Y = 0.0005X	93.9	29.3
9	GDH	Y = 0.0007X	95.5	25.2	Y = 0.0008X	94.4	28.2
10	GDH	Y = 0.0008X	94.5	27.8	Y = 0.0009X	93.7	29.6

² Regression equation without interception ¹ H.U.=heat unit ³ c.v.= coefficient of variation ⁴ GDD = growing degree days

⁵ GDH = growing degree hours

Table 19. Regression of heat unit summations and stage of snap bean development using ten methods of calculation based on five planting dates at Crossville, 1990.

Method	H.U. ¹	Eagle			Provider		
		Equation ² Y = bX	R ² %	C.v. ³ %	Equation Y = bX	R ² %	C.v. %
1	GDD ⁴	Y = 0.0128X	96.6	22.5	Y = 0.0141X	97.8	18.3
2	GDD	Y = 0.0083X	97.4	19.6	Y = 0.0094X	98.2	16.5
3	GDD	Y = 0.0126X	97.1	20.7	Y = 0.0144X	98.1	16.9
4	GDD	Y = 0.0087X	97.5	19.5	Y = 0.0099X	98.3	16.3
5	GDD	Y = 0.0127X	97.3	20.1	Y = 0.0144X	98.1	17.1
6	GDD	Y = 0.0092X	97.6	19.0	Y = 0.0105X	98.4	15.8
7	GDD ⁵	Y = 0.0092X	97.6	19.0	Y = 0.0105X	98.4	15.8
8	GDH ⁵	Y = 0.0005X	96.5	22.9	Y = 0.0006X	98.1	17.0
9	GDH	Y = 0.0007X	97.4	19.8	Y = 0.0008X	98.1	17.1
10	GDH	Y = 0.0009X	97.4	19.9	Y = 0.0009X	98.1	17.1

² Regression equation without interception ¹ H.U=heat unit ³ c.v.= coefficient of variation ⁴ GDD = growing degree days

⁵ GDH = growing degree hours

Conventional method is the calculation of heat unit in which mean daily temperatures minus base temperature were summed. The conventional method (1) was further analyzed since the ten methods did not result in the same response to give the lowest c.v. for each experiment at Knoxville and at Crossville. This further analysis was used to compare actual (observed) and estimated growing degree days needed for harvest maturity. In addition, there were not any great differences among the 10 methods. Thereafter, the conventional method (1) was used due to its simplicity and wide acceptance. As a result, the time of harvest maturity of snap bean can be predicted using growing degree days. The requirements of heat unit summation in terms of growing degree day for snap bean development are listed in Tables 20 and 21. 'Provider' reached harvest earlier than 'Eagle'. 'Provider' required 712 growing degree days while 'Eagle' required 842 growing degree days at Knoxville (Table 20 on p. 47). At Crossville, 'Provider' required 667 growing degree days and 'Eagle' required 787 growing degree days (Table 21 on p. 48). The estimated harvest for 'Eagle' was 767 growing degree days and for 'Provider' was 690 growing degree days at Knoxville whereas at Crossville, the estimated harvest for 'Eagle' was 703 growing degree days and for 'Provider' was 640 growing degree days. Actual (observed) growing degree days of harvest time for each planting date and each cultivar both at Knoxville and at Crossville were compared. There was a significant difference in growing degree days at Knoxville between the two cultivars (data were not shown).

Table 20. Heat unit requirements (method 1*) for phenological stages for 2 snap bean cultivars at Knoxville (35.53°N) based on two-year data.

Stage	Stage characteristic	Actual		Estimated	
		Eagle	Provider	Eagle	Provider
		_ GDD (base temperature of 10°C) _			
0	Planting	0	0	0	0
V0	Germination	74	79	85	77
V1	Emergence	114	109	170	153
V2	Unfolded	164	155	256	230
V3	First trifoliate	259	255	341	307
V4	Third	389	417	426	384
R5	Preflowering	444	432	511	460
R6	Flowering	490	459	596	537
R7	Pod set	626	565	682	614
Harv	Harvest	842	712	767	690

Data were pooled from 1989 and 1990. GDD = growing degree days
Actual (observed) and estimated GDD calculation was rounded to nearest whole number.

* Method 1 = $\frac{(\text{max} + \text{min temperature})}{2} - \text{base temperature (10°C)}$

Table 21. Heat unit requirements (method 1*) for phenological stages for 2 snap bean cultivars at Crossville (33°N) in 1990.

Stage	Stage characteristic	Actual		Estimated	
		Eagle	Provider	Eagle	Provider
_ GDD (base temperature of 10°C)_					
0	Planting	0	0	0	0
V0	Germination	-	-	78	71
V1	Emergence	85	89	156	142
V2	Unfolded	137	137	234	213
V3	First trifoliate	227	237	312	284
V4	Third	342	352	391	356
R5	Preflowering	426	506	469	427
R6	Flowering	510	507	547	498
R7	Pod set	650	567	625	569
Harv	Harvest	787	667	703	640

GDD = growing degree days.

Actual (observed) and estimated GDD calculation was rounded.

* Method 1 = $\frac{(\text{max} + \text{min temperature})}{2} - \text{base temperature (10°C)}$

- = Data not available

There was no statistical difference in growing degree days required among planting dates for harvest time at Crossville (Table 22). On the other hand, planting date significantly affected the growing degree days required for harvest time at Knoxville. Fewer growing degree days were required for earlier planting dates.

According to Arnold (1959), the correct base temperature will give the lowest c.v. for calculation of growing degree days. These experiments used only a base temperature of 10°C (50°F) for snap bean since snap bean is a warm season vegetable. The inconsistency of c.v.'s in these experiments was probably due to (1) improper base temperature and (2) phenological observations. Brooker (1987) explained that 50°F is the base temperature for snap bean, supported by Gould (1950) and Kish and Ogle (1980). Gbur et al. (1979) suggested that the base temperature in heat unit accumulation model can be determined with the use of segmented regression using least squares approach. Tyldesley (1978) suggested using daily mean temperature for calculating heat accumulations instead of using maximum and minimum temperatures.

Another source of the variability of c.v.'s in these experiments was phenological observation. Since the main objective of these experiments was to improve the heat unit method using phenological observations, the phenological observations both in vegetative and reproductive stages will be discussed further.

Table 22. Effects of cultivar and planting date on estimated harvest time using method 1 of heat unit summation at Knoxville and Crossville.

Factor	Knoxville [∞] 35.53°N	Crossville ^{∞∞} 33°N
Cultivar		
Eagle	748 ^a	623 ^a
Provider	657 ^b	584 ^a
Planting date		
1	555 ^b	647 ^a
2	553 ^b	712 ^a
3	577 ^b	685 ^a
4	664 ^{ab}	569 ^a
5	708 ^{ab}	-
6	753 ^a	-
7	790 ^a	-
8	842 ^a	-
9	809 ^a	-
10	778 ^a	-
Interaction		
(Year X Cultivar)	NS	-
Year	***	-
Cultivar	***	NS
Planting date	***	NS
C ₂ v.	11.47	7.8
R ²	83.8	93.5

, *, NS significant at 1%, 0.1% probability level or not significant, respectively.
 ~ Means separation within column by SNK, 5 % level.
 ∞ Means with the same letters are not significantly different.
 ∞ Data were pooled from 2 year, 1989 and 1990.
 ∞∞ Data were only from 1990.

* Method 1 = $\frac{(\text{max} + \text{min temperature})}{2}$ - base temperature (10°C)

- = Data not available

Abbe (1905) pointed out that according to the doctrine of thermal constraints, a given stage in the development of a plant is reached when that plant has received a certain amount of heat, regardless of the length of time required (Kish and Ogle, 1980). Most studies involving heat units deal with specific stages of crop development such as flowering or silking to predict harvest time but not all stages of crop development. Van de Sande-Bakhuyzen (1928) showed that the science of phenology has important practical application to agriculture since it provides a thorough understanding of the degrees of harmony between climate and the vegetative rhythms of plants and enables the grower to better control the phasic development of the plants and to shift the 'critical periods' of plant development to a time when better climatic conditions prevail.

