ADAPTING THE CROPGRO LEGUME MODEL TO SIMULATE GROWTH AND FRESH MARKET YIELD OF SNAP BEAN

By

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Production of snap bean (*Phaseolus vulgaris* L.) faces various challenges with respect to crop management and decision-making throughout the growing season. As a vegetable grown for fresh market, commercial snap bean production is a trade-off between yield and quality. Crop growth models can be used to address many of the crop production management by increasing our understanding of crop growth, development and yield in relation to weather, soil, and management practices. However, existing simulation models that predict production on a dry matter basis have limited capability in addressing production of crops such as snap bean which are primarily grown for fresh market. The purpose of this study was therefore to develop a snap bean simulation model to predict the fresh market yield and quality of pods as affected by irrigation and nitrogen (N) levels. Snap bean cultivar Ambra was grown in a field study under three irrigation regimes (66, 100 and 133% of crop ET) and four N levels (37, 74, 111 and 148 kg ha^{-1}) as sub-factors split within the irrigation regimes. Data were collected on crop growth and development, single pod growth and quality, fresh market yield, and N uptake. Weekly measurements of growth and development included canopy height and width, plant growth stages, leaf area index, pod and seed number, pod and seed fresh weight, and dry weight of plant components. For the single pod growth and quality aspects, 2-cm pods were tagged at 10 days

after anthesis, and per-pod measurements were taken at 3-day intervals for pod sieve size, pod length, pod diameter, pod fresh weight, pod dry weight, number of seed, seed fresh weight and seed dry weight. For the final yield estimation, an area of 2.44 m^2 was harvested and fresh weight of marketable pods and unmarketable pods categories were recorded.

Using these data, a computer experiment was created in DSSAT Version 4.5 using one dry bean cultivar (erect, determinate plant type). Following a systematic approach, parameters of the species, ecotype and cultivar files (of the model) were calibrated to best fit the life cycle, dry matter accumulation, yield and yield components of snap bean. The data were also used to develop functional algorithms of pod dry matter concentration versus thermal time and pod size versus pod fresh weight and were introduced into the calibrated CROPGRO model to simulate fresh market yield and physical quality of snap bean.

The interaction of irrigation and N was significant on fresh market production of snap bean. There was no yield benefit with N-rates over 111 kg ha^{-1} (IFAS recommended N rates for snap bean) at low or medium irrigation. However, at high irrigation (133% ET), increasing N fertilizer from 37 to 148 kg N ha^{-1} substantially increased fresh market yield. With calibration of genetic coefficients and addition of the fresh weight module, the CROPGRO Dry bean model had adequate capabilities to predict the life cycle, biomass accumulation, yield components, as well as fresh market yield and pod quality of snap bean over time. Pod dry matter concentration was well predicted but fresh market yield was somewhat under-predicted in late season at low N treatment. Simulation of pod sieve sizes and pod diameter which define pod quality was acceptable. However, there is a need to further examine the functional relationships between fresh market variables as well as soil N supplying and water balance aspects in order to improve simulation capability of the model.

CHAPTER 1
INTRODUCTION

Snap bean (*Phaseolus vulgaris* L.) is a food legume that provides an important dietary source of carbohydrates and proteins in both developing and developed countries (Yamaguchi, 1983). For instance, about 2% of Americans consume daily fresh snap beans, also known as green beans or string beans (Lucier and Lin, 2002). Florida is the largest snap bean producing state in the United States. In 2007, Florida accounted for 35% of the total harvested U.S. fresh market snap bean and 55% of the overall U.S. crop value (USDA, 2007). As a vegetable grown for fresh market, managing snap bean production to meet market standards is a complex trade-off between yield and quality; growers select a time for harvest that produces the highest possible yield and the optimum quality parameters before quality deteriorates to an unacceptable level.

As any commodity with increasing commercial importance, tools and techniques are always needed to assist in developing strategies that can enable maintaining a higher productivity based on better understanding of the effects of weather, pests, soil, and management practices. For these purposes, crop simulation models, which dynamically simulate crop growth by numerical integration of constituent processes with the aid of computer (Sinclair and Seligman, 2000), are valuable tools developed around the world for a wide array of crops to predict crop growth, development and yield in relation to the weather and management practices and help in decision-making processes throughout the crop growing season. The use of crop models, incorporating climatic conditions and management practices, may assist in making more timely and better management decisions during the crop growing season (Singh and Jones, 2000). Additionally, well-calibrated crop simulation models can be useful in reducing the cost and time of field experiments, gaining insights into relevant crop growth and development processes, and predicting long-term trends in the production system.

Many studies have demonstrated or discussed the capability of these models to predict crop yield, plant growth and development, and nutrient and water dynamics. Indeed, models such as CROPGRO (Hoogenboom *et al*. 1994, Boote *et al.* 1998a,b), CERES (Ritchie, 1998), and InfoCrop (Aggarwal *et al*., 2006), developed over the past decades integrate the influence of different factors on productivity and have been used to predict the potential production, optimize crop response to nitrogen fertilization, and quantify yield gaps. Nitrogen accumulation and uptake has been modeled for soybean (*Glycine max* L.) by Sinclair *et al.* (2003) and for wheat (*Triticum* spp) by Jamieson and Semenov (2000).

However, when a vegetable crop grown for fresh market like snap bean is to be simulated, most of these dynamic models present some limitations because they only take into account the dry matter accumulation to generate the final dry weight grain yield as affected by different management practices. Furthermore, Gary et *al.* (1998) mentioned that the modeling of quality aspects which determine vegetable market value is still in its infancy in most simulation models. For example, the grain legume model CROPGRO enables predicting growth and yield of crops such as soybean (*Glycine max* L. Merr), peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata*) (Jones *et al.,* 2003), but does not simulate legumes harvested for fresh market such as snap bean. The research conducted by Ferreira *et al.* (1997) tried to predict phasic development of green beans using a model with thermal time accumulation to optimum harvest time, but that work did not predict fresh market yield or pod quality, notably pod sizing over time.

Owing to its generic and versatile structure, the CROPGRO model has the ability to be adapted to new species or different environmental conditions to meet specific interests. Indeed, based on values and relationships reported from the literature and observed experimental data, Boote *et al.* (2002) were able to adapt the CROPGRO model to simulate the growth and yield of faba bean (*Vicia faba* L.). This approach has also been implemented for velvet bean (*Mucuna pruriens*; Hartkamp *et al*. 2002) as well as non leguminous crops such as tomato (*Lycopersicon esculentum* L.; Scholberg, 1997) and bahiagrass (*Paspalum notatum*; Rymph, 2004).

Consequently, the goal of this study is to use the CROPGRO model for legumes as a framework to develop a simulation model to predict the growth, development, fresh market production, and quality of snap bean as affected by different irrigation regimes and nitrogen rates. More specifically, this study aims to

- Evaluate the growth and N uptake response of snap bean to nitrogen fertilization;
- Evaluate the response of snap bean to interactive effects of irrigation regimes and nitrogen fertilization on yield, yield components and quality;
- Adapt the CROPGRO-Dry bean model to simulate the growth and development of snap bean; and
- Add a new module to the calibrated model to simulate fresh marketable yield and quality of snap bean.

The following hypotheses were be tested: 1) Increased N rates stimulate crop growth and increase N accumulation in snap bean, 2) Interactive effect of irrigation regime and nitrogen fertilization will enhance snap bean yield and pod quality, and 3) CROPGRO dry bean model can be used to develop a simulation model for snap bean.

This thesis is organized in seven sections. In form of a general introduction, this current Chapter 1 outlines the rationale and background underlying the goals and objectives proposed in this study. Chapter 2 presents literature pertaining to snap bean growth, development and yield as influenced by management practices, namely irrigation and nitrogen fertilization. Additionally, this chapter provides a conceptual framework and the scope of previous research efforts related to crop simulation models in general and snap bean simulation in particular. Chapter 3 is oriented at crop physiology and assesses crop growth processes at a plant level. It describes experimentally observed biomass and nitrogen accumulation patterns of snap bean as affected by nitrogen fertilization. Chapter 4 discusses the interactive effects of irrigation regimes and nitrogen (N) fertilizer application rates on yield, yield components and pod quality. Chapters 5 and 6 are oriented to crop model prediction and present the process used to develop a CROPGRO Snap Bean Model from the CROPGRO Dry Bean model as a starting point. Finally, Chapter 7 provides summary and conclusions and offers suggestions for future research activities in order to improve the current version of this model.

CHAPTER 2
LITERATURE REVIEW

Introduction

Common beans (*Phaseolus vulgaris* L.) are native to southern Mexico, Guatemala, Honduras and Costa Rica (Rubatzky and Yamaguchi, 1997). They are an annual twining vine with alternate trifoliate leaves, grown now in the tropics, subtropics and, during warm months, in the temperate regions of the world (Yamaguchi, 1983). Beans are usually grown in tropical countries for dry seeds and in temperate countries for dry seeds as well as for fresh pod consumption or fresh processed as frozen vegetables (Fageria *et al.*, 1997).

Snap bean is a type of common bean grown for fresh market consumption selected for tasty pods with reduced fiber (Silbernagel and Drake, 1978). Snap bean is an economically important vegetable with a U.S. fresh market crop value of more than $390 million (USDA, 2007). Florida is the largest snap bean producing state in the United States. In 2007, Florida accounted for 35% of the total harvested U.S. snap bean fresh market and 55% of the overall U.S. crop value (USDA, 2007). Florida has a significant comparative advantage among other states in the production of horticultural vegetable crops in general and snap bean in particular due to its mild winters.

This review presents information on the characteristics of snap bean plants and the growth and development as influenced by environmental factors (water and nitrogen namely). Importance of crop simulation models and previous research on their development and application are also reviewed.

Snap Bean Growth and Development

Root Growth

Snap bean, like many other legumes, has a taproot system with extensive lateral roots. The roots may grow to a depth of 1 m, but the lateral root system is mainly confined to the top 25 cm of the soil profile (Rubatzky and Yamaguchi, 1997). In general, during germination and emergence, the radicle grows rapidly, developing a primary root. Subsequently, the primary root growth subsides, and many laterals develop an extensive fibrous root system in the upper 15 to 25 cm of soil. In the presence of *Rhizobium* bacteria, nodules develop on lateral roots (Rubatzky and Yamaguchi, 1997). These lateral roots are less effective in extracting water stored deep in the soil. The pattern of root development is determined by the growth habit (determinate or indeterminate) of the whole plant. Indeed, Kelly *et al.* (1999) mentioned that early flowering erect determinate cultivars tend to develop shallow root systems, while erect indeterminate cultivars tend to have a more prominent tap root that can better exploit deep soil layers and can be effective with terminal droughts. More prostrate indeterminate cultivars tend to have a more sprawling fibrous root system which can be effective under intermittent droughts.

Plant Growth

Common bean in general is a highly polymorphic species showing considerable variation in growth habit, vegetative characters, flower color, and the size, shape, and color of both seeds and pods (Laing et *al.*, 1984). Growth and development of snap beans are divided into vegetative and reproductive stages. The vegetative (V) stages are defined on the basis of number of nodes on the main stem, including the primary leaf node, whereas reproductive (R) stages are defined on the basis of pod and seed characteristics in addition to nodes (Fageria, 1997).