From the graphs illustrated in Figures 1 and 2 for all phenological stages with method 1, it seems that the responses to growing degree days are not linear although the regression equations have relative high R^2 's for both cultivars. Arnold (1959) used a method in which a regression equation is calculated using the mean temperatures as the independent variable and the heat unit summation as the dependent variable. In these experiments, the heat unit summation was the independent variable and the developmental stage of snap bean was the dependent variable. The model was used to determine a phenological time scale, especially time of harvest maturity. In principle, the regression coefficient in such an equation should be

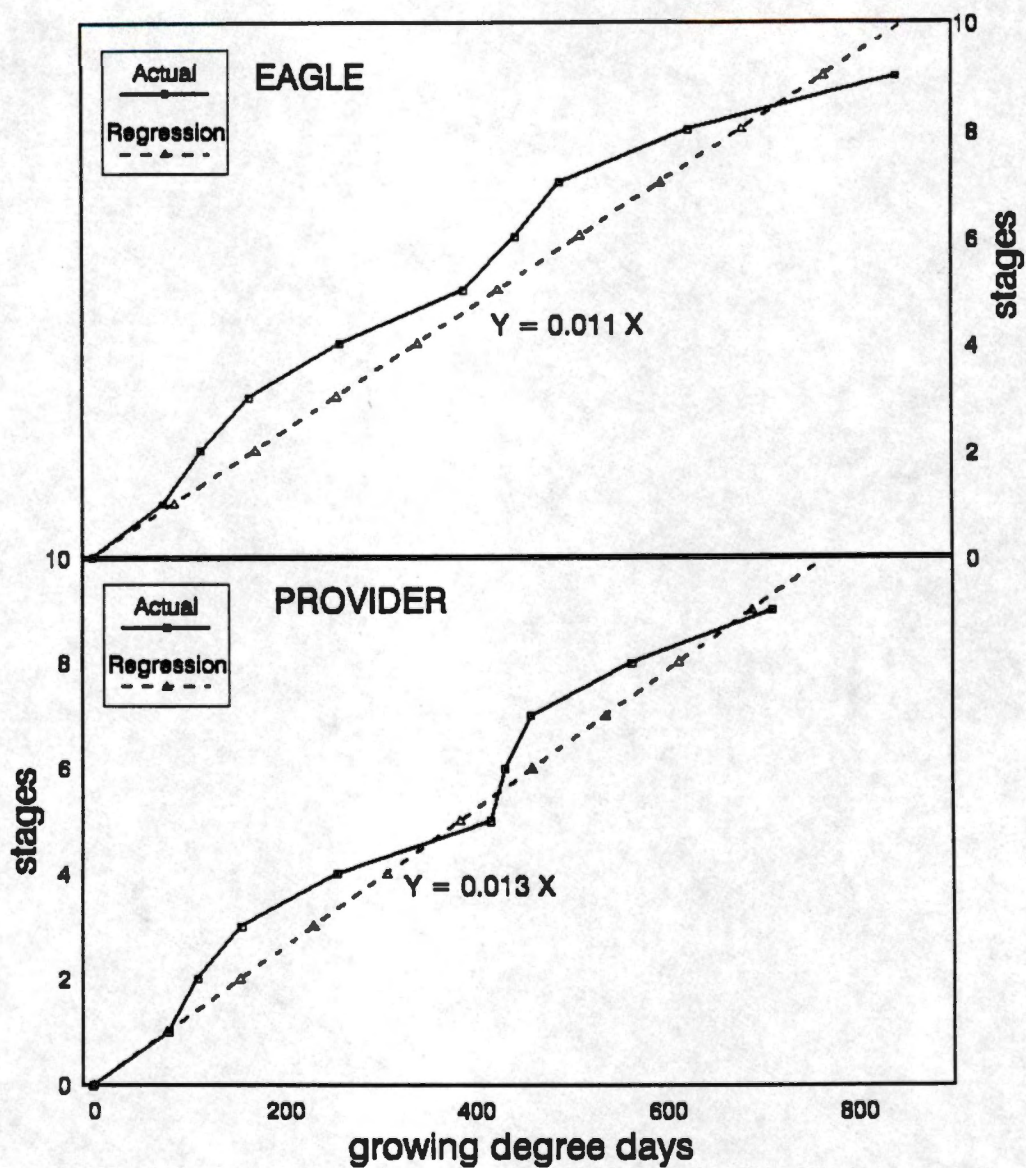


Figure 1. Relationship between growing degree days and developmental stages of snap bean cultivars 'Provider' and 'Eagle' at Knoxville based on 2 year study, 1989 and 1990 (0=V0; 2=V1; 4=V3; 6=R5; 8=R7).

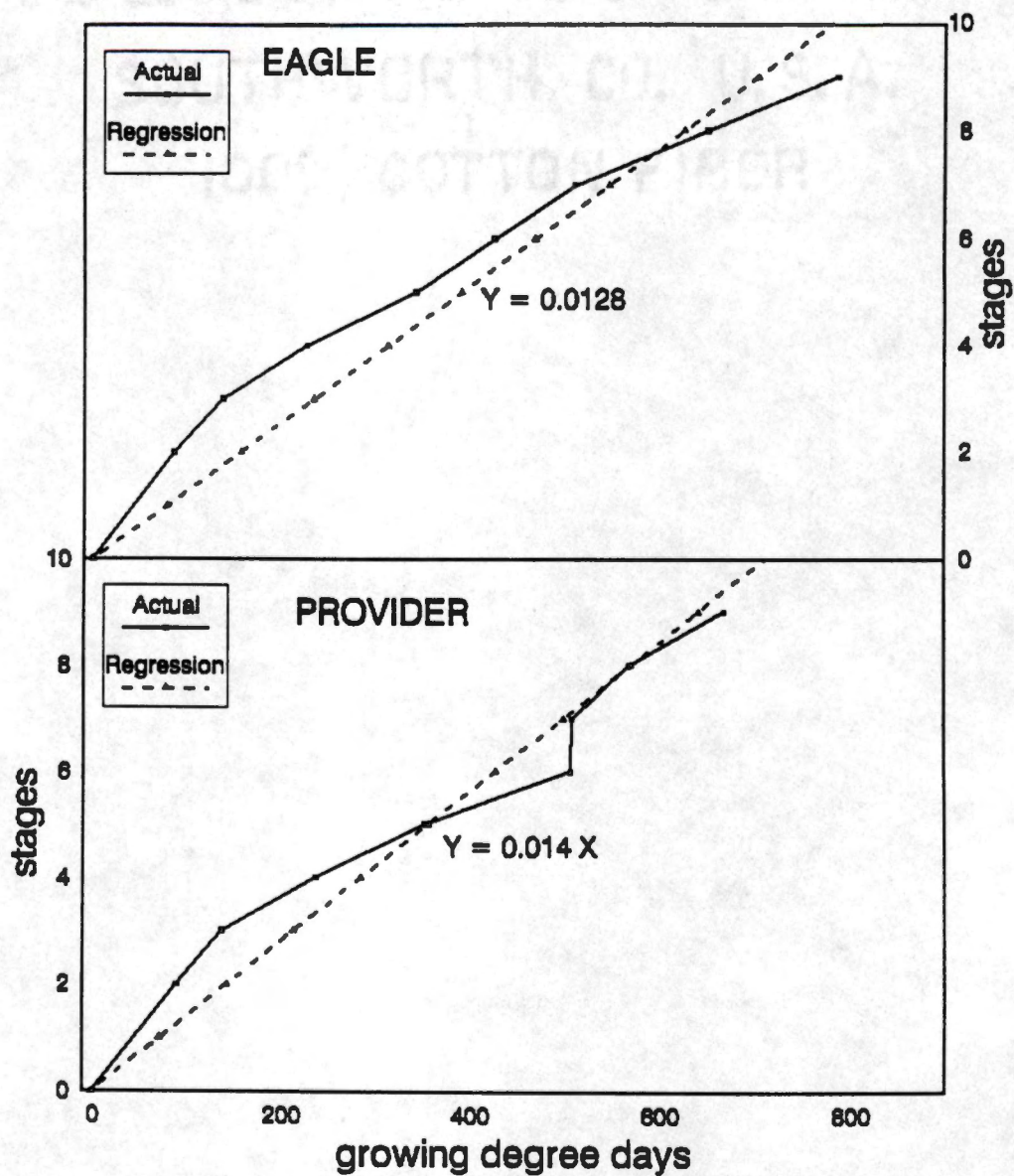


Figure 2. Relationship between growing degree days and developmental stages of snap bean cultivars 'Provider' and 'Eagle' at Crossville, in 1990 (0=V0; 2=V1; 4=V3; 6=R5; 8=R7).

positive if the base temperature used is too high, negative if it is too low and zero if the base temperature is correct (Arnold, 1959).

Went (1957) suggested that in the vegetative phase of the pea plant, nodes may be considered as units of development. The heat unit equation must also be used to measure development in the reproductive phase, but in this phase the morphological development cannot be measured in nodes. Furthermore, development in the latter part of the reproductive phase is followed primarily by the biochemical changes associated with maturation of the fruit and seeds rather than by the formation of new racemes. Went also suggested that with present knowledge of plant development, it is impossible to equate development in the vegetative and reproductive phases even within a single species.

Developmental stages of snap bean have been defined (Fernandez et al., 1986). Related to heat unit summation using method 1, snap bean development was not linear with the heat unit equation in the three experiments. The responses during vegetative stages were rather sigmoid rather than linear. The reproductive stages, however, were almost linear. Both cultivars at Knoxville showed that earlier vegetative stages required fewer growing degree days than the later reproductive stages. At Crossville, the response of cultivar 'Eagle' was similar to that at Knoxville. However, 'Provider' showed a sudden break between R5 and R6 (Figure 2). The break point was the result of a 'split set' in the phenological observation.

Besides the correct base temperature, phenological observations need to be very specific in order to calculate

heat unit accumulations for predicting developmental stages. Precise descriptions of snap bean development can lead to easier and more accurate phenological observations.

The CIAT's guide states that V0 begins on the day that the seed has sufficient moisture to germinate; in other words, V0 is on the day of planting if the soil is moist, or the first rain/irrigation if soil is dry. In this study, the first visible cotyledon on the soil surface not the conditions as stated in CIAT's guide was considered as the germination stage (V0) of snap bean. This type of observation can lead to the misinterpretation for germination time. First, radicles had developed before the cotyledons appeared on the surface of the soil, but the first appearance of cotyledons was considered as a time of germination. Second, the first appearance of a cotyledon on the soil surface was difficult to observe. Sutcliffe (1977) found that high temperatures reduce the viability of seeds, and that germination of lima bean and peas were inhibited by brief periods of chilling to 5°C during the imbibition phase. The rate of respiration was affected and this effect persisted for some time under these conditions. Physiological studies of germinating seed have shown that high temperatures exert effects only during the early period of imbibition by the seed (Charles-Edward et al., 1986). The three experiments reported here did not have any chilling stress during the germination period. However, high temperatures did affect the process of germination and emergence.

Delayed emergence (V1) was observed in planting dates 8 and 9 in 1990 at Knoxville when high temperature, low

humidity, and less precipitation occurred. In the concept of phasic development, it is assumed that each stage of development in a plant has a definite requirement for temperature and that this requirement may vary for the different stages (Angus et al., 1981). In addition, progression from one stage to the next may be prevented by unfavorable climatic factors. This is one of the criticisms of the heat system (Wang, 1963): it does not take into account many other factors which influence plant growth and development both internally and externally. In the three experiments conducted, not only temperature but also precipitation, humidity, soil temperature and radiation varied within the same stage at different planting dates (data not shown). These differences suggested that there are other climatic factors which influenced snap bean to accelerate the rate of stage development resulting in fewer growing degree days required to reach each stage. Finally, the germination stage (V0) might overlap with emergence stage (V1) at which 50% of cotyledons appear on the surface of the soil. If the characteristics of CIAT guide for germination stage was used, this overlap would have occurred.

According to the regression equations for both cultivars (Figure 1 and 2), the heat unit requirements for unfolded unifoliate leaves (V2) were triple that of germination. In fact, fewer heat units were required to reach V2. Germination (V0), emergence (V1), and unfolded unifoliate (V2) occurred very closely to each other. When counting 50% of snap bean plants that is required to reach the next stage for phenological observation, this

observation resulted in fewer growing degree days for stages V0, V1, and V2. Subsequently, the actual response between these stages were slightly lower than estimated linear regression in term of growing degree days. If counting more than 50% of snap bean plants required to reach these stages, it will probably increase the accuracy to be more closely linear regression; therefore, it will increase linearity. The reason is that within stage V2, germination and emergence were still occurring. Other reasons for this variability of developmental stages are probably due to soil moisture differences or depth of the seeds (hydroactive and photoactive processes). This situation gave a vague number of total snap bean plants at the observed stage.

After the first trifoliate leaf developed (stage V3), the number of plants in a given stage was likely to be more stable. Most bean plants had already emerged and those which did not germinate were probably dead. Thereafter, bean plant numbers were relatively stable, and counting 50% of snap bean plants can be used to determine the next developmental stage of snap bean.

During these experiments, each planting was fertilized with ammonium nitrate (33.6 kg ha^{-1}) at stage V2 or V3. Although the snap bean is a legume, it is generally considered weak in N_2 -fixation. Nitrogen fertilization of snap beans is usually recommended (Graham, 1981). The study of plant development by Magalhaens et al. (1970) showed that nitrogen fertilization enhanced plant growth until the bean plant reached the flower stage at which the plant growth rate was slowed down. The data showed that between the growing degree day requirements between vegetative stages of

germination (V0) to emergence (V1) was less than at between V2 and V3 and between V3 and V4. However, to reach stages of preflowering (R5) and flowering (R6), the number of growing degree days required was as low as those required between emergence (V1) and germination (V0). Thereafter, an increase in growing degree days was required to reach pod set formation (R7) and harvest time (Harv).

To reach the stage V4, heat unit requirements increased at a higher rate than earlier vegetative stages for all experiments because up until this stage (V4), bean plants developed by increasing leaf numbers and foliage area. Energy was required to sustain this type of growth.

By stage R5, the crop had already developed the third trifoliolate. The energy requirement increased as plants started to reproduce. The crop not only developed the reproductive part such as flower but also developed branches. However, Tables 20 and 21 (p. 47-48) showed that heat unit requirement for snap bean development at this stage was as low as for earlier vegetative stages. Numbers of flower buds and leaf buds were similar at the top of the bean plant at this stage. Therefore, observations of anatomy or dissection will probably improve the observations of preflowering (R5).

The flowering stage was easily recognized. However, double observations were found in the field when the crops experienced 'split set' in which the early flowers aborted due to high temperature and moisture stress and the plants started to reproduce flowers when environmental conditions were more favorable. In these experiments, the second flowering was recorded and at the same time, some earlier

flowers that did not abort had developed pod formation resulting in double stage observations. To be consistent with heat units, each stage has to be considered only one time to avoid double stages in the same time. It is suggested to use the first stage since the later stage resulted in double stage observations.

According to Gepts (1987), stage R7 is reached when the pod is already 2.5 cm in length. In this experiment, stage R7 began when the pod set and corolla became withered. The maximum length of pod was variable. Therefore, the definition of Fernandez et al. (1986) was not used to end stage R7. Instead, harvesting time (Harv) was chosen as the end of stage R7. Maximum pod length had developed, but seeds had not developed (sieve size No. 4). Harvest was between stages R7 and R8 as defined by Fernandez et al. (1986). Since the pod set was sensitive to temperature stress, harvest maturity was influenced greatly by temperature. In general, the cultivar 'Provider' reached harvest maturity earlier than did cultivar 'Eagle' in these studies.

One assumption of heat unit system is that as the temperature increases, the growth rate increases proportionally in a linear fashion. In other words, under this assumption the developmental stage of plants is expected to increase in the same manner. Data recorded in these experiments did not support this assumption. As shown in Table 21 (p. 48), harvest maturity of snap bean was earlier at Crossville than at Knoxville. The results in 1989 trials at Knoxville required growing degree days of 818 and 670 for 'Eagle' and 'Provider', respectively (data not

shown). Whereas the results in 1990 at Knoxville required growing degree days of 861 and 750 for 'Eagle' and 'Provider', respectively. High temperatures, especially in 1990 at Knoxville delayed snap bean harvest maturity. Overall, the average heat unit requirements based on the two year study at Knoxville were higher than from the one year study at Crossville.

Since the results from the two locations, Knoxville and Crossville, and between the two years, 1989 and 1990 at Knoxville did not occur similarly, it is suggested to repeat the experiment to verify the results of these experiments.

E. Multivariate regression

Multivariate regression was utilized to give an idea of how other particular climatic factors might influence the development of bean plants in these experiments. Multiple regression was used because the temperature in terms of growing degree days did not result in the same effect for each model of heat unit summation in each experiment at both locations. In addition to growing degree days, other climatic factors such as solar radiation (RAD), precipitation (PPT), air relative humidity (ARH), and wind speed (WSP) were regressed on bean development as dependent variables. The conventional method (1) was used to represent heat unit models for this multivariate regression.

In 1989 at Knoxville, wind speed (WSP) had a negative effect on rate of plant development for both cultivars 'Eagle' and 'Provider' (Table 23). All variables together did not contribute significantly to multicollinearity in

cultivar 'Provider' whereas air relative humidity (ARH) alone contributed to multicollinearity in cultivar 'Eagle' based on Variation Inflation Factors (VIF) (Table 23). The VIF is useful in determining which variables may be involved in the multicollinearity. If the individual VIF of a variable in the multiple regression equation exceeds the VIF of the model, that variable may be statistically insignificant due to multicollinearity and not due to the fact that the variable is not related to the dependent variable (Freund and Littell, 1986). In Table 23, VIF of 'Eagle' was 37.29. The VIF of ARH was 38.62. Therefore, ARH was not significant due to higher value of its VIF; in other words; ARH was more related to other independent variables included in the model. If wind speed (WSP) was excluded from the model for 'Eagle', the model had a highest R^2 of 98.7% (data not shown) using the stepwise procedure with the variables of GDD, RAD, ARH and PPT. However using the R^2 procedure, including WSP in the model resulted in the highest R^2 of 95.7% for 'Eagle' (Table A6). Growing degree days (GDD) had the highest chance among other variables to give the highest R^2 (Table A6) for both cultivars using R^2 procedure. Using all 5 variables GDD, RAD, PPT, ARH, and WSP resulted in the highest R^2 of 99.5% for 'Provider' using stepwise procedure (data not shown). The best combination of the variables in the model for both cultivars was GDD RAD PPT ARH WSP using stepwise procedure.

Table 23. Multivariate regression with five variables for two snap bean cultivars at Knoxville in 1989.