Based on plant growth characteristics, bean ecotypes can be classified into four groups (Davis et al. 1984): type 1a, determinate bush, erect, with 5 to 7 nodes on the main stem; 1b, determinate bush with more than 7 nodes on the main stem, erect, prostrate or climbing; 2a, indeterminate bush with erect main stem and branches; 2b, indeterminate bush with erect main stem and branches but with medium to elongated development; 3a, indeterminate sprawling type with little or nor climbing tendency; 3b, a facultative climber less than 1.5-m high with little branching and pod bearing on the lower part of the plant; 4a, indeterminate climber, 1.5-2.0 m high with little branching, medium vigor, and pods evenly distributed along the whole length of the plant; and 4b, a vigorous indeterminate climber, more than 2-m high, little branching, and pod bearing on the upper portion of the plant. These four major classes are defined using the type of terminal bud (vegetative versus reproductive), stem strength (weak versus strong), climbing ability (non-climber versus strong climber), and fruiting patterns (mostly basal versus along entire stem length or only in the upper part) (Singh, 1982). Indeterminate cultivars can grow 2-3-m in height, while determinate cultivars reach only 20-60 cm, with the stems terminating in an inflorescence. Most snap bean cultivars, especially for fresh market and processing, have a determinate bush (type I) growth habit. The type I growth habit is easier to handle in mechanized agricultural systems and lends itself to a once-over mechanical harvest (Fernandez et al., 1986).

A classification based on the temperature requirement for optimum growth and development is valuable in determining which crops may be planted in a given region and at what time during the year. Studies on the ecophysiology of snap bean revealed that snap bean is classified as a “warm-season vegetable” and sub-grouped as “tender”, implying that the young plants are susceptible to damage during cold weather. In fact, the bean plant is intolerant to frost and a short exposure to 0 ^{o}C or below will kill bean tissue (Wallace, 1980). The intensity of light and the relative length of the light and dark periods can dramatically affect the pattern of crop development and yield. Long daylengths result in high rates of net photosynthesis, favoring high growth and yield potentials. The relative length of day and night influences the initiation of flowers and storage organs for many vegetable crops. Daylength is a major factor affecting adaptation of the common bean. Although some temperate zone cultivars are relatively insensitive to daylength, many genotypes of tropical origin are sensitive to daylength for both the initiation and development of flower buds (Ojehomon *et al.*, 1973). In general, later-maturing, indeterminate genotypes are more sensitive to photoperiod than are determinate or determinate bush types (Purseglove, 1968; Wallace et al., 1982).

In most climates, the date of sowing is such that flowering occurs when temperatures are within ± 2^{o}C of the apparent optimum of 21^{o}C for flowering and the supply of water is adequate for growth (Laing et al., 1984). Seedlings emerge after about 17 days when soil temperatures are 10-11^{o}C, after 6-8 days at 13-14^{o}C, and after only 5 days at 15-16^{o}C (Scarisbrick et al., 1976). The optimum air temperature range for the germination of common bean is 20-30 ^{o}C (Scully and Waines, 1987). Temperature has a pronounced effect on the photoperiod response. The effect of increasing temperature on completely day neutral cultivars is to decrease the number of days to flowering (Hall, 2004). Wallace (1980) found that at daylength of 9 to 12 h, days to first flower varied from 37 to 42. As the night temperature rose from 18 to 21 to 24 ^{o}C, the days to first flower decreased.

Foliage is pinnately trifoliate and somewhat hairy, and each leaf has a well-developed pulvinus at the base (Summerfield and Roberts, 1984). Present-day cultivars have small leaves which improve light penetration into the canopy, especially for high density plantings. However, Rubatzky and Yamaguchi (1997) mentioned that although this characteristic tends to increase total yield, small leaf size is linked to small pod size.

Snap bean stems and petioles are slender, twisted, angled, and ribbed; in climbing forms they have more nodes, which are further apart than in determinate bush types (Summerfield and Roberts, 1984).

Growth in plants can be measured in many ways. The most direct method is by measuring the increase in plant dry weight over time, which in turn reflects the potential for assimilation of photosynthates by the plant (Sader, 1980). The growth analysis procedure requires only measurements of plant dry weight and leaf area on samples of the crop at intervals throughout its growth. Parameters of growth analysis such as crop growth rate (CGR), relative growth rate (RGR), leaf area (LA), leaf area index (LAI) and others with their respective formulae have been described by Evans (1972) and Radford (1967). Maximum dry matter accumulation of tops as well as roots occurred in the time period of 30-60 days after sowing (Fageria, 1997). The decrease in top dry matter at the later growth stage may be related to more photosynthate translocation to grains and senescence and abscission of old leaves. Sader (1980) observed that snap bean leaf area index increased rapidly, attaining maximum values of 3.0 to 4.2 by 63 days after emergence depending to N fertilization.

Flowering, Pod Set and Development

Generally, snap bean cultivars are selected for a near-simultaneous bloom of the terminal and branch node racemes, and for pod fill to occur over a short period of time (Singh, 1999). Beans, in general, are normally self-pollinating and generally little out-crossing occurs. Flowers are large and showy and may be white, pink, or purple. In some determinate cultivars flower primordia are formed on the raceme in the axil of the uppermost leaf of the mainstem first and differentiation then proceeds in a downward direction and along the branches (Ojehomon et al., 1973). The proportion of opened flowers that do not form mature pods is influenced by a very wide range of environmental and biotic factors. Even in favorable field environments about 60 to 70 % of the flowers are ultimately shed. Additionally, Gross and Kigel, (1994) found that raising night temperature from 17°C to 27°C strongly reduced pod production by causing a reduction of buds and flowers, mature pod size and seeds per pod, while an increase in day temperature from 22°C to 32°C had smaller and less consistent effects. The preferential mobilization of available photosynthate to first-formed reproductive structures and the associated abscission of ones formed later suggest that in *Phaseolus vulgaris*, as in other species of grain legume, the plant is conservative in the allocation of resources and gives survival of a few fruits precedence over productivity (Fageria, 1997).

Pods are narrow (1-1.5 cm wide) and long (8-20 cm). Depending on cultivar, pod ends may have a pointed or blunt tip; cross-sectional shapes vary from round to elongated oval, and some are heart shaped. The number of seed depends on the cultivar and can vary from 3 to 7, while dry bean types may have several more (Rubatzky and Yamaguchi, 1997). At maturity, seed size can vary from 0.7 to 1.5 cm in length, and weigh from 0.2 to 0.6 g each, while the form can be globular to kidney shape (Rubatzky and Yamaguchi, 1997, Yamaguchi, 1983). Pod traits are the most important aspect of snap bean cultivars. Traits of importance include color (relative internal and external color, and uniformity of color), pod shape, length, cross-sectional shape, straightness, smoothness, fiber content, rate of seed development, and point of detachment (Silbernagel, 1986, Myers and Baggett, 1999).

Within snap beans, fiber content appears to be quantitatively inherited, with reported values from 0.02% to about 3.0% of pod fresh weight for pods with acceptable quality (Silbernagel and Drake, 1978). Fiber content increases with sieve size and maturity, with some cultivars having as high as 20% fiber in mature six-sieve (Silbernagel and Drake, 1978).

Yield is more complex in a vegetable crop such as snap bean, compared to a seed crop. Both physiological and morphological characteristics of the bean plant are thought to play a major and interdependent role in determining yields (Denis and Adams, 1978). Nienhuis and Singh (1986) observed that yield was positively correlated with pod density, seeds per pod, and all architectural traits except branches per plant. A detailed analysis of plant structure, pod development and ripening indicated that the higher pod yields are related to a shorter flowering stage, a more homogeneous pod development and an advanced ripening of the pods (Deproost et al., 2004).

Pod Quality

The greatest quality of green beans is reached well in advance of maximum yield (de Varennes et al., 2002). Pods harden as they mature, becoming rich in fiber and less palatable. As the pods of snap bean plants approach optimum harvest time for fresh market, the quality decreases while the yield of pods increases (Robinson et al., 1965). Although pods of different sizes are processed for various uses and styles of product, the market value of the pods decreases as the pods become larger and more mature (Peck and MacDonald, 1983). The quality of snap bean pods grown for processing and fresh market is defined by many chemical and physical properties of the pods including diameter of the pods and weight of the seeds in the pods (Peck and VanBuren, 1975; Robinson et al., 1965). The fresh weight of the seeds as a percentage of the fresh weight of the pods (including seeds) is used as a determination of quality of the pods for processing (Robinson et al., 1965). Unlike legumes harvested for seed, snap bean pods should have less than 10% seed in the pods on a fresh weight basis at optimum harvest time for processing for human consumption (Peck and MacDonald, 1983). For best quality, pods should be about half-grown to about three-fourths of maximum length (before the pods reach full size and while the seeds are succulent and not starchy) (Watada and Morris, 1966). Yield and quality have an inverse relationship. There is no clear defined point at which yield and quality are maximized. To a grower or processor, quality in snap bean is defined in terms of sieve size, percent seed by weight of total pod weight, pod fiber content, pod smoothness and straightness, pod color, and flavor. Sieve size is probably the single most important quality factor in processed and fresh market snap beans. The sieve distribution may vary from the expected normal when pod set is disrupted by hot weather, resulting in a “split set”. Smaller sieve beans have straighter pods because pods are inherently shorter. Maturity for snap bean harvest is based on the diameter of the bean pod. USDA has six standard size designations for snap beans. Size 1 and 2 are any pod less than 18.5/60 inch in diameter and they are considered too small, and size 6 is any pod more than 27/64 inch in diameter and is considered overmature (Gast, 1994).

With a once-over mechanical harvest, growers must select a time for harvest that produces the highest possible yield and the optimum percentages of sieve sizes before quality deteriorates to an unacceptable level. Small-sieve cultivars are those that maximize quality and yield at a smaller sieve size. Parameters such as percentage of fiber in the pod, size of seeds, and pod sieve size are all important to the marketability of the crop (Bonanno and Mack, 1983).

Crop Production

Growth and development of a plant is influenced by various environmental factors such as temperature, water, and nitrogen. Among these factors, effects of water supply and nitrogen deficiency have been studied extensively. This section presents the effects of water and nitrogen on snap bean and different techniques of managing these two important crop production factors starting out first with a brief review of the production systems currently used in Florida.

Production Systems

Snap beans grow best on soils that have higher water holding capacity and have good air and water infiltration. Snap beans require a constant supply of moisture during the growing season. In a sandy soil prevailing in Florida, irrigation is important to ensure optimum plant growth, a uniform pod set, and robust development (Mossler and Nesheim, 2000). Snap bean production is typically intensively managed with high inputs of fertilizers and irrigation water. Snap bean seeds are planted 5-10 cm apart in rows 60-90 cm apart and 2-4 cm in depth. Snap beans are planted in Florida between August 15 and April 1, with some variation by region. In north Florida, usual planting dates are from March to April and from August to September. Planting occurs in central Florida from February to April and from August to September, while in south Florida snap beans may be planted anytime from September to April. Approximately 33 percent of snap bean acreage is harvested during the winter season (January to March from South Florida fields), with approximately 44 percent harvested during the spring season (April to May) and 23 percent harvested during the fall season (October to December) (Pernezny, 1997; FDACS, 1998, Olson et al., 2007). Crop production is fully mechanized, and the entire yield is harvested by a single picking.