Var.	Eagle			Provider			
	Df	Parameter Est.	Prob.	VIF	Parameter Est.	Prob.	VIF
GDD [*]	1	0.007003	0.0001	14.66	0.005126	0.0001	37.84
RAD	1	0.000001	0.2165	1.16	0.000181	0.0001	51.39
PPT	1	0.146635	0.0001	12.32	0.015076	0.3231	16.92
ARH	1	0.021718	0.0001	38.62	0.03213	0.0001	51.99
WSP	1	-0.039758	0.6814	32.77	-0.501739	0.0001	49.36

* GDD = Growing Degree Day (Method 1) Rad = Solar Radiation PPT = Precipitation ARH = Air Relative Humidity WSP = Wind speed VIF = Variation Inflation Factors

Equation for Eagle : $Y = 0.007 \text{ GDD} + 0.000001 \text{ RAD} + 0.147 \text{ PPT} + 0.022 \text{ ARH}$

Equation for Provider : $Y = 0.005 \text{ GDD} + 0.000181 \text{ RAD} + 0.015 \text{ PPT} + 0.032 \text{ ARH} - 0.5017 \text{ WSP}$

Eagle :	
R^2	= 0.9865
C.V	= 14.028
VIF	= 1/1- R^2 = 37.29

Provider :
R² = 0.9950
C.V. = 8.44
VIF = 100.25

In 1990 at Knoxville, GDD had negative effect which means GDD reduced the rate of bean development for both cultivars (Table 24). GDD, RAD, ARH, and WSP contributed to multicollinearity due to higher value of their VIF's than 41.92 and 28.34 for 'Eagle' and 'Provider', respectively (Table 24). Statistically but not biologically, these variables (GDD, RAD, ARH, and WSP) probably related to each other than to dependent variable. There were all 5 variables (RAD, WSP, PPT, ARH, and GDD) resulting in a R^2 of 98.8% for 'Eagle' and a R^2 of 98.2% for 'Provider' when analyzed using stepwise (data not shown). The R^2 procedure resulted similarly (Table A7). Contrary to Knoxville in 1989, solar radiation (RAD) rather than GDD was the best predictor of developmental stage for both cultivars (Table A7). The best combination of the variables in the models for both cultivars was GDD RAD PPT ARH WSP using the stepwise procedure (data not shown).

Adding two more variables, growing degree days of soil temperatures at 2.54 and 10.16 cm (1 and 4 inches) depth to the model caused GDD to have negative effect on bean development for both cultivars (Table 25). A R^2 of 98.8% for 'Eagle' and a R^2 of 98.4% for 'Provider' were obtained when all 7 variables were included in the model using stepwise and R^2 (Table A8). Once again, solar radiation had the highest chance among other variables to give a high R^2 for both cultivars.

Table 24. Multivariate regression with five variables for two snap bean cultivars at Knoxville in 1990.

Var.	Df	Eagle			Provider		
		Parameter Est.	Prob.	VIF	Parameter Est.	Prob.	VIF
GDD*	1	-0.001465	0.0483	74.79	-0.002142	0.0170	69.63
RAD	1	0.000490	0.0001	67.70	0.000577	0.0001	64.43
PPT	1	0.160007	0.0001	9.84	0.154539	0.0001	8.88
ARH	1	0.000081	0.9900	78.91	-0.016639	0.0573	91.91
WSP	1	0.332415	0.0036	64.63	0.583897	0.0001	71.08

* GDD = Growing Degree days (Method 1) RAD = Solar Radiation PPT = Precipitation ARH = Air Relative Humidity WSP = Wind speed VIF = Variation Inflation Factors

Equation for 'Eagle' : $Y = -0.0015 \text{ GDD} + 0.0005 \text{ Rad} + 0.16 \text{ PPT} + 0.00008 \text{ ARH}$

Equation for 'Provider': $Y = -0.002 \text{ GDD} + 0.0006 \text{ Rad} + 0.15 \text{ PPT} - 0.0166 \text{ ARH}$
 $+ 0.33 \text{ WSP}$
 $+ 0.58 \text{ WSP}$

Eagle :
 R^2 : 0.9880
 C.V. : 13.18
 VIF : 41.92

Provider:
 R^2 : 0.9822
 C.V. : 16.1
 VIF : 28.34

Table 25. Multivariate regression with seven variables for two snap bean cultivars at Knoxville in 1990.

Var.	Df	Eagle			Provider		
		Parameter Est.	Prob.	VIF	Parameter Est.	Prob.	VIF
GDD*	1	-0.006470	0.0942	2032.91	-0.017501	0.0001	1377.40
RAD	1	0.000480	0.0001	77.68	0.000565	0.0001	70.39
PPT	1	0.146962	0.0001	11.93	0.098789	0.0006	10.48
ARH	1	0.000314	0.9615	80.14	-0.009824	0.2485	93.98
WSP	1	0.333074	0.0037	65.35	0.493793	0.0008	72.25
Soil1	1	0.000635	0.7933	1181.89	-0.004642	0.0793	9171.80
Soil4	1	0.004065	0.2926	2552.09	0.019288	0.0001	2246.19

* GDD = Growing Degree Day (Method 1) RAD = Solar Radiation PPT = Precipitation ARH = Air Relative Humidity WSP = Wind speed Soil1 = Soil in 1 inch depth and Soil4 = Soil in 4 inch depth using growing degree day (method 1). VIF = Variation Inflation Factors

Equation for 'Eagle':

$$Y = -0.0065 \text{ GDD} + 0.0005 \text{ RAD} + 0.15 \text{ PPT} + 0.0003 \text{ ARH} + 0.33 \text{ WSP} + 0.0006 \text{ Soil1} + 0.004 \text{ Soil4}$$

Equation for 'Provider':

$$Y = -0.0175 \text{ GDD} + 0.0006 \text{ RAD} + 0.099 \text{ PPT} - 0.0098 \text{ ARH} + 0.49 \text{ WSP} - 0.0046 \text{ Soil1} + 0.019 \text{ Soil4}$$

Eagle : R² : 0.9881
C.V. : 13.19
VIF : 84.03

Provider:
R² : 0.9837
C.V. : 15.46
VIF : 30.93

In 1990 at Crossville, wind speed (WSP) had negative effect on bean development for 'Eagle'. GDD and RAD had extremely high multicollinearity (Table 26) assumed that both variables had more influence on each other as independent variables than on bean plant development as the dependent variables. Using both R^2 and stepwise procedures, RAD had a high chance among other variables to give the highest R^2 (Table A9). The best combination of the variables for both models was GDD RAD PPT ARH WSP. RAD gave the highest R^2 for both cultivars when analyzed using stepwise procedure involving 9 variables (GDD, RAD, PPT, ARH, WSP, Soil1, Soil4, CGDD. and CRH). When 9 variables were included in the model at Crossville, air relative humidity, wind speed, and canopy height relative humidity did not contribute to multicollinearity due to their lower VIF's than the model VIF (Table 27). With the computer facilities available, it was not possible to calculate for 9 variables using R^2 procedure due to large number.

Multivariate analysis resulted in different effects of variables in the models. No consistency of growing degree day effect was performed on multivariate regression model in all three experiments for both cultivars. Besides growing degree days, solar radiation was the variable giving a high R^2 in the model.

Table 26. Multivariate regression with five variables for two snap bean cultivars at Crossville in 1990.

Eagle					Provider		
Var.	Df	Parameter Est.	Prob.	VIF	Parameter Est.	Prob.	VIF
GDD*	1	0.003568	0.0122	156.37	0.004687	0.0200	251.58
RAD	1	0.000139	0.0001	120.14	0.000151	0.0003	192.03
PPT	1	0.060132	0.2593	19.27	0.122090	0.0326	16.12
ARH	1	0.026805	0.0001	34.27	0.012902	0.0194	38.12
WSP	1	-0.143889	0.3424	27.62	0.098535	0.5578	31.67

* GDD = Growing Degree Day (Method 1.) RAD = Solar Radiation PPT = Precipitation ARH = Air Relative Humidity WSP = Wind speed VIF = Variation Inflation Factors

Equation for 'Eagle' : $Y = 0.004 \text{ GDD} + 0.00014 \text{ RAD} + 0.06 \text{ PPT} + 0.027 \text{ ARH} - 0.144 \text{ WSP}$

Equation for 'Provider' : $Y = 0.0047 \text{ GDD} + 0.00015 \text{ RAD} + 0.122 \text{ PPT} + 0.0129 \text{ ARH} + 0.096 \text{ WSP}$

Eagle : $R^2 = 0.9927$
 $C.V. = 10.73$
 $VIF = 68.74$

Provider: $R^2 = 0.9928$
 $C.V. = 10.84$
 $VIF = 69.7$

Table 27. Multivariate regression with nine variables for two snap bean cultivars at Crossville in 1990.

Var	Df	Eagle			Provider		
		Parameter Est.	Prob.	VIF	Parameter Est.	Prob.	VIF
GDD*	1	0.000234	0.8433	171.6	0.003358	0.0952	335.6
RAD	1	-0.000537	0.1078	25602.6	0.000116	0.0286	426.3
PPT	1	-0.361438	0.0205	257.0	-0.412656	0.0013	103.9
ARH	1	0.025774	0.0018	53.2	0.011418	0.0443	53.6
WSP	1	0.357032	0.0207	43.6	0.191515	0.2739	45.1
Soil1	1	0.047396	0.0828	99168.4	0.020698	0.0202	7004.6
Soil4	1	-0.134950	0.0004	292087.6	-0.151398	0.0001	168657.1
CGDD	1	0.130827	0.0001	172250.5	0.147579	0.0001	125662.9
CRH	1	-0.000885	0.0121	1.9	-0.000842	0.0279	1.8

* GDD = Growing Degree day (Method 1.) RAD = Solar Radiation PPT = Precipitation ARH = Air Relative Humidity WSP = Wind speed Soil1 = Growing degree day using method 1 at 1 inch depth of soil Soil4 = Growing degree day using method 1 at 4 inch depth of soil CGDD = Canopy Growing degree day using method 1 CRH = Canopy Relative Humidity.

Equation for 'Eagle' :

$$Y = 0.0002 \text{ GDD} - 0.0005 \text{ RAD} - 0.36 \text{ PPT} + 0.0158 \text{ ARH} + 0.357 \text{ WSP} + 0.047 \text{ Soil1} - 0.135 \text{ Soil4} + 0.131 \text{ CGDD} - 0.00088 \text{ CRH}$$

Equation for 'Provider' :

$$Y = 0.0034 \text{ GDD} + 0.00012 \text{ RAD} - 0.413 \text{ PPT} + 0.0114 \text{ ARH} + 0.192 \text{ WSP} + 0.0207 \text{ Soil1} - 0.15 \text{ Soil4} + 0.148 \text{ CGDD} - 0.00084 \text{ CRH}$$

Eagle : $R^2 = 0.9956$
C.V. = 8.61
VIF = 113.89

Provider : $R^2 = 0.9948$
C.V. = 9.43
VIF = 96.40

CHAPTER V

CONCLUSIONS

Two experiments were conducted in 1989 and 1990 at Knoxville, and one experiment was conducted in 1990 at Crossville, Tennessee to develop heat unit summation models using phenological observations in snap bean. Ten methods of heat unit summation were calculated to obtain the most appropriate model for prediction. None of the ten methods gave a consistently small coefficient of variation (c.v.) in all the three experiments conducted. Therefore, growing degree days based on the conventional method (daily mean temperatures-10°C were summed) were used in subsequent analysis.

Using the predictive heat unit models requires further research to test the validity of the models. Using different base temperatures other than 10°C may further reduce the c.v.'s. Better phenological observations, especially for vegetative stages, are needed. Additional anatomical observations on preflowering stage are also needed. Other possibilities for developing a more accurate predictive model are as follows: 1) to use different base temperatures for vegetative and reproductive stages since energy requirements are different for both stages, and 2) to use the actual mean temperature instead of maximum and minimum temperatures to calculate heat unit requirements.

Planting date greatly affected the yield in all experiments. This relationship was based mainly on the fluctuation of temperature. Pod yields were lower in the

later planting dates at Knoxville and were associated with high temperatures, low moisture, weeds and insect competition. Pod distribution by number and by size was influenced by planting date. The content of crude fiber of the pod was primarily influenced by planting date in 1989 at Knoxville, but it was not influenced by size. However, the contents of crude fiber from experiments in 1990 at Knoxville and at Crossville were affected by size.

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APPENDIX

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78

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Table A1. Climatic variables for snap bean development of cultivars 'Eagle' and 'Provider' at Knoxville, 1989 based on 10 planting dates.

Phenological stage	Eagle				Provider			
	Radiation acc.	Precip. acc.	Windsp. avg.	AIRRH avg.	Radiation acc.	Precip. acc.	Windsp. avg.	AIRRH avg.
	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%
Planting (0)	0	0	0	0	0	0	0	0
Germination (V0)	1.9×10^6	34	1.2	82.3	2.5×10^6	30	1.4	81.9
Emergence (V1)	2.8×10^6	43	1.5	88.9	2.7×10^6	38	1.2	82.2
Unifoliate (V2)	3.9×10^6	62	1.3	85.7	3.7×10^6	54	1.2	81.6
First trifol. (V3)	6.6×10^6	118	1.2	84.0	6.5×10^6	91	1.2	82.7
Third trifol. (V4)	8.5×10^6	139	1.1	83.7	6.7×10^6	117	0.9	83.5
Preflowering (R5)	10.4×10^6	169	1.1	85.9	9.5×10^6	160	1.1	83.7
Flowering (R6)	13.5×10^6	176	1.1	83.9	11.5×10^6	199	1.2	84.1
Pod set (R7)	14.3×10^6	249	1.1	84.7	13.3×10^6	232	1.1	83.6
Harvest (Harv)	17.3×10^6	336	1.1	86.4	16.3×10^6	289	1.1	81.7

RAD = Solar radiation PPT = Precipitation VSP = Wind speed ARH = Air relative humidity

Table A2. Climatic variables for snap bean development of cultivar 'Eagle' at Knoxville, 1990 based on 10 planting dates.

Phenological stage	RAD acc.	PPT acc.	WSP avg.	ARH avg.	Soil4 acc.	Soil1 acc.
	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%	GDD - base $10^{\circ}C$	GDD
Planting (0)	0	0	0	0	0	0
Germination (V0)	-	-	-	-	-	-
Emergence (V1)	1.6×10^6	30	1.4	57.7	163	148
Unifoliolate (V2)	2.7×10^6	63	1.4	57.4	234	214
First trifol. (V3)	4.2×10^6	98	1.3	56.9	360	330
Third trifol. (V4)	4.8×10^6	138	1.2	57.9	535	493
Preflowering (R5)	6.6×10^6	151	1.3	56.8	563	518
Flowering (R6)	7.1×10^6	157	1.3	57.9	574	539
Pod set (R7)	9.0×10^6	182	1.2	56.1	813	751
Harvest (Harv)	11.5×10^6	230	1.3	56.2	966	888

RAD = Solar Radiation PPT = Precipitation WSP = Wind speed ARH = Air Relative Humidity Soil1 = Accumulation Growing Degree Days at 2.54 cm depth of soil Soil4 = Accumulation Growing Degree Days at 10.16 cm depth of soil GDD = Growing Degree Days - = data of stage are not available

Table A3. Climatic variables for snap bean development of cultivar 'Provider' at Knoxville, 1990 based on 10 planting dates.

Phenological stage	RAD acc.	PPT acc.	WSP avg.	ARH avg.	Soil4 acc.	Soil1 acc.
	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%	GDD - base $10^{\circ}C$	GDD
Planting (0)	0	0	0	0	0	0
Germination (V0)	-	-	-	-	-	-
Emergence (V1)	1.7×10^6	30	1.4	57.9	168	152
Unifoliate (V2)	2.6×10^6	62	1.4	56.9	217	206
First trifol. (V3)	4.2×10^6	97	1.3	56.9	356	328
Third trifol. (V4)	5.1×10^6	137	1.2	54.4	539	521
Preflowering (R5)	6.5×10^6	146	1.3	57.5	574	524
Flowering (R6)	7.5×10^6	152	1.3	57.9	579	525
Pod set (R7)	8.4×10^6	174	1.2	56.6	763	702
Harvest (Harv)	10.4×10^6	191	1.3	55.9	915	837

RAD = Solar Radiation PPT = Precipitation WSP = Wind speed ARH = Air Relative Humidity Soil1 = Accumulation Growing Degree Days at 2.54 cm depth of soil Soil4 = Accumulation Growing Degree Days at 10.16 cm depth of soil GDD = Growing Degree Days - = data of stage are not available

Table A4. Climatic variables for snap bean development of cultivar 'Eagle' at Crossville, 1990 based on 6 planting dates.

Phenological stage	RAD acc.	PPT acc.	WSP avg.	ARH avg.	Soil1 acc.	Soil4 acc.	CRh. avg.	CGDD acc.
	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%	GDD	GDD	%	GDD
Planting (0)	0	0	0	0	0	0	0	0
Germination (V0)	-	-	-	-	-	-	-	-
Emergence (V1)	3.3×10^6	22	0.9	66.2	127	106	79.8	120
Unifoliolate (V2)	4.5×10^6	32	0.8	63.1	195	149	82.2	175
First trifol. (V3)	7.7×10^6	50	0.7	51.9	320	261	76.6	309
Third trifol. (V4)	10.6×10^6	71	0.6	54.1	467	368	75.2	445
Preflowering (R5)	15.2×10^6	120	0.6	52.1	678	531	75.3	648
Flowering (R6)	16.15×10^6	122	0.7	56.7	696	553	74.9	647
Pod set (R7)	20.2×10^6	150	0.7	60.5	787	695	76.3	818
Harvest (Harv)	23.5×10^6	195	0.6	56.9	1033	810	76.2	987

RAD = Solar radiation, PPT = Precipitation, WSP = Wind speed, ARH = Air relative humidity, Soil1 = Growing degree days at 2.54 cm, Soil4 = Growing degree days at 10.16 cm depth, CRH = Canopy Height Relative Humidity, CGDD = Canopy growing degree days, GDD = Growing degree days - = data of stage are not available.