Irrigation

Snap beans have high water requirements and in general, irrigation is necessary for successful vegetable crop production. The growth and development of a plant is significantly dependent on the moisture levels in the soils as water deficit can reduce growth. Irrigation water management always aims at providing sufficient water to replenish depleted soil water in time to avoid physiological water stress in growing plants. Due to its relatively shallow water-extracting root system, snap bean is very responsive to frequent irrigations (Smittle, 1976). Water uptake occurs mainly from the first 0.5 to 0.7 m depth (FAO, 2008). High irrigation frequencies generally favored strong vegetative development and stimulate the generation of flowers and pods (Deproost *et al.,* 2004). Plant growth stages are modified by the moisture availability patterns during the growth cycle (Ramirez and Kelly, 1998). Water requirements are extremely important at all stages of plant development (Sezen et *al.*, 2005). But, controversy exists as to what development stage is most susceptible. Doorenbos and Kassam (1979) reported yield response coefficients of 0.2, 1.1 and 0.75 for the vegetative stage, flowering, and pod development, respectively, indicating that flowering is the most sensitive period. Also, Dubetz et al. (1969) and Kattan and Fleming (1956) found that water stress during the flowering phase results in the greatest yield reduction. Water stress during fruit development reduced both yield and pod quality (Kattan and Fleming, 1956). Water deficit during the yield formation period gives rise to small, short discolored pods with malformed beans. Also, the fiber content of the pods is higher and seeds lose their tenderness (Rubatzky and Yamaguchi, 1997, FAO, 2008). Bonanno and Mack (1983) observed that pod quality was less sensitive to water stress than was pod yield. Low irrigation level reduced total leaf area/plant and number of leaves (Bonanno and Mack, 1983, Nielsen and Nelson, 1998) and caused reduction in the crop growth (Bergamaschi et al., 1988). Singh (1989) observed that vegetative growth (number of leaves, leaf area and leaf dry weight) increased linearly with irrigation amounts from 0 to 100 % pan evaporation.

On the other hand, Deproost et al. (2004) reported that observed that moderate drought stress during flowering induced yield increases of 30 to 70% as compared to frequently irrigated snap beans. Other researchers concluded that frequent irrigation was necessary during the entire growth cycle in order to obtain optimal yield levels (Stansell and Smittle, 1980; Bonnano and Mack, 1983).

Irrigation method and scheduling affect crop growth and development, fruit yield and water use efficiency. For example, Locascio (2005) mentions that the use of frequent but relatively low water application volumes gives generally greater advantage to plant productivity as opposed to the more traditional scheduling of few applications of large irrigation volumes. In a study involving different irrigation regimes and crop coefficients, Sezen et al. (2005) found that maximum yields of beans (20,558 kg ha^{-1}) were obtained from a treatment consisting of 13-17 mm every 2 to 3 days with a crop pan coefficient of K_{cp} of 1 as opposed to treatments irrigated 58-62 mm every 10 to 12 days with a K_{cp} of 0.50 which yielded 12,243 kg ha^{-1}. Several methods have been proposed for scheduling irrigation in snap bean based on environmental factors. These methods usually evaluate the soil water content and soil water potential. Soil water content can be measured by a neutron probe, which directly measures soil water on a volumetric basis. But, Bonnano and Mack (1983) reported that radiation hazards, high cost, and the need for calibrations restrict its use principally to a research tool. Irrigation scheduling methods based on pan evaporation are widely used. Plant response to irrigation is better correlated with soil water potential than with soil content (Bonnano and Mack, 1983). Soil water potential at which water should be applied for maximum yields of snap bean grown in deep, well drained and fertilized soils is between -75 to -200 kPa (Wallace, 1980). The use of tensiometers enables one to monitor soil water tension at a given depth and allows scheduling irrigation applications with more efficient use of water. Soil water tension (SWT) represents the magnitude of the suction (negative pressure) the plant roots have to create to free soil water from the attraction of the soil, and move it into the root cells (Simonne et al., 2007). The tensiometer consists of a tube with a porous cup at the bottom and a water reservoir and vacuum gauge at the top. Field investigations carried out in Bangalore (India) with French bean crops, indicated that irrigation when soil matric potential at 0.15 m depth reached -45 kPa resulted in highest dry matter production, green pod yield, nutrient uptake and water use efficiency (WUE) as compared to irrigations scheduled at -65 or -85 kPa (Hegde and Srinivas, 1990). For most vegetable crops grown on the sandy soils of Florida, soil water tension in the rooting zone should be maintained between 6 (field capacity) and 15 kPa (Simonne et *al.,* 2007).

Furthermore, soil water balance and evapotranspiration measurements which are an assessment of water loss by a cropped surface can also be used to predict irrigation needs for crop. According to Ritchie (1998), this method is based on the water balance in the soil-plant-atmosphere continuum and can be calculated as follows: $\frac{dW}{dt} = P + I - R - D - E_S - E_P$ where, dW/dt = Net rate of change in stored soil water, in units of mm^3[water] mm^{-2}[area] d^{-1}, or mm d^{-1}; P = Precipitation on day t, mm d^{-1}; I = Irrigation amount on day t, mm d^{-1}; R = Surface runoff on day t, mm d^{-1}; D = Drainage from bottom of profile on day t, mm d^{-1}; E_s = Soil evaporation on day t, mm d^{-1}; and E_p = Plant evaporation (transpiration) on day t, mm d^{-1}.

Bonanno and Mack (1983) reported that one of the most commonly used methods for predicting irrigations by evapotranspiration is a computerized irrigation scheduling program developed by Jensen et al. (1971), commonly referred to as the USDA-ARS Irrigation Scheduling Program. This program provides estimates of the timing and amount of irrigation water based on weather data and specific characteristics of the crop and soil. Under conditions when maximum evapotranspiration (ETmax) is 5 to 6 mm/day, 40 to 50 percent of the total available soil water can be depleted before water uptake is affected (FAO, 2008). But, this is related to the type of soil. Crop coefficient (kc) relating reference evapotranspiration (ETo) to water requirements (ETm) for different development stages is, for snap bean: during the initial stage 0.3-0.4 (15 to 20 days); the early-season development stage 0.65-0.75 (next 15 to 20 days); the mid-season stage 0.95-1.05 (next 20 to 30 days); the late-season stage 0.9-0.95 (next 5 to 20 days) and at harvest 0.85-0.9 (FAO, 2008).

Smittle et al. (1990) used pan evaporation with continuous crop factor function to estimate ET and a dynamic root depth function to schedule irrigation for snap bean in Georgia, USA. Also, Bharat (1989) compared different pan coefficients and suggested a pan coefficient of 0.80 for optimal yield in Fort Valley, Georgia USA. Another method is the one developed by FAO which consists of establishing the irrigation schedule using a computer model (Cropwat) based on Penman equation. The peak water use for green beans use is approximately 4 to 5 mm per day for April and June plantings, respectively. Weekly irrigation during the peak is adequate, however with sandy and sandy loam soils, irrigation may be required as frequently as every 3 to 4 days. Also, under conditions when ETm is 5 to 6 mm/day, 40 to 50 percent of the total available soil water can be depleted before water uptake is affected.

Once the irrigation scheduling is determined, various methods or techniques are currently available for providing irrigation water to snap bean in Florida. These methods include the seepage system, overhead irrigation system and drip irrigation system. Smajstrla and Haman (1997) reported that nearly 43% of the total irrigated land in Florida utilizes seepage irrigation system, while about 30% and 25% of irrigated land is under center pivot and linear moves and drip system, respectively. With the application efficiency around 60 to 80%, overhead irrigation represents the most common irrigation method practiced for snap bean in Florida.

Efficiency of the method and technique used to manage irrigation in the cropping system is estimated with two coefficients called water use efficiency (WUE) and irrigation water use-efficiency (IWUE). In a specific case of snap bean, WUE and IWUE values are usually calculated as fresh market yield divided by seasonal ET and total seasonal irrigation water applied, respectively (Tanner and Sinclair, 1983). The water utilization efficiency for harvested yield (Ey) for fresh bean containing 80 to 90% moisture is 1.5 to 2.0 kg/m^3. Good commercial yield in favorable environments under irrigation is 6 to 8 ton/ha fresh bean (FAO, 2008).

Plant Nutrition

Nitrogen is an essential component of protoplasm, chlorophyll molecules, nucleic acids (DNA and RNA), and amino acids, from which proteins are made. Nitrogen enhances the vegetative parts to produce large, green leaves, and is also necessary for pod filling period (Neeteson, 1995; Brady and Weil, 1997, Foth and Ellis, 1997). An appropriate supply of N stimulates root growth and development, as well as the uptake of other nutrients. Healthy plant foliage generally contains 2.5 to 4.0% N, depending on the age of the leaves and whether the plant is a legume (Brady and Weil, 1997). In contrast, plants deficient in N tend to have a pale yellowish green color (chlorosis), a stunted appearance, and develop thin, spindly stems (Foth and Ellis, 1997). Nitrogen deprivation decreased shoot to root ratio as a consequence of a decreased weight of above ground organs, especially of leaves, while chlorophyll content declined significantly (Lima et al., 2000).

As a legume, the enzymatic reduction of atmospheric nitrogen to ammonia and protein N in lateral root nodules by the symbiotic bacterium *Rhizobium*, may supply part of the N requirements of beans. However, snap beans are generally considered to be weak in N_2 fixation and show a variable response to inoculation (Vincent, 1974, Calvache and Reichardt, 1999). Poor N_2 fixation by *P. vulgaris* has been attributed to the difficulty of establishing effective symbioses in the field and to genetic variability in the capacity to fix N (Graham, 1981; Rubatzky and Yamaguchi, 1997). Owing to this ineffective potentiality of fixing N_2, supplemental N fertilizer is always required in commercial production of snap bean for vigorous crop development (Graham, 1981, Piha and Munns, 1987, Calvache and Reichardt, 1999, Redden and Herridge, 1999).

More specifically, N fertilization affects the vegetative growth of snap bean plants as well as the pod set and development (Peck and MacDonald, 1983). The nitrate form of N is preferred to the ammonium form. In experimental conditions where nitrification is limited, plants supplied with moderate concentrations of NH_4^+ generally do not grow as well as plants supplied with equal amount of N as NO^-_3 or NH_4^+ and NO^-_3 combined (Kirkby, 1981). In Florida, the recommended N rate for snap bean is 110 kg N ha^{-1}, and recommended K_2O and P_2O5 (for soil testing low in P and K) are 120 kg ha^{-1} for P_2O5 and K_2O, respectively (Olson et *al.*, 2007). Typically, all P_2O_5 is broadcasted at planting and 20 to 50% of N and K_2O are banded also at planting. The remaining N and K_2O is sidedressed at pre-bloom stage. Nitrogen application rates should consider plant populations because high-density plantings generally require higher levels of supplemental fertilizer. In a study involving different N rates, Peck and Macdonald (1983) observed that dry matter accumulation in the snap bean plants was slow from planting to the seedling stage, more rapid from the seedling to the bloom stage and reached a rapid rate of 22 g m^{-2} day^{-1} from the bloom stage to the pod stage. In the study conducted by Nicholaides et al.