Table A5. Climatic variables for snap bean development of cultivar 'Provider' at Crossville, 1990 based on 6 planting dates.

Phenological stage	RAD acc.	PPT acc.	WSP avg.	ARH avg.	Soil1 acc.	Soil4 acc.	CRh. avg.	CGDD acc.
	$W \cdot m^{-2}$	mm	$m \cdot s^{-1}$	%	GDD	GDD	%	GDD
Planting (0)	0	0	0	0	0	0	0	0
Germination (V0)	-	-	-	-	-	-	-	-
Emergence (V1)	3.3×10^6	22	0.9	66.2	127	106	79.8	120
Unifoliate (V2)	4.5×10^6	32	0.8	63.1	195	149	82.2	175
First trifol. (V3)	7.7×10^6	50	0.7	51.9	320	261	79.6	309
Third trifol. (V4)	10.9×10^6	59	0.7	54.1	477	382	74.2	453
Preflowering (R5)	-	108	0.6	57.1	675	522	-	648
Flowering (R6)	15.2×10^6	120	0.6	52.1	686	536	75.4	656
Pod set (R7)	17.2×10^6	133	0.7	57.0	721	581	72.6	686
Harvest (Harv)	19.6×10^6	163	0.7	57.4	868	681	76.4	823

RAD = Solar radiation PPT = Precipitation WSP = Wind speed ARH = Air relative humidity Soil1 = Growing degree days at 2.54 cm Soil4 = Growing degree days at 10.16 cm depth CRH = Canopy height Relative humidity CGDD = Canopy growing degree days - = data of stage are not available.

Table A6. Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with five variables in 1989 at Knoxville.

----- EAGLE -----			
N = 257 Regression Models for Dependent Variable: STAGE			
Number in Model	R-square	C(p)	Variables in Model
1	0.90666976	286.79397	GDD
1	0.75130341	1185	PPT
1	0.46556069	2838	ARH
1	0.22384196	4236	WSP
1	0.03385905	5335	RAD
2	0.94619839	60.17226	GDD WSP
2	0.94340492	76.32890	GDD ARH
2	0.92826576	163.88922	GDD PPT
2	0.90724903	285.44364	GDD RAD
2	0.81686715	808.18519	PPT ARH
2	0.75765032	1151	RAD PPT
2	0.75269803	1179	PPT WSP
2	0.49902349	2646	ARH WSP
2	0.47233087	2801	RAD ARH
2	0.24302204	4127	RAD WSP
3	0.95633620	3.53823	GDD PPT ARH
3	0.94950945	43.02214	GDD PPT WSP
3	0.94811925	51.06260	GDD ARH WSP
3	0.94639571	61.03103	GDD RAD WSP
3	0.94351661	77.68289	GDD RAD ARH
3	0.92908621	161.14396	GDD RAD PPT
3	0.88381732	422.96559	PPT ARH WSP
3	0.81976568	793.42093	RAD PPT ARH
3	0.75880749	1146	RAD PPT WSP
3	0.50429873	2618	RAD ARH WSP
4	0.95658225	4.11515	GDD RAD PPT ARH
4	0.95635418	5.43426	GDD PPT ARH WSP
4	0.94982446	43.20020	GDD RAD PPT WSP
4	0.94825775	52.26155	GDD RAD ARH WSP
4	0.88529364	416.42699	RAD PPT ARH WSP
5	0.95660216	6.00000	GDD RAD PPT ARH WSP
----- PROVIDER -----			

N = 250 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	C(p)	Variables in Model
1	0.93223271	713.91625	GDD
1	0.89347415	1263	RAD

Table A6. (continued)

PROVIDER			
N = 250 Regression Models for Dependent Variable: STAGE			
Number in Model	R-square	C(p)	Variables in Model
1	0.72250742	3685	PPT
1	0.47630496	7172	ARH
1	0.27372988	10042	WSP
2	0.96298237	280.35065	GDD WSP
2	0.96203059	293.83249	GDD RAD
2	0.95741175	359.25786	GDD ARH
2	0.94902773	478.01664	GDD PPT
2	0.92345014	840.32040	RAD ARH
2	0.89605348	1228	RAD PPT
2	0.89348954	1265	RAD WSP
2	0.80442482	2526	PPT ARH
2	0.72556831	3643	PPT WSP
2	0.49031111	6976	ARH WSP
3	0.97956148	47.50937	GDD RAD ARH
3	0.97178805	157.61921	RAD ARH WSP
3	0.97132342	164.20066	GDD RAD WSP
3	0.96967206	187.59190	GDD PPT ARH
3	0.96579777	242.47078	GDD PPT WSP
3	0.96345788	275.61512	GDD ARH WSP
3	0.96205003	295.55709	GDD RAD PPT
3	0.92554383	812.66354	RAD PPT ARH
3	0.89606790	1230	RAD PPT WSP
3	0.87998679	1458	PPT ARH WSP
4	0.98270095	5.03908	GDD RAD ARH WSP
4	0.97958047	49.24043	GDD RAD PPT ARH
4	0.97203034	156.18713	RAD PPT ARH WSP
4	0.97150990	163.55915	GDD RAD PPT WSP
4	0.96968543	189.40252	GDD PPT ARH WSP
5	0.98277431	6.00000	GDD RAD PPT ARH WSP

GDD = Growing degree days RAD = Solar radiation PPT =
Precipitation A = Air relative humidity WSP = Wind speed

Table A7. Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with five variables at Knoxville, 1990.

----- EAGLE -----		
N = 244 Regression Models for Dependent Variable: STAGE		
Number in Model	R-square	Variables in Model
1	0.97378662	RAD
1	0.94345330	GDD
1	0.89884634	PPT
1	0.83369376	ARH
1	0.77373150	WSP
2	0.98546313	RAD WSP
2	0.98477180	RAD ARH
2	0.97795738	RAD PPT
2	0.97473120	GDD RAD
2	0.97441362	GDD WSP
2	0.97001765	GDD ARH
2	0.95293705	GDD PPT
2	0.93782270	PPT ARH
2	0.93517310	PPT WSP
2	0.85034167	ARH WSP
3	0.98775674	RAD PPT WSP
3	0.98665656	RAD PPT ARH
3	0.98547118	RAD ARH WSP
3	0.98546866	GDD RAD WSP
3	0.98496781	GDD RAD ARH
3	0.98062716	GDD RAD PPT
3	0.97667980	GDD PPT WSP
3	0.97568955	GDD ARH WSP
3	0.97265683	GDD PPT ARH
3	0.93782359	PPT ARH WSP
4	0.98801203	GDD RAD PPT WSP
4	0.98781447	RAD PPT ARH WSP
4	0.98757722	GDD RAD PPT ARH
4	0.98547226	GDD RAD ARH WSP
4	0.97810876	GDD PPT ARH WSP
5	0.98801204	GDD RAD PPT ARH WSP
----- PROVIDER -----		

N = 246 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	Variables in Model
1	0.96843542	RAD
1	0.92834560	GDD
1	0.87782788	PPT

Table A7. (continued)

PROVIDER		
N = 246 Regression Models for Dependent Variable: STAGE		
Number in Model	R-square	Variables in Model
1	0.83153369	ARH
1	0.76051606	WSP
2	0.97930975	RAD WSP
2	0.97759305	RAD ARH
2	0.97148065	GDD RAD
2	0.97118737	RAD PPT
2	0.96392484	GDD WSP
2	0.95861940	GDD ARH
2	0.93825991	GDD PPT
2	0.92454948	PPT ARH
2	0.92070561	PPT WSP
2	0.85672436	ARH WSP
3	0.98084825	RAD PPT WSP
3	0.97970703	RAD ARH WSP
3	0.97960428	GDD RAD WSP
3	0.97885216	RAD PPT ARH
3	0.97867287	GDD RAD ARH
3	0.97626191	GDD RAD PPT
3	0.96642091	GDD ARH WSP
3	0.96607107	GDD PPT WSP
3	0.96107306	GDD PPT ARH
3	0.92466134	PPT ARH WSP
4	0.98188563	GDD RAD PPT WSP
4	0.98172788	RAD PPT ARH WSP
4	0.98102573	GDD RAD PPT ARH
4	0.97977374	GDD RAD ARH WSP
4	0.96892056	GDD PPT ARH WSP
5	0.98215584	GDD RAD PPT ARH WSP

GDD = Growing degree days RAD = Solar radiation PPT = Precipitation A = Air relative humidity WSP = Wind speed

Table A8. Rsquare procedure performance of cultivar 'Eagle' and 'Provider' with seven variables at Knoxville, 1990.