(1985), total snap bean fresh weight yield response to N fertilization was quadratic with maximum yield at 168 kg N ha^{-1}. The 112 kg N ha^{-1} rate produced greater yield when 66% rather than 50% or 100% of the N was applied preplant. Yield increased as the level of NPK increased while pod quality, i.e. pod length, thickness and fiber content were not significantly affected by the level of NPK application (Abdel Mawgoud et al., 2006). In the study carried out by Tewari and Singh (2000), successive increase in the doses of N (up to 120 kg ha^{-1}) as well as P increased plant height, number of branches, length of pod and seed yield. Nitrogen fertilization at 40 to 80 kg ha^{-1} produced the optimum quality and yield of snap bean pods for processing.

Nitrogen Uptake

Understanding elemental accumulation in horticultural crops is important for optimizing growth and development and designing fertility practices for nutrient management programs. Nutrient uptake from soils is essentially the product of the nutrient concentration of the soil solution and the absorbing power of roots when there is no other limiting factor. Root-absorbing power is affected by root length and/or surface area, kind and age of roots, plant age, temperature, plant species, and ion competition or interaction (Foth and Ellis, 1997). Both NH_4^+ and NO^-_3 are commonly present in soil solutions, and both are readily taken up by roots but plants absorb predominately NO_3^-. Nitrate remains soluble in the soil solution and is readily moved to plant roots by mass flow. Nitrogen is highly mobile in plants. It can be translocated from older leaves to newly developing leaves, and to storage or reproductive organ. This ability helps plants to optimize their N use and plays an important role in plant development. As the crop matures, N is re-mobilized from leaves to the developing grain (Lawlor et al., 2001).

In general, the N concentration of plants within dense canopies declines throughout ontogeny, even when N supply is not limiting growth. Lemaire *et al.* (2007) reported that this phenomenon has usually been interpreted as a direct result of plant ageing and has often been related simply to phenology, leading to large differences in N concentration between species or genotypes within a given environment, and between different environments for a given genotype. There is a relationship between crop *N* uptake (N, kg ha^{-1}) and crop biomass accumulation (W, t ha^{-1}) expressed as follows: $N = aW^{b}$ where parameter *a* represents the amount of *N* accumulated by the crop at $W = 1$ t ha^{-1} and coefficient *b* represents the ratio between the relative accumulation rates of N and biomass. In a steady state non-limiting supply of N, the relationship between N uptake and biomass accumulation reflects the feed-back regulation of N absorption capacity of roots by shoot growth itself (Lemaire et al., 2007).

For grain legumes, Ney et al. (1997) observed that until the pod setting, plant N content declines as a consequence of the increase in crop mass, but after pod set and during seed filling, the accumulation of N in reproductive organs with a high N concentration counterbalances the decline in N% of the vegetative plant components (leaves and stems), and therefore total plant N% remains almost constant. Application of N fertilizer generally increased the concentrations of nitrate N and total N in all plant parts at all stages of growth, development, and maturation. Nitrate N represented 4.6 to 7.2% of the total N in the small pods. Fertilizer N increased the content of total N in the plants at the pod stage. Partitioning of dry weight and N in the plant parts depends upon time after planting or stage of physiological growth. Concentrations of nitrate N and total N generally decrease in all plant parts with later stages of growth. Accumulation of total N in the plants was similar to, but preceded dry weight accumulation. Total N represented 3.5 to 4.6% of the dry weight at the seedling stage, 3.1 to 3.8% at the bloom stage and 2.5 to 3.1% at the pod stage (Peck and MacDonald, 1983). When N supply is non-limiting, an empirical linear relationship between the amount of N accumulated in the above ground biomass and the crop leaf area index (LAI) during the period of leaf area expansion has been proposed for maize (Plenet and Lemaire, 2000).

Nitrogen Use Efficiency

Different definitions are used in literature to describe the agronomic and physiological range of N efficiency referring to external and internal N-status. Among these different definitions exhaustively reviewed by Rathke et al. (2006), two are emphasized in this study. N-uptake efficiency (the efficiency with which soil-applied N can be taken up by the plant) and N utilization efficiency (the seed dry weight or pod fresh weight per unit of absorbed fertilizer-N). N-uptake efficiency depends substantially on spatial root development (rooting depth, rooting intensity) and thus governs uptake of the total amount of N (capacity of the uptake system). From an agronomic perspective, Below (2002) mentioned that NUE refers to three main functions detailing the relationships between N availability and yield, N availability and N recovered, and yield and N recovered. High N-utilization efficiency can result from effective remobilization of N from vegetative parts of the plant to developing tissues representing strong sinks for N but also from reduced N-demand of these tissues. It is a measure of the extent to which a crop transforms available N to economic yield (Ma et al., 1999). Nitrogen use efficiency is generally highest where little N has been applied. The NUE declines considerably as the amount of applied N is increased. This is especially true once the plant N concentration exceeds the level required for optimal dry matter growth. Improved N use efficiency (NUE: capacity to produce a supplement of yield for each added unit of N fertilizer) has the potential to enhance yield under low N supply and thereby improve crop nutritional quality while reducing ground water contamination by nitrates.

Nitrogen Leaching

Undoubtedly, intensive agriculture has led to an increase in N leaching in the environment, particularly as nitrate. Ammonium and nitrate are all available in the rooting zone to be taken up. In contrast to ammonium ions, which carry a positive charge, the negatively charged nitrate ions are not adsorbed by the negatively charged soil colloids. Therefore, nitrate ions move downward freely with drainage water, and are thus readily leached from the root zone (Brady and Weil, 1997). Nitrate may reach domestic wells, and may also eventually flow underground to surface waters such as streams, lakes, and estuaries. The nitrate may contaminate drinking water and cause eutrophication and associated problems. Excessive N fertilizer application (especially common for some vegetables) when combined with high intensity rainfall events and poor water and nutrient holding capacity of soils may result in N leaching below the active root zone (Prakash et al., 1999). Very sandy soils such in Florida are particularly susceptible to nitrate leaching losses. Various factors influence the rate of nitrate loss below the rooting zone. Actual N leaching losses depend on N source and application rates, crop removal capacity, and water displacement below the rooting zone (Zotarelli et al., 2007b). Also, plants that have high aboveground biomass and adequate root density are generally more effective at reducing residual soil NO_3 (Sainju et al., 1998). Therefore, with its relatively shallow rooting system and combined with the low water-holding capacity of sandy Florida soils, the snap bean cropping system is expected to induce a higher nitrate leaching rate.

A number of different methods have been used to study the rate of *in situ* soil nitrate leaching in different cropping systems. Zotarelli et al. (2007a) compared three methods to monitor nitrate leaching in sandy soils grown with different vegetables crops. These methods include the ceramic suction cup lysimeters, subsurface drainage lysimeters and soil cores. Soil coring is simple, relatively cheap, widely used, and applicable to most soils. Regardless the technique used, these authors found that applying N rates in excess of standard recommendations increased N leaching by 64, 59, and 32%, respectively, for pepper, tomato, and zucchini crops.

The challenge is to define cropping techniques which will give the best compromise between good agricultural production (in quantity and quality) and an acceptable level of N losses.

Crop Modeling

Crop simulation models are mathematical representations of plant growth processes as influenced by interactions among genotype, environment, and crop management (Yang et al., 2004). They may provide quantitative information from which decisions, such as crop timing, irrigation, fertilization, crop protection, and climate control, can be taken at the field scale (Gary et al., 1998). Models can be used to estimate values that could be useful for the optimization of management decisions, such as fertilization, plant population, genetics, or planting dates, providing a framework for comparison. Some process-based crop growth models use the concept of radiation use efficiency (RUE) and intercepted solar radiation for computing biomass accumulation (Monteith, 1977, Sinclair and Shiraiwa, 1993), and others consider detailed processes of gross photosynthesis and respiration (maintenance and growth) to estimate biomass accumulation (van Keulen et al., 1982, Penning de Vries and van Laar, 1982). Based on either of these two approaches, a wide range of crop simulation models have been developed for different crops under various environment conditions. The concept of Radiation Use Efficiency (RUE) is followed in CERES crop models (Ritchie, 1998). In the maize model (CERES-Maize), growth of organs is primarily driven by temperature, and dry matter production is computed directly from absorbed solar radiation by means of a fixed value for RUE that accounts for respiration costs implicitly. In generic models such as WOFOST (Van Diepen et al., 1989) and INTERCOM, growth of plant organs is driven primarily by the availability of assimilates from simulation of canopy photosynthesis, and both growth and maintenance respiration are explicitly accounted for to predict dry matter production. Among the photosynthesis-driven models, the CROPGRO model (Hoogenboom et *al.,* 1994) can simulate the impacts of genetics, weather, soil, management practices, and their dynamic interactions on crop growth, development, and yield based on C, N and water balance principles (Batchelor et al., 2002). Both the radiation use efficiency and photosynthesis-driven models allow predicting potential production, but also include modules to account for water and/or N limitation and/or modules describing effects of pests, diseases or weeds (van Ittersum et al. 2003).

The purpose in the next section is to review the major features of CROPGRO pertinent to adapting the model for a new crop and present some previous adaptation efforts.

CROPGRO Model and Model Adaptation Approach

CROPGRO is a process descriptive model that considers crop phenology and canopy development and crop carbon, nitrogen and water balances. Crop phenology includes the rates of vegetative and reproductive development that govern the partitioning of C and N to plant organs over time. Crop N balance includes daily soil N uptake, N_2 fixation, N mobilization from vegetative to storage tissues and N loss in abscised parts. Soil water balance includes infiltration of rain and irrigation, crop and soil evaporation, root uptake, and water drainage and distribution within the soil profile. State variables are the amounts, masses and numbers of tissues, and rate variables are the rates of inputs transformations, and losses from state variable pools (Boote et al. 1998a).

Crop development in CROPGRO during the various growth phases is differentially sensitive to temperature and photoperiod. In CROPGRO there are 13 possible life-cycle phases from sowing to maturity, each with its own unique development rate. A developmental phase change occurs when the integrated development rate reaches a cultivar-dependent threshold and, for example, seed growth starts.

The physiological development rate, expressed as physiological days per calendar day, is modeled as a function of temperature, photoperiod, water deficit, and N deficit. If conditions are optimal, one physiological day is accumulated per calendar day and the number of physiological days equals the number of calendar days for a development phase. If conditions are not optimal (water or N stress, for instance) for development, the physiological days per calendar day will be less than 1.0 and the crop will require more calendar days to achieve the physiological day threshold for a given development phase.

The soil water balance processes include infiltration of rainfall and irrigation, soil evaporation, crop transpiration, distribution of root water uptake, and drainage of water through the soil profile (Ritchie, 1998). The crop N balance processes include N uptake, N_2 fixation, N mobilization from vegetative tissues, rate of N use for new tissue growth and rate of N loss in abscised parts (Boote et al., 1998a,b).

CROPGRO was developed as a generic approach for modeling crops in the sense that it has one common source code, yet it can predict the growth of a number of different crops (Jones et al., 2003). Currently, it simulates ten crops; including seven grain legumes (soybean; peanut; dry bean; chickpea; cowpea; velvet bean (Hartkamp et al., 2002); and faba bean (*Vicia faba* L.)) (Boote et al. 2002),; non-legumes such as tomato (Lycopersicon esculentum Mill.) (Scholberg et al., 1997; Boote et al., 1998a,b); and forages (*Brachiaria decumbens)* Rymph et *al.*, 2004; Giraldo et *al.*, 1998). This versatility is achieved through three input files that define species traits, ecotypes and cultivar traits (Boote et al., 2002). The species file contains information on base temperatures (Tb) and optimum temperatures (Topt) for developmental processes (rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity) and growth processes (photosynthesis, nodule growth, N_2-fixation, leaf expansion, pod addition, seed growth, N mobilization, etc.). These parameters are set during model development for a particular crop and are not generally changed by the user. The ecotype file contains information that describes broad groups of cultivars, such as determinate vs. indeterminate growth habit groups. Cultivar differences are represented in a file containing 15 coefficients (Boote et al., 2003). The cultivar file allows users to specify how cultivars differ in life cycle progression, daylength sensitivity, canopy and fruit growth characteristics. The cultivar traits lead to differences in yield potential in different environments (Boote and Tollenaar, 1994; Boote et al., 2003) and the traits can be solved from field trial or growth analyses data (Mavromatis et *al.*, 2001). Parameters in these files include factors such as physiological time between growth stages, relative differences in photosynthetic rate, and leaf size, among others. The CROPGRO model uses a 1-day time step, except for hourly time steps for development rate leaf-to-canopy assimilation calculation.

Owing to the structure of the CROPGRO model, the model is well suited to be adapted to new species. Literature reports several cases of adaptation processes on different crops including tomato (Scholberg et al., 1997), faba bean (Boote et al., 2002), and chickpea (Singh and Virmani, 1994) and bahiagrass (Rymph et al., 2004). These adaptations and parameterizations followed a systematic approach as proposed by Boote (1999) and Boote et al. (2002). First, cardinal temperatures, light, and daylength dependencies of various processes (leaf development, leaf photosynthesis, respiration, onset of anthesis, onset of fruit growth, rate of fruit growth, and photothermal time to maturity) are obtained from the literature where possible. The second step is calibration of model parameters using growth data, whether available from published literature or new experiments for representative production environments to derive model parameters that can not be directly obtained from the literature. Calibration is the process by which model parameters are adjusted to give the best fit between simulated results and observed data at a particular site. In other words, calibration involves adjusting certain model parameters by systematically comparing simulated results with observations while model structure remains the same (Jones and Luyten, 1998). It is hypothesized that this approach should also be successful in adapting the CROPGRO for another horticultural crop such as snap bean.

Previous Efforts of Modeling Horticultural Crops and Quality

Several process-oriented crop growth models have been extensively developed and validated for use in predicting dry matter accumulation on the pod or seed weight basis. As Boote and Scholberg (2006) pointed it out, these models fall short of permitting accurate simulation of growth and development of vegetable crops such snap bean which are primarily marketed based on fresh weight, pod size. When fresh vegetables are the crops to be modeled, the approach of photosynthesis-based or RUE-based models has to be altered to account for the fact that these crops are nearly 90 to 95% water and therefore the fresh weight growth is related to the flows of water and carbon into individual harvestable organs such as immature pod in snap bean. For such crops, model predicted fruit dry matter needs to be converted to fresh weight and/or fruit size (Marcelis et al., 1998) as yield is predominantly determined by the water content. These authors summarized in concise way, the different approaches to simulate the fresh market yield with the photosynthesis-based models. First, the interception of light by the leaf area is calculated to simulate the production of photosynthates. Subsequently, the use of photosynthates for respiration, conversion into structural DM, the partitioning of assimilates or DM among the different plant organs is calculated and finally the fresh weight can be estimated from the dry weight. More specifically for the CROPGRO model use in predicting fresh market and size of fruit, Boote and Scholberg (2006) envisioned that since the CROPGRO model already predicts explicit fruit addition and fruit growth rates over time for specific cohorts, this model ability can be adapted for predicting fresh market yields and individual fruit quality aspects (fruit sizing) over time.

Following these steps, few mechanistic models have been developed for horticultural crops. Among these, the model KOSI was developed to predict the yield and quality of cucumber fruits (Marcelis and Gijzen, 1998). These authors showed that with such a modeling approach, fruit size distribution in cucumber could be predicted in good agreement with observed distribution for commercial situation. Also, Tan et al. (2000a,b) developed a model to predict broccoli development which showed that the development is predominantly determined by temperature rather than photoperiod.

Although quality is now the compulsory motto of every advertising campaign for horticultural products and hence a component of their price (Gary et al., 1998), efforts to include product quality aspects in crop modeling is still in its infancy (Heuvelink et al., 2004). There are various dimensions of quality, such as shape, color, taste, composition, and shelf-life (Marcelis and Gijzen 1998, Gary et al., 1998).

In the case of snap bean, Ferreira et al. (1997, 2006) illustrated sparse literature in which they attempted to develop a simulation model of this vegetable crop. Several other studies have addressed the growth and development of dry bean (Hoogenboom et al., 1994; Gutierrez et al. 1994). Indeed, Ferreira et al. (1997) predicted phasic development of green beans using a model with thermal time accumulation, understanding the importance of developmental stages to monitor and predict with accuracy, especially harvest time date which is determinant for pod quality. Ferreira et al. (2006), on the other hand, integrated in their model some internal as well as external variables such as alcohol-insoluble solids, dry matter content, seed: pod ratio, fiber content, length of 10 seeds, Kramer shear press, color, lipid content and mineral composition, to evaluate quality and maturity of snap bean pod.

This chapter reviewed literature pertaining to snap bean growth, development and yields as influenced by management practices, namely irrigation and N fertilization. Additionally, this chapter provides a conceptual framework and the scope of previous research efforts related to crop simulation models in general and snap bean simulation in particular.

CHAPTER 3
GROWTH AND NITROGEN UPTAKE OF SNAP BEAN IN RESPONSE TO NITROGEN FERTILIZATION

Introduction

Intensification of cropping systems to attain higher crop yields per unit of land area is typically achieved through the use of high yielding varieties, which usually require larger doses of inorganic fertilizers. Under optimal water supply, crop performance is influenced substantially by the supply of N from soil and fertilizer sources (Below, 2002). Therefore, soil and fertilizer management must be designed to furnish a continuous supply of available N and other nutrients to produce high yield and quality while withstanding unpredictable plant stress conditions (Peck and MacDonald, 1983). Nitrogen is essential for crop growth, being a constituent of proteins, amino acids, chlorophyll, nucleic acids, and cell walls (Neeteson, 1995). Nitrogen nutrition influences leaf growth and leaf area duration and thus the size of the photosynthetic system, the photosynthetic rate per unit of leaf area as well as the generative storage organs which is the sink capacity (Below, 2002).

Assessing plant response to nutrients in general, and to nitrogen (N) in particular, is an important step towards understanding plant growth and development patterns and developing appropriate nutrient management techniques in cropping systems. More specifically, knowledge of crop N demand is essential in predicting crop N uptake and, therefore, in developing reliable N fertilization recommendations for growers (Nkoa et *al.,* 2001). Analysis of plant growth response to N fertilization involves quantifying patterns of crop growth parameters (dry matter production in plants and leaf area index for instance) which allow computing different crop growth coefficients such as the Crop Growth Rate (CGR) (Radford, 1967; Hunt, 1982). Generally, varying N rates from low to high as well as using different N sources can be used on the same type of soil to evaluate crop response to N (Peck and MacDonald, 1983; Sader, 1980).

Although snap beans are legumes with symbiotic N fixation capability, the literature contains different N recommendation rates on snap bean in different environments. Nitrogen fertilization affects the vegetative growth of snap bean plants as well as the pod set and development (Peck and MacDonald, 1983). Further, Sader (1980) reported that ”green manure” and inorganic nitrogen fertilization affected growth of dry bean during the early phases of plant development, causing a significant increase in leaf area index (LAI) and crop growth rate up to the time of flowering, but decreased growth in the later stages.

The present chapter describes field experiments conducted in Gainesville, Florida, in Spring 2007 based on the hypothesis that higher nitrogen rates stimulate greater crop growth. The underlying objective in this study was to determine the effects of N fertilization on growth attributes of snap bean plants, N uptake and N partitioning within plant parts over the growing period.

Materials and Methods

Cultural Practices

Snap bean was grown in the field on a Millhopper fine sand soil (loamy, siliceous, hyperthermic Arenic Paleudult) during spring growing season 2007 at the Plant and Soil Science Field Teaching Laboratory at the campus of the University of Florida, Gainesville (29° 38´ N, 82° 22´ W). Before sowing (9 March 2007), the experimental area was moldboard plowed and 925 kg ha^{-1} of 4-12-12 (N-P_2O_5-K_2O) commercial fertilizer was broadcast. Also, weeds were controlled with herbicides and hand weeding. Sowing occurred on 15 March 2007 and was performed with a custom no-till planter equipped with notched, double disk openers and spring-loaded angled closing wheels. An in-row sowing density of 21 seeds per meter of cultivar 'Ambra' snap bean was adopted. Spacing between rows was 0.61 m and the sowing depth was 25.4 mm, resulting in a final plant population of 34 plant m^{-2}.

Daily weather data, including daily ET_0, minimum temperature, and maximum temperature were obtained from the weather database of the Florida Automated Weather Network (FAWN) located at the Citra site. Also, rainfall data were also collected on-site.

Experimental Treatments

Treatments were imposed in a 3 x 4 factorial split plot design with water management treatments as main plots and N levels as subplots. All treatments were replicated four times. Main plots (13.7 m × 13.7 m) consisted of the following three water-management treatments: (I_1) medium irrigation which was 100% of crop evapotranspiration; (I_2) low irrigation which received 1/3 less the amount received by the medium regime; and (I_3) high irrigation which received 1/3 more water than the medium treatment. Water was applied by overhead sprinkler irrigation on all the treatments on the same day with the frequency set by the medium irrigation regime, and the amount of water for the medium irrigation was determined from water balance developed by Ritchie (1998). The water balance in the soil-plant-atmosphere continuum was calculated as follows: $\frac{dW}{dt} = P + I - D - E_S - E_P$ where,

dW/dt = Net rate of change in stored soil water, in units of mm^3[water] mm^{-2}[area] d^{-1}, or mm d^{-1}; *P* = Precipitation on day t, mm d^{-1}; *I* = Irrigation amount on day t, mm d^{-1}; *D* = Drainage from bottom of profile on day t, mm d^{-1}; E_s = Soil evaporation on day t, mm d^{-1}; and E_p = Plant evaporation (transpiration) on day t, mm d^{-1}. Depletion of 60% of the available soil water (ASW) was allowed for the 20 cm soil profile depth; then irrigation up to drained upper limit (DUL) was scheduled. The calculation accounts for the soil water content at saturation (SAT), the lower limit of plant water availability (LL) and the drained upper limit (DUL). Values of these parameters appropriate for this soil were taken from Carstile et al. (1981). Daily crop water use (ETcrop) was computed using values of potential evapotranspiration (ETpot) collected from the

FAWN web site and values of the crop coefficient (K_{cp}) which is function of development stage. The depth increment used in the water balance and irrigation scheduling procedure was 20 cm. Drainage from a soil profile takes place when the soil water content (SW) is above the drained upper limit (DUL). Thus, the drainage (D) used above occurs when the precipitation (P) and irrigation (I) minus E_s and E_p exceed the DUL on a given date. These equations and parameters were entered in EXCEL Spreadsheet and allowed to develop the schedule and amount of water required at each irrigation event. Differential irrigation started 14 DAS after applying three uniform irrigations for germination and crop establishment. Irrigation amounts and dates applied for each of the three water management treatments are shown in Table 3-1.