----- EAGLE -----		
N = 244 Regression Models for Dependent Variable: STAGE		
Number in Model	R-square	Variables in Model
1	0.97378662	RAD
1	0.94794305	SOIL1
1	0.94560222	SOIL4
1	0.94345330	GDD
1	0.89884634	PPT
1	0.83369376	ARH
1	0.77373150	WSP
2	0.98546313	RAD WSP
2	0.98477180	RAD ARH
2	0.97795738	RAD PPT
2	0.97628135	WSP SOIL1
2	0.97570561	WSP SOIL4
2	0.97473120	GDD RAD
2	0.97449294	RAD SOIL1
2	0.97444425	RAD SOIL4
2	0.97441362	GDD WSP
2	0.97209312	ARH SOIL1
2	0.97141407	ARH SOIL4
2	0.97001765	GDD ARH
2	0.95560397	PPT SOIL1
2	0.95328765	PPT SOIL4
2	0.95293705	GDD PPT
2	0.95019713	GDD SOIL1
2	0.94840036	SOIL1 SOIL4
2	0.94670306	GDD SOIL4
2	0.93782270	PPT ARH
2	0.93517310	PPT WSP
2	0.85034167	ARH WSP
3	0.98775674	RAD PPT WSP
3	0.98665656	RAD PPT ARH
3	0.98551772	RAD WSP SOIL4
3	0.98549367	RAD WSP SOIL1
3	0.98547118	RAD ARH WSP
3	0.98546866	GDD RAD WSP
3	0.98496781	GDD RAD ARH
3	0.98489120	RAD ARH SOIL1
3	0.98484903	RAD ARH SOIL4
3	0.98062716	GDD RAD PPT
3	0.98059634	RAD PPT SOIL4
3	0.98039757	RAD PPT SOIL1
3	0.97808613	PPT WSP SOIL1
3	0.97754113	ARH WSP SOIL1
3	0.97726670	PPT WSP SOIL4
3	0.97693609	ARH WSP SOIL4
3	0.97679450	GDD WSP SOIL1

Table A8. (continued)

EAGLE

N = 244 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	Variables in Model
3	0.97667980	GDD PPT WSP
3	0.97640711	GDD WSP SOIL4
3	0.97628136	WSP SOIL1 SOIL4
3	0.97568955	GDD ARH WSP
3	0.97552981	GDD RAD SOIL4
3	0.97492386	GDD RAD SOIL1
3	0.97449465	RAD SOIL1 SOIL4
3	0.97419498	PPT ARH SOIL1
3	0.97329137	PPT ARH SOIL4
3	0.97292555	GDD ARH SOIL1
3	0.97265683	GDD PPT ARH
3	0.97240981	GDD ARH SOIL4
3	0.97210460	ARH SOIL1 SOIL4
3	0.95725151	GDD PPT SOIL1
3	0.95709069	PPT SOIL1 SOIL4
3	0.95329602	GDD PPT SOIL4
3	0.95063197	GDD SOIL1 SOIL4
3	0.93782359	PPT ARH WSP
4	0.98801203	GDD RAD PPT WSP
4	0.98795659	RAD PPT WSP SOIL4
4	0.98795011	RAD PPT WSP SOIL1
4	0.98781447	RAD PPT ARH WSP
4	0.98757722	GDD RAD PPT ARH
4	0.98746164	RAD PPT ARH SOIL1
4	0.98745976	RAD PPT ARH SOIL4
4	0.98632539	GDD RAD WSP SOIL4
4	0.98586577	GDD RAD ARH SOIL4
4	0.98564067	GDD RAD WSP SOIL1
4	0.98557049	RAD WSP SOIL1 SOIL4
4	0.98551875	RAD ARH WSP SOIL4
4	0.98549368	RAD ARH WSP SOIL1
4	0.98547226	GDD RAD ARH WSP
4	0.98509200	GDD RAD ARH SOIL1
4	0.98496238	RAD ARH SOIL1 SOIL4
4	0.98063466	GDD RAD PPT SOIL1
4	0.98063272	GDD RAD PPT SOIL4
4	0.98060340	RAD PPT SOIL1 SOIL4
4	0.97948955	PPT ARH WSP SOIL1
4	0.97860115	PPT ARH WSP SOIL4
4	0.97852433	GDD PPT WSP SOIL1
4	0.97819273	PPT WSP SOIL1 SOIL4
4	0.97810876	GDD PPT ARH WSP
4	0.97790671	GDD ARH WSP SOIL1
4	0.97754217	ARH WSP SOIL1 SOIL4
4	0.97744782	GDD PPT WSP SOIL4
4	0.97744117	GDD ARH WSP SOIL4
4	0.97740707	GDD WSP SOIL1 SOIL4
4	0.97553177	GDD RAD SOIL1 SOIL4
4	0.97490566	GDD PPT ARH SOIL1

Table A8. (continued)

EAGLE

N = 244 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	Variables in Model
4	0.97440217	PPT ARH SOIL1 SOIL4
4	0.97364016	GDD ARH SOIL1 SOIL4
4	0.97358419	GDD PPT ARH SOIL4
4	0.95737742	GDD PPT SOIL1 SOIL4
5	0.98809640	GDD RAD PPT WSP SOIL4
5	0.98804404	GDD RAD PPT WSP SOIL1
5	0.98801204	GDD RAD PPT ARH WSP
5	0.98795792	RAD PPT ARH WSP SOIL4
5	0.98795728	RAD PPT WSP SOIL1 SOIL4
5	0.98795116	RAD PPT ARH WSP SOIL1
5	0.98766833	GDD RAD PPT ARH SOIL4
5	0.98759203	GDD RAD PPT ARH SOIL1
5	0.98747212	RAD PPT ARH SOIL1 SOIL4
5	0.98633332	GDD RAD ARH WSP SOIL4
5	0.98632540	GDD RAD WSP SOIL1 SOIL4
5	0.98587220	GDD RAD ARH SOIL1 SOIL4
5	0.98564128	GDD RAD ARH WSP SOIL1
5	0.98557049	RAD ARH WSP SOIL1 SOIL4
5	0.98064994	GDD RAD PPT SOIL1 SOIL4
5	0.97978248	GDD PPT ARH WSP SOIL1
5	0.97958077	PPT ARH WSP SOIL1 SOIL4
5	0.97867175	GDD PPT ARH WSP SOIL4
5	0.97860761	GDD PPT WSP SOIL1 SOIL4
5	0.97841594	GDD ARH WSP SOIL1 SOIL4
5	0.97500209	GDD PPT ARH SOIL1 SOIL4
6	0.98810005	GDD RAD PPT WSP SOIL1 SOIL4
6	0.98809671	GDD RAD PPT ARH WSP SOIL4
6	0.98804417	GDD RAD PPT ARH WSP SOIL1
6	0.98795837	RAD PPT ARH WSP SOIL1 SOIL4
6	0.98766842	GDD RAD PPT ARH SOIL1 SOIL4
6	0.98633340	GDD RAD ARH WSP SOIL1 SOIL4
6	0.97981618	GDD PPT ARH WSP SOIL1 SOIL4
7	0.98810017	GDD RAD PPT ARH WSP SOIL1 SOIL4

PROVIDER

N = 244 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	Variables in Model
1	0.96864334	RAD
1	0.93222544	SOIL4
1	0.93197275	SOIL1
1	0.92830600	GDD

Table A8. (continued)

----- PROVIDER -----
 N = 244 Regression Models for Dependent Variable: STAGE

Number in Model	R-square	Variables in Model
1	0.87754255	PPT
1	0.83113779	ARH
1	0.75998196	WSP
2	0.97969290	RAD WSP
2	0.97797427	RAD ARH
2	0.97165705	GDD RAD
2	0.97133951	RAD SOIL1
2	0.97120077	RAD PPT
2	0.97073732	RAD SOIL4
2	0.96701466	WSP SOIL4
2	0.96672412	WSP SOIL1
2	0.96432600	GDD WSP
2	0.96180680	ARH SOIL4
2	0.96155666	ARH SOIL1
2	0.95898311	GDD ARH
2	0.94014671	PPT SOIL1
2	0.93963810	PPT SOIL4
2	0.93789665	GDD PPT
2	0.93538117	GDD SOIL4
2	0.93255411	GDD SOIL1
2	0.93237711	SOIL1 SOIL4
2	0.92399420	PPT ARH
2	0.92018997	PPT WSP
2	0.85632481	ARH WSP
3	0.98104761	RAD PPT WSP
3	0.98007558	RAD ARH WSP
3	0.97996538	GDD RAD WSP
3	0.97982067	RAD WSP SOIL1
3	0.97973025	RAD WSP SOIL4
3	0.97906008	RAD PPT ARH
3	0.97901927	GDD RAD ARH
3	0.97870515	RAD ARH SOIL1
3	0.97844926	RAD ARH SOIL4
3	0.97620337	GDD RAD PPT
3	0.97593028	RAD PPT SOIL1
3	0.97543905	RAD PPT SOIL4
3	0.97361461	GDD RAD SOIL4
3	0.97184247	RAD SOIL1 SOIL4
3	0.97166811	GDD RAD SOIL1
3	0.96984712	GDD WSP SOIL4
3	0.96939315	ARH WSP SOIL4
3	0.96904522	ARH WSP SOIL1
3	0.96811541	PPT WSP SOIL1
3	0.96810770	PPT WSP SOIL4
3	0.96726164	GDD WSP SOIL1
3	0.96705509	WSP SOIL1 SOIL4
3	0.96681103	GDD ARH WSP
3	0.96619807	GDD PPT WSP
3	0.96557236	GDD ARH SOIL4

Table A8. (continued)