Within each water-management treatment, the following four N treatments were randomly imposed: (N_{37}) low N, consisting of a total of 37 kg N ha^{-1} corresponding to the preplant N application described above; (N_{74}) Medium N, consisting of a total of 74 kg N ha^{-1} applied in three side-dress applications. (N_{111}) recommended N, consisting of a total of 111 kg N ha^{-1} applied in three side-dress applications, and (N_{148}) High N, consisting of a total of 148 kg N ha^{-1} applied in three side-dress applications. The first application of N to the three higher N (N_{74}, N_{111} and $N_{148)}$ treatments was same as the N_{37} treatment, which corresponded to the amount of N applied as preplant application. The remaining amount of N for the other three treatments was applied in two equal applications at the rate of 18.5, 37 and 55.5 kg ha^{-1} for the treatments 74, 111 and 148 kg ha^{-1}, with the last application occurring right after the flowering. The remaining N for the treatments N_{74}, N_{111} and N_{148} was supplied as ammonium nitrate (34-0-0) and was side-dressed between rows according to the schedule shown in Table 3-2. Nitrogen treatments were applied to 9 subplot rows, each 7.5 m long. Subsequently, there were 12 combination treatments consisting of three irrigation regimes and four N rates. It should be noted that the (N_{111}) rate of

111 kg N ha^{-1} is the current nitrogen recommendation rate for snap bean by the Institute of Food and Agricultural Sciences (IFAS) of the University of Florida (Olson et al., 2007).

Measurements

During the experiment, the following data were collected on crop growth and nitrogen uptake.

Crop growth analysis

The growth analysis study emphasized the snap bean response to N fertilization (four treatments) only studied in the medium irrigation treatment in order to reduce the workload. Growth analysis samples were collected at 7-day intervals beginning 14 DAS and, first measurements involved taking the canopy height and width on two random plants within 1 m of row. Then, all the plants from this 1-m of row were cut off at ground level and the number of plants recorded. From these harvested plants, four plants of median size were selected and vegetative and reproductive stages were measured based on soybean development stages established by Fehr et al. (1971). Then the four sub-sampled plants were partitioned into leaves, stems, and pods. Leaf area was determined with a LI-COR 3100 area meter. Total number of main stem nodes was determined. Also, total number and fresh weight of pods were measured and a sub sample of 10 median pods was taken from the total pods and their fresh weight was taken. These sub-sampled pods were partitioned into seeds and podwall, and the fresh weight and total number of the seeds was recorded. The rest of the sampled plants from the 1-m row, the leaves of the four sampled plants, the stems of the four plants, the total rest of pods, the podwalls and the seeds of the 10 sampled pods were separately conserved and dried at 60^{o} C in a forced-air oven for at least 72 hours and dry weights were measured. Fraction allocation of assimilates among plant organs was calculated as the ratio of dry weight of individual parts to that of total plant dry matter at each sampling date. Leaf, stem, pod, and seed dry matter (DM) mass (kg DM ha^{-1}) was calculated from the respective ratios multiplied by the total crop land-area DM (kg DM ha^{-1}) from the combined sample and sub sample masses of leaf, stem, pod, and seed, respectively (Boote, 1999). Also, specific leaf area (SLA) (m^2 leaf kg^{-1} leaf) was calculated from the measured leaf area and leaf mass for each sub sample. Leaf area index (LAI) (m^2 leaf m^{-2} land) was then calculated by multiplying the SLA by the total leaf mass.

Crop growth rates (CGR) were computed for each treatment as follows:

$$CGR = \frac{W_2 - W_1}{t_2 - t_1} \tag{3-1}$$

where W_1 and W_2 represent the biomass weights at time t_1 and t_2, respectively.

Using a base temperature for snap bean of 4 ^{o}C (Ferreira et al., 1997), thermal time was calculated as follows:

$$\tau_T = \sum_{i=1}^{n}(T_{a,i} - T_b) \tag{3-2}$$

Where $T_{a,i}$ is the daily mean air temperature of day i, T_b is the base temperature at which development stops, and n is the number of days used in the summation.

Plant tissue nitrogen analyses

Oven-dried samples of component plant parts (leaf, stem, pods and seed) from each sampling date were ground in a Wiley mill to pass through a 1-mm screen. For N analysis, samples were digested using a modification of the aluminum block digestion procedure of Gallaher et al. (1975). Sample weight was 0.25 g, catalyst used was 1.5 g of 9:1 K_2SO_4:$CuSO_4$, and digestion was conducted for at least 4h at 375°C using 6 ml of H_2SO_4 and 2 ml H_2O_2. Nitrogen in the digestate was determined by semiautomated colorimetry (Hambleton, 1977).

Shoot N accumulation was computed by multiplying dry mass of leaves, stem, pod and seed by the corresponding N concentrations. The distribution among plant organs (leaf, stem, pod and seed) was calculated as the ratio of N accumulation of individual parts to that of shoot N accumulation at each sampling date.

Data Analysis

Statistical analysis was performed with SAS (Statistical Analysis Systems, Cary, NC). Since sampling dates were correlated over time (covariance), the “Proc Mixed” procedure of SAS was used to analyze results with sampling date (DAS), N, and the DAS by N interaction being the main fixed effects in the model. Repetition (block) and its interaction with N were included in the random effects term. Also, linear, quadratic and cubic trends were tested for sampling time (DAS). This is a repeated measures statistical analysis where repetition (block) and its interaction with N were included in the random effects term. When the interaction N*DAS was significant for a given response variable, the LSMEANS differences were used to compare the N treatments at each sampling date. Shoot and N shoot growth rates were estimated with linear regressions of shoot and N shoot mass and the resulting slopes were compared for differences between N rates.

Response variables tested included node number, canopy height and width, LAI, plant and organs dry matter (DM) accumulation (kg ha^{-1}), tissue N concentration (g N kg^{-1}), and crop and organs N accumulation (kg N ha^{-1}).

Results and Discussion

Effects of N Fertilizer Rates on Canopy Characteristics

Numbers of nodes formed were not significantly affected by the N rates and the interactions between day after sowing and N treatments (P-values = 0.76 and 0.68, respectively) (Table 3-3). Regardless of the N treatments, the number of nodes formed on the main stem increased linearly with thermal time (up to about 750 ^{o}C d^{-1}) (Figure 3-1). This number of nodes produced was stable for all treatments with the maximum number of 7 followed by a plateau which presumably marked the end of leaf appearance on the main axis and associated initiation of a terminal inflorescence. The leaf appearance rate for snap bean as affected by N rates was compared by plotting accumulative node number versus thermal time. The slopes taken in the linear portion of the accumulative node number against thermal time, corresponded to the development rate (rate of leaf appearance). These were 0.010, 0.009, 0.009 and 0.009 node $^{o}C\ d^{-1}$ for 37, 74, 111, and 148 kg N ha^{-1}, respectively.

Similarly, repeated-measures analysis of variance performed on the canopy height and width did not show a significant effect of the individual of N treatments (P-values = 0.88 and 0.82, respectively, Table 3-3). The interaction effect between N treatments and days after sowing was not significant either on the canopy height and width (P-values = 0.63 and 0.23, respectively, Table 3-3). Figures 3-2A and 3-2B indicate that canopy height and canopy width increased linearly with thermal time to a maximum at about 750 $^{o}C\ d^{-1}$. The maximum height reached on the recommended N rate (N_{111}) was about 46 cm as opposed to 37 cm for the lowest N rate (N_{37}). These values of height and width are typical to a type 1 determinate snap bean as reported by Fageria (1997). Regardless of the N rates, flowering occurred 40 to 42 days after planting.

Effects on Leaf Area Index

The effects of N treatments on leaf area index (LAI) averaged over the sampling dates were not significant (Pr = 0.86, Table 3-3). The interaction of N rate and time (days after sowing) were not significant for leaf area index (Pr = 0.11, Table 3-3).

Seasonal patterns of the effect of N rates on the development of LAI are shown in Figure 3-3. The LAI increased rapidly, with minor effects of N rates. The exponentially increasing phase of LAI represents the period of fast development of the canopy, which determines light interception and photosynthetic activity, resulting in higher carbon assimilation of leaf canopies.

The time course of the LAI appeared to be subdivided into three sub phases as follows. A lag phase from emergence to crop establishment (0-20 days) which was a period of slow growth; the second sub phase (20-35 days) was characterized by almost linear growth and finally a more rapid linear phase (35-50 days) during which the LAI increased at a constant rate leading to a full canopy. Higher photosynthesis production can be expected during this phase. After about 34 days after sowing (DAS), the lowest N rate (N_{37}) started to show a slower increase compared to the other three rates. This slower increase was marked by symptoms of N stress and was visible by the yellow color of the leaves. The maximum LAI was approximately 2.6 and 2.0 for N_{111} and N_{37}, respectively, at 55 DAS. Thereafter, a decline in LAI was observed which was relatively more rapid at the lowest nitrogen level N_{37}. This decline of leaf growth was associated with increased leaf senescence and abscission of the lower leaves. Penning de Vries and van Laar (1982) estimated the relative leaf senescence rate during this stage at 3% per day. Similar overall responses of LAI to N fertilization have been reported for dry beans (Montojos and Magalhaes, 1971; Wallace and Munger, 1965). However, the values of LAI measured in this study were lower than the ones reported by the above authors. It is of interest to note that the peak LAI observed for the highest N treatment was only numerically similar to the one observed on the lowest N rate (2.2 versus 2.1). This may be due to over-fertilization which to some extent limited plant growth and foliar expansion, especially under high evaporative conditions with marginally adequate irrigation regime where any excessive N was not leached.

Effects on Biomass Accumulation

Significant effects of N treatments on total dry matter accumulation averaged over the growing period were highly significant ($Pr = 0.001$, Table 3-4). A similar result was also found with respect to the interaction between N rate and days after sowing ($Pr < 0.0001$); implying that there was a significant difference among N treatments at individual time points (days after sowing). Indeed, significant differences in shoot dry matter were observed mostly from mid to late season (50 to 83 days after sowing), notably between the lowest N rate and the three higher N rates which did not show any significant difference from each other (Appendix Table A-1).

Figure 3-4 illustrates the seasonal patterns of shoot dry matter in relation to the N rates. Regardless of the N rates applied, shoot dry matter (DM) accumulation (kg ha^{-1}) increased continuously throughout the growing season until reaching its maximum value near maturation (77 days after sowing). As shown by the statistical analysis, the dry matter accumulation of snap bean did not differ across N rates until about 50 DAS and thereafter the lowest N rate began to show a lower dry matter accumulation rate than the three higher N rates which did not show any significant difference from each other (Appendix Table A-1). The greatest amount of DM (5000 kg ha^{-1}) was produced at the 148 kg ha^{-1} N rate. A similar trend was observed by Peck and MacDonald (1983) who found that dry weight accumulation in the snap bean plants was slow from planting to the seedling stage, more rapid from seedling to the bloom stage and reached a rapid rate of 22 g m^{-2} day^{-1} from the bloom to the pod stage. Increase in DM production as a consequence of N can be explained by increase in Net Assimilation Rate (NAR) (Sader, 1980). Average crop growth rates estimated from the slopes of near-linear periods of total biomass increase (34-76 DAS) were 80.7, 107.9, 108.6 and 109.0 kg ha^{-1} d^{-1} for 37, 74, 111 and 148 kg N ha^{-1}, respectively, with significant difference observed only between the lowest N rate (37 kg ha^{-1}) and the three higher N rates (74, 111 and 148 kg ha^{-1}) which did not show any significant different from each other (Pr = 0.003, 0.89, 0.99 and 0.99, respectively). With differences between N rates typically becoming more evident over time, final DM accumulation was 26% higher for the three higher N-fertilizer rates than at the lowest N rate. The decrease in dry matter at the later growth stage may be related to more photosynthate translocated to grain and abscission of old leaves (Fageria, 1997).

Effects on Plant Organ Mass and Distribution

Differences between N treatments on the leaf and stem dry weights measured in this study were not significant across the overall growing period (Pr = 0.94 and 0.74, respectively, for leaf and stem dry weights; Table 3-4). The interaction of time (DAS) and N was not significant on these two response variables either (Table 3-4). On the contrary, the effect of N and the interaction effect of N and DAS showed highly significant difference for the pod mass and seed mass (Pr < 0.0001 and 0.04, respectively, Table 3-4). The pair wise comparison of N treatments showed significant differences in pod dry mass mostly during late season from 62 to 83 days after sowing, notably between the lowest N rate and the three higher N rates (Appendix Table A-2). Similarly, Appendix Table A-3 indicated that significant differences between N treatments for the seed dry weights were observed from 69 days after sowing through the end of season, mostly between the lowest N rate and the three higher N rates which did not show any significant difference from each other.

The time course of dry matter accumulation in different plant organs is presented in the Figures 3-5A, 3-5B, 3-5C, and 3-5D. As indicated by the statistical analysis, dry matter accumulation in different plant organs under the lowest N rate (N_{37}) was slightly lower than the three other rates especially towards the end of the growing season. This difference was more pronounced on the reproductive organs (pods and seeds). The pattern of DM increase over time included linear, quadratic, and cubic terms.

Figures 3-6A, 3.6B, 3.6C, and 3.6D present the fraction of the total plant dry matter in the respective plant organs over time. Inspection of these figures revealed that approximately 80% of the plant dry matter was present in leaf during initial growth compared to roughly 20% in stems.

But throughout the growing season, the fraction of plant dry matter in leaf and stem declined continuously. About 50 DAS, assimilates were predominantly directed to the newly-developing pods, resulting in a rapid increase in fraction of total dry matter found in pod and later in seed. Finally, when pods reached physiological maturity about 75 to 80 DAS, pods and seeds accounted for most of the top dry weight, with pods accounting for 75 to 80%, and seeds, 55 to 60%, respectively, of the total shoot dry matter. Gutierrez et al. (1994) argued that the switch in dry matter allocation from vegetative growth to fruit growth is seen as plateau in stem growth, and also seen as a decline in leaf mass due to leaf abscission and to the slowing of leaf initiation. While N rate had no effect on fraction dry matter in plant organs/components early in the season, it was observed later in the season that the lowest N rate (N_{37}) had a lower fraction of dry matter in stem and leaf towards the end of the growing season.

Effects of Nitrogen Supply on Nitrogen Uptake

Plant tissue nitrogen concentration

Knowledge of nutrient concentrations and distribution in plant parts is important for a basic understanding of plant nutrition (Fageria, 1997). Tissue N concentrations were variably affected by the N treatments. Except for the stem and seed, the N concentrations in the leaf and pod were significantly different as result of N treatments with P values of 0.02 and < 0.0001 for leaf and pod, respectively, (Table 3-5). The N*DAS interaction effect was also significant only for leaf and pod N concentration (Table 3-5). The pair wise contrast analysis based on the least square means of leaf N concentration and pod N concentration are presented in Tables A-4 and A-5, respectively. These tables showed that highly significant differences between the lowest N treatment (37 kg ha^{-1}) and the three higher N treatments (74, 111 and 148 kg ha^{-1}) were observed from 50 days after sowing through the end of season for the leaf N concentration; and from 50 to 69 days after sowing for the pod N concentration.

Tissue N concentrations over time for snap bean grown at four N rates are shown in Figures 3-7A, 3-7B, 3-7C, and 3-7D. Irrespective of the tissue types, N concentration showed a decreasing trend over the growing season. Typically, initial values of N concentration were higher early in the season across all the N rates with reproductive organs (pod and seed) having relatively higher values. Similar declines in shoot N concentration have been commonly observed (Peck and MacDonald, 1983; Fageria et al., 1997; Barker and Bryson, 2006; Lemaire et al., 2007). The N concentration in leaf decreased from 6% to about 2% near the end of the growing season irrespective of N treatments. Similarly, the N concentration in stem decreased from 4.5% during initial growth to 0.7% in the end of season. Respective values for pod and seed were 5 to 1%, and 7 to 3%. But of all organs, the N concentrations in the seed at the end of the season were higher. Lemaire *et al.* (2007) reported that this observation of tissue N decline has usually been interpreted as a direct result of plant ageing and has often been related simply to phenology, leading to large differences in N concentration between species or genotypes within a given environment, and between different environments for a given genotype. Mobilization of N from old leaves to meristems, young leaves, and fruits leads to a diminished N concentration in old, lower leaves of plants (Barker and Bryson, 2006).

Nitrogen accumulation by snap bean plants

There was a highly significant difference between N treatments for the total N accumulation in snap bean ($P = 0.0001$). The interaction of N and days after sowing was also highly significant, showing that there was a significant difference among N treatments at individual time points (days after sowing). Indeed, highly significant differences in total shoot N were observed mostly during late season from 50 DAS towards the end of season (83 DAS), notably between the lowest N rate and the three higher N rates (Appendix Table A-6). Seasonal total N accumulation pattern over time is presented in Figure 3-8. The N accumulation in the plant followed a linear increase over time similar to total plant dry matter accumulation. From germination until about 34 DAS, the response of N accumulation to the four N rates was similar with no obvious treatment effect. The average N accumulated during this early growth ranged from 11 to 13 kg N ha^{-1}. The maximum N accumulation occurred late in the season at 76 DAS and was 95 and 149 kg N ha^{-1} for the lowest and highest N rates, respectively. Similar seasonal accumulation pattern of N by crop plants was reported by Below (2002). At an N rate of 300 kg ha^{-1}, Sader (1980) found a maximum N accumulation in the seed of 125 kg ha^{-1}. These values compared fairly well with those observed in this study.

Similarly, during the vegetative growth period from sowing to 40 DAS, the four N rates accumulated on average 1.10, 1.38, 1.30, and 1.37 kg N ha^{-1} d^{-1} for 37, 74, 111 and 148 kg ha^{-1}, respectively, indicating little effect of observed N-rates until that time. Later in the growing season, the average daily N accumulation rate was 1.71, 2.45, 2.31 and 3.04 kg N ha^{-1} d^{-1}, for the treatments 37, 74, 111 and 148 kg N ha^{-1}, respectively. However, Peck and MacDonald (1983) observed that during the 20 days from the bloom to the pod stage, the total N in the plants grown with soil N but without fertilizer N increased an average rate of 4.4 kg N ha^{-1} d^{-1} while plants grown with soil N plus fertilizer N at 120 kg N ha^{-1}increased on average rate of 6.6 kg N ha^{-1} d^{-1}.

Effects of N supply on nitrogen distribution

Unlike the seed, the N accumulation in the leaf, stem and pod did not show any significant difference with N treatments. The P-values were 0.93, 0.96, 0.10 and 0.003 for leaf, stem, pod and seed, respectively (Table 3-5). The DAS*N interaction term was significant for pod N mass and seed N mass response variables with differences between N rates based on the pair wise comparison typically becoming more pronounced over time (Tables A-7 and A-8). The effects of N rates on cumulative N-distribution for snap bean are shown in Figures 3-9A, 3-9B, 3-9C and 3-9D. Independent of the N rate applied, during vegetative growth about 70 to 80% of the N was accumulated in the leaves compared to 20 to 30% in stems. While the fraction of N present in the leaves declined throughout the season, the fraction of N found in the stem initially followed an increase to 40 to 50 DAS and thereafter showed decline until the end of season. The lowest N-rate showed greater decline in the N fraction found in the vegetative organs while the three other rates followed a slow decrease. At the end of the growing season, N accumulation in the fruit accounted for 64% at the highest N rate and 72% at the lowest N rate. Sader (1980) observed that re-mobilization of N from vegetative plant material to the snap bean seed occurred regardless of the rate of fertilizer application.

Conclusion

The purpose of our experiment was to evaluate the pattern of some crop growth variables over the full growth life cycle to maturity for field-grown snap bean plants under different N rates. Snap bean growth parameters analyzed in this study responded variably to N fertilization. Number of nodes on the main stem, canopy height and width did not show any significant difference with N treatments. Maximum values of LAI for treatments of 37 and 111 kg N ha^{-1} were 2.0 and 2.6, respectively, at 55 days after planting. Thereafter, a decline in LAI was observed which was relatively more rapid at the lowest N rate. The dry matter accumulation of snap bean did not differ statistically across N rates until about 55 days after planting but thereafter the lowest N rate showed lower dry matter accumulation rate as opposed to the three higher N rates which did not show any apparent differences from each other. Generally, the temporal pattern of plant total, leaf, and stem mass showed an initial exponential increase and a near linear increase to the peak followed by a decline phase later during the end of the growing season irrespective of N treatments. Fractional distribution of total dry matter in aerial plant parts indicated that irrespective of N treatments, all treatments produced maximum allocation to the leaves followed by the stem during the early stage of development, and after the onset of reproductive organs, more dry matter was allocated to the pod and seed towards the end of growing season. This study confirmed the positive relationship between biomass accumulation and N accumulation in the plant. Indeed, the pattern of total N accumulated over time was closely associated with aerial biomass. Nitrogen distribution in plant components was largely affected by N fertilization. N accumulated in vegetative parts at all treatments was relatively high at very early stages of plant development, and started declining throughout the growing season. A sustained slower increase in N accumulation occurred after 50 DAS due to remobilization of N to other plant parts, mainly pod. Total N accumulated in plant was considerably affected by N fertilization. At the end of growing cycle, the majority of the N was allocated to the seed irrespective of the N treatments.