----- PROVIDER -----		
N = 244 Regression Models for Dependent Variable: STAGE		
Number in Model	R-square	Variables in Model
3	0.96316481	PPT ARH SOIL1
3	0.96311703	PPT ARH SOIL4
3	0.96243410	GDD ARH SOIL1
3	0.96184433	ARH SOIL1 SOIL4
3	0.96114523	GDD PPT ARH
3	0.94081098	GDD PPT SOIL4
3	0.94063450	GDD PPT SOIL1
3	0.94014881	PPT SOIL1 SOIL4
3	0.93566371	GDD SOIL1 SOIL4
3	0.92409985	PPT ARH WSP
4	0.98250179	GDD RAD WSP SOIL4
4	0.98200692	GDD RAD PPT WSP
4	0.98188203	RAD PPT ARH WSP
4	0.98175314	RAD PPT WSP SOIL1
4	0.98173643	GDD RAD ARH SOIL4
4	0.98156725	RAD PPT WSP SOIL4
4	0.98113091	GDD RAD PPT ARH
4	0.98074823	RAD PPT ARH SOIL1
4	0.98045177	RAD PPT ARH SOIL4
4	0.98024426	RAD WSP SOIL1 SOIL4
4	0.98019800	GDD RAD WSP SOIL1
4	0.98013386	GDD RAD ARH WSP
4	0.98008921	RAD ARH WSP SOIL4
4	0.98007990	RAD ARH WSP SOIL1
4	0.97922331	GDD RAD ARH SOIL1
4	0.97910788	RAD ARH SOIL1 SOIL4
4	0.97677278	GDD RAD PPT SOIL4
4	0.97621378	GDD RAD PPT SOIL1
4	0.97600111	RAD PPT SOIL1 SOIL4
4	0.97444571	GDD RAD SOIL1 SOIL4
4	0.97130669	GDD ARH WSP SOIL4
4	0.97075469	PPT ARH WSP SOIL1
4	0.97073353	PPT ARH WSP SOIL4
4	0.97021084	GDD PPT WSP SOIL4
4	0.96996010	GDD WSP SOIL1 SOIL4
4	0.96944884	ARH WSP SOIL1 SOIL4
4	0.96927123	GDD ARH WSP SOIL1
4	0.96902401	GDD PPT ARH WSP
4	0.96861585	GDD PPT WSP SOIL1
4	0.96822532	PPT WSP SOIL1 SOIL4
4	0.96593772	GDD PPT ARH SOIL4
4	0.96569224	GDD ARH SOIL1 SOIL4
4	0.96396477	GDD PPT ARH SOIL1
4	0.96324030	PPT ARH SOIL1 SOIL4
4	0.94140269	GDD PPT SOIL1 SOIL4
5	0.98336426	GDD RAD PPT WSP SOIL4
5	0.98283800	GDD RAD WSP SOIL1 SOIL4
5	0.98258574	GDD RAD PPT ARH SOIL4
5	0.98255699	GDD RAD ARH WSP SOIL4

Table A8. (continued)

----- PROVIDER -----		
N = 244 Regression Models for Dependent Variable: STAGE		
Number in Model	R-square	Variables in Model
5	0.98227169	GDD RAD PPT ARH WSP
5	0.98216426	GDD RAD ARH SOIL1 SOIL4
5	0.98211858	RAD PPT ARH WSP SOIL1
5	0.98209092	GDD RAD PPT WSP SOIL1
5	0.98201272	RAD PPT ARH WSP SOIL4
5	0.98188561	RAD PPT WSP SOIL1 SOIL4
5	0.98119576	GDD RAD PPT ARH SOIL1
5	0.98086479	RAD PPT ARH SOIL1 SOIL4
5	0.98052724	RAD ARH WSP SOIL1 SOIL4
5	0.98036587	GDD RAD ARH WSP SOIL1
5	0.97725583	GDD RAD PPT SOIL1 SOIL4
5	0.97191310	GDD PPT ARH WSP SOIL4
5	0.97142428	GDD ARH WSP SOIL1 SOIL4
5	0.97093755	GDD PPT ARH WSP SOIL1
5	0.97089008	PPT ARH WSP SOIL1 SOIL4
5	0.97037780	GDD PPT WSP SOIL1 SOIL4
5	0.96611419	GDD PPT ARH SOIL1 SOIL4
6	0.98360699	GDD RAD PPT WSP SOIL1 SOIL4
6	0.98348547	GDD RAD PPT ARH WSP SOIL4
6	0.98290306	GDD RAD PPT ARH SOIL1 SOIL4
6	0.98287359	GDD RAD ARH WSP SOIL1 SOIL4
6	0.98235231	GDD RAD PPT ARH WSP SOIL1
6	0.98226039	RAD PPT ARH WSP SOIL1 SOIL4
6	0.97210450	GDD PPT ARH WSP SOIL1 SOIL4
7	0.98369906	GDD RAD PPT ARH WSP SOIL1 SOIL4

GDD = Growing degree days RAD = Solar radiation PPT = Precipitation ARH = Air relative humidity WSP = Wind speed
 Soil1 = Growing degree days at 2.54 cm Soil4 = Growing degree days at 10.16 cm in depth

Table A9. Rsquare procedure performance of cultivar 'Eagle' and 'Provider' at Crossville, 1990.

----- EAGLE -----			
N = 102 Regression Models for Dependent Variable: STAGE			
Number in Model	R-square	C(p)	Variables in Model
1	0.97644106	213.70114	RAD
1	0.96935649	308.03640	GDD
1	0.90205635	1204	PPT
1	0.78810069	2722	ARH
1	0.69208821	4000	WSP
2	0.99112249	20.20924	RAD ARH
2	0.99083594	24.02481	GDD ARH
2	0.98901596	48.25898	GDD WSP
2	0.98821727	58.89399	RAD WSP
2	0.97667663	212.56447	GDD RAD
2	0.97653442	214.45807	RAD PPT
2	0.96996482	301.93608	GDD PPT
2	0.96288877	396.15797	PPT ARH
2	0.95845506	455.19533	PPT WSP
2	0.81600556	2352	ARH WSP
3	0.99253249	3.43428	GDD RAD ARH
3	0.99205594	9.77979	RAD PPT ARH
3	0.99153687	16.69157	RAD ARH WSP
3	0.99083729	26.00696	GDD ARH WSP
3	0.99083609	26.02291	GDD PPT ARH
3	0.99030488	33.09628	GDD RAD WSP
3	0.98956566	42.93937	RAD PPT WSP
3	0.98903233	50.04102	GDD PPT WSP
3	0.97667707	214.55852	GDD RAD PPT
3	0.96288893	398.15575	PPT ARH WSP
4	0.99264695	3.91014	GDD RAD PPT ARH
4	0.99261860	4.28776	GDD RAD ARH WSP
4	0.99222503	9.52825	RAD PPT ARH WSP
4	0.99083733	28.00642	GDD PPT ARH WSP
4	0.99047692	32.80540	GDD RAD PPT WSP
5	0.99271531	5.00000	GDD RAD PPT ARH WSP
----- PROVIDER -----			
N = 98 Regression Models for Dependent Variable: STAGE			
Number in Model	R-square	C(p)	Variables in Model
1	0.98481353	99.69546	RAD
1	0.98083109	151.01388	GDD

Table A9. (continued)

----- PROVIDER -----			
N = 98 Regression Models for Dependent Variable: STAGE			
Number in Model	R-square	C(p)	Variables in Model
1	0.89267446	1287	PPT
1	0.77341128	2824	ARH
1	0.68726849	3934	WSP
2	0.99151327	15.36147	GDD WSP
2	0.99131337	17.93744	GDD ARH
2	0.99032543	30.66814	RAD ARH
2	0.98930904	43.76560	RAD WSP
2	0.98592537	87.36810	RAD PPT
2	0.98546875	93.25224	GDD RAD
2	0.98100634	150.75554	GDD PPT
2	0.94969463	554.24371	PPT ARH
2	0.94371269	631.32795	PPT WSP
2	0.79679253	2525	ARH WSP
3	0.99234585	6.63268	GDD RAD ARH
3	0.99233611	6.75819	RAD PPT ARH
3	0.99208434	10.00260	GDD RAD WSP
3	0.99167464	15.28202	GDD ARH WSP
3	0.99152453	17.21637	GDD PPT WSP
3	0.99148739	17.69498	RAD PPT WSP
3	0.99132532	19.78338	GDD PPT ARH
3	0.99042466	31.38948	RAD ARH WSP
3	0.98594543	89.10959	GDD RAD PPT
3	0.94986901	553.99659	PPT ARH WSP
4	0.99275611	3.34605	GDD RAD PPT ARH
4	0.99241771	7.70673	GDD RAD ARH WSP
4	0.99234832	8.60091	RAD PPT ARH WSP
4	0.99234404	8.65597	GDD RAD PPT WSP
4	0.99168894	17.09772	GDD PPT ARH WSP
5	0.99278296	5.00000	GDD RAD PPT ARH WSP

GDD = Growing degree days RAD = Solar radiation PPT =
Precipitation A = Air relative humidity WSP = Wind speed

VITA

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