Table 3-1. Irrigation amounts (mm) and dates of application of the three water management treatments

Date	DAS	Water Management Treatments (mm)		
		Low	Medium	High
03/14/2007	0	15.2	15.2	15.2
03/15/2007	1	13.2	13.2	13.2
03/22/2007	7	5.8	5.8	5.8
03/26/2007	12	8.2	8.2	8.2
03/30/2007	16	7.9	9.7	13.0
04/03/2007	20	7.5	9.7	17.7
04/12/2007	29	5.8	7.4	11.0
04/14/2007	31	7.4	9.1	12.6
04/20/2007	37	7.5	9.0	12.4
04/24/2007	41	9.8	11.7	20.6
04/27/2007	44	11.2	14.8	22.3
04/30/2007	47	11.9	15.3	19.9
05/03/2007	50	14.6	15.4	26.9
05/06/2007	53	13.4	17.4	24.2
05/10/2007	57	11.4	14.9	22.9
05/13/2007	60	17.0	21.0	31.6
05/15/2007	62	3.1	3.3	3.7
05/20/2007	67	11.8	13.3	20.2
05/24/2007	71	14.6	15.2	23.1
05/25/2007	72	6.5	7.1	11.7
05/30/2007	77	12.4	14.2	21.5
Total	**-**	**216**	**251**	**354**

Table 3-2. Amounts and dates of N application of the four nitrogen treatments

Date	DAS	Nitrogen Rates (kg ha^{-1})			
		37	74	111	148
03/09/2007	Preplant	37.0	37.0	37.0	37.0
03/29/2007	15	-	18.5	37.0	55.5
04/26/2007	43	-	18.5	37.0	55.5

Table 3-3. Probability levels (P) for the effects of nitrogen rate (N) and interaction (N*DAS) on canopy characteristics

Source of variation	Number of Nodes	Height	Width	LAI
DAS-L	<0.0001	0.55	0.58	<0.0001
DAS-Q	<0.0001	<0.0001	<0.0001	<0.0001
DAS-C	0.10	<0.0001	<0.0001	<0.0001
N	0.76	0.88	0.82	0.86
N*DAS	0.68	0.63	0.23	0.11

L= Linear, Q= Quadratic and C= Cubic

Table 3-4. Probability levels (P) for the effects of nitrogen rate (N) and interaction (N*DAS) on plant mass variables

Source of variation	Shoot biomass	Leaf mass	Stem mass	Pod mass	Seed mass
DAS-L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
DAS-Q	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
DAS-C	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
N	0.001	0.94	0.74	<0.0001	0.04
N*DAS	0.0001	0.08	0.16	<0.0001	0.04

L= Linear, Q= Quadratic and C= Cubic

Table 3-5. Probability levels (P) for the effects of nitrogen rate (N) and interaction (N*DAS) on plant organ N concentrations

Source of variation	Leaf N conc.	Stem N conc.	Pod N conc.	Seed N conc.
DAS-L	0.51	0.0002	<0.0001	0.34
DAS-Q	0.002	0.84	<0.0001	0.82
DAS-C	0.007	0.84	<0.0001	0.73
N	0.02	0.21	<0.0001	0.30
N*DAS	0.02	0.49	0.005	0.46

L= Linear, Q= Quadratic and C= Cubic

Table 3-6. Probability levels (P) for the effects of nitrogen rate (N) and interaction (N*DAS) on total plant N mass and plant organ N mass

Source of variation	Shoot N mass	Leaf N mass	Stem N mass	Pod N mass	Seed N mass
DAS-L	0.0004	0.03	0.78	0.009	<0.0001
DAS-Q	<0.0001	0.02	0.001	0.01	<0.0001
DAS-C	<0.0001	<0.0001	<0.0001	0.07	0.02
N	0.0001	0.93	0.96	0.10	0.003
N*DAS	0.0001	0.21	0.06	0.003	0.01

L= Linear, Q= Quadratic and C= Cubic

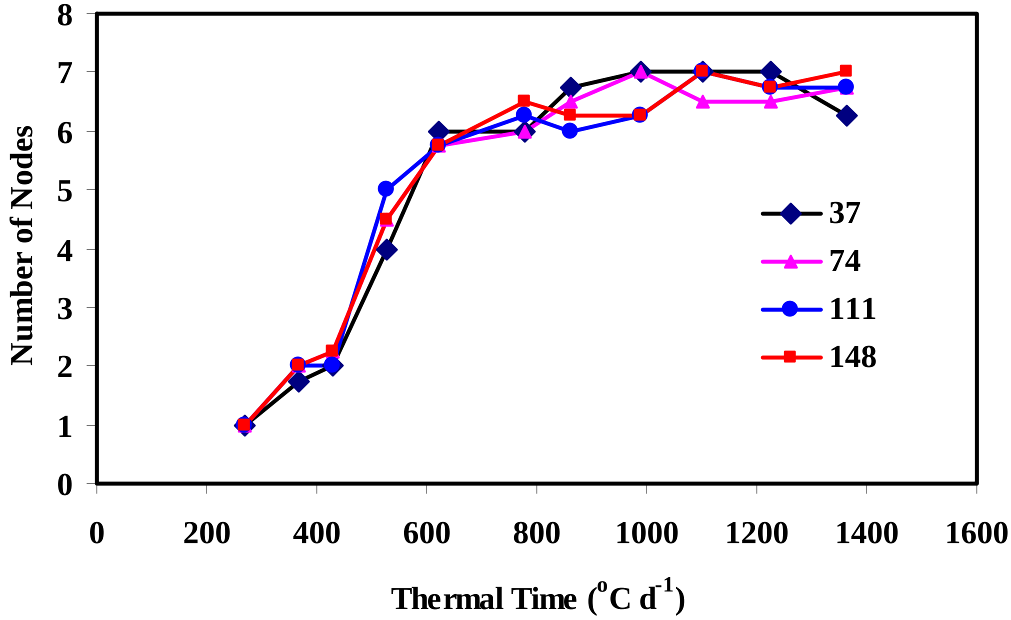


Figure 3-1. Number of nodes formed on snap bean versus thermal time as affected by four N fertilization rates in Gainesville FL during Spring 2007

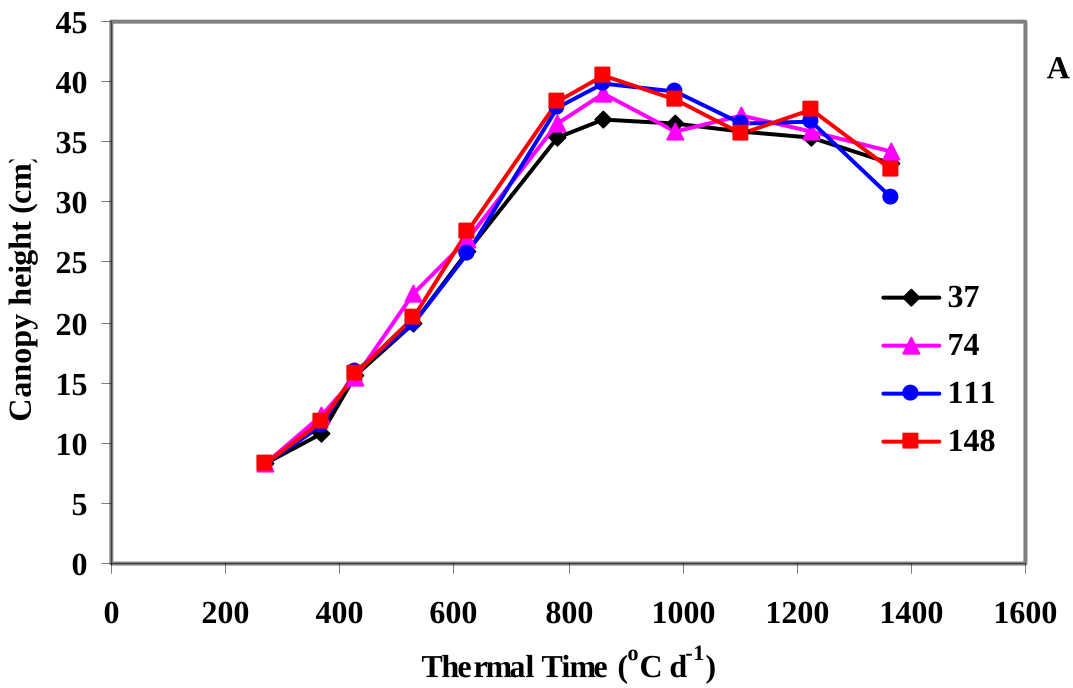
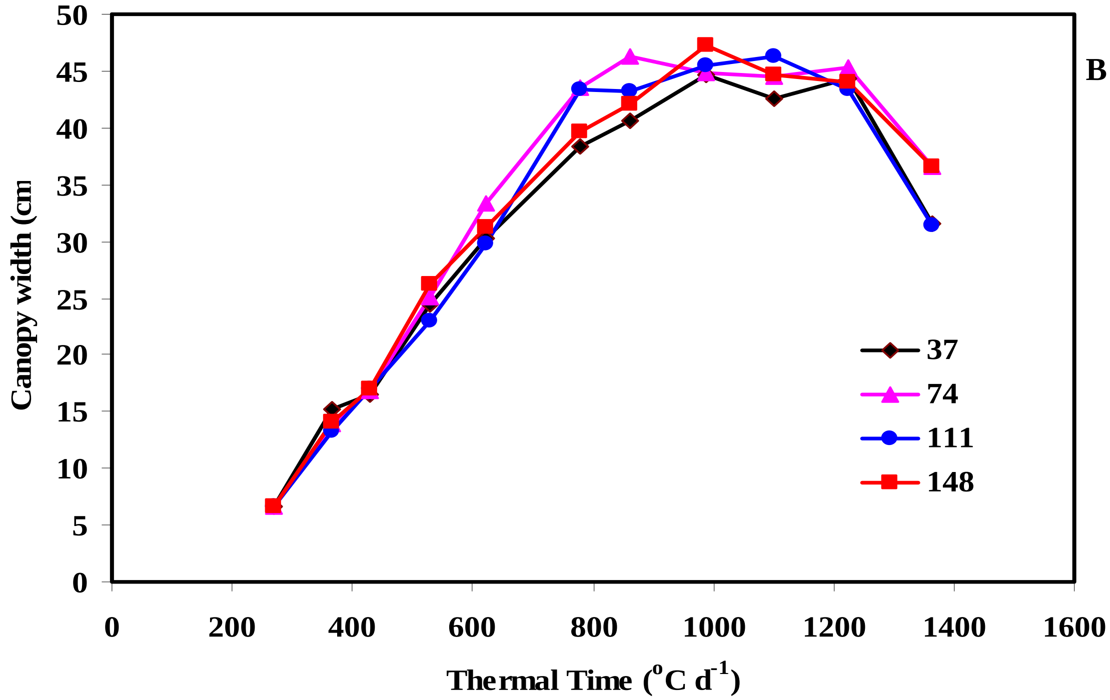


Figure 3-2. Canopy height (A) and canopy width (B) of snap bean versus thermal time as affected by N fertilization rates in Gainesville FL during Spring 2007



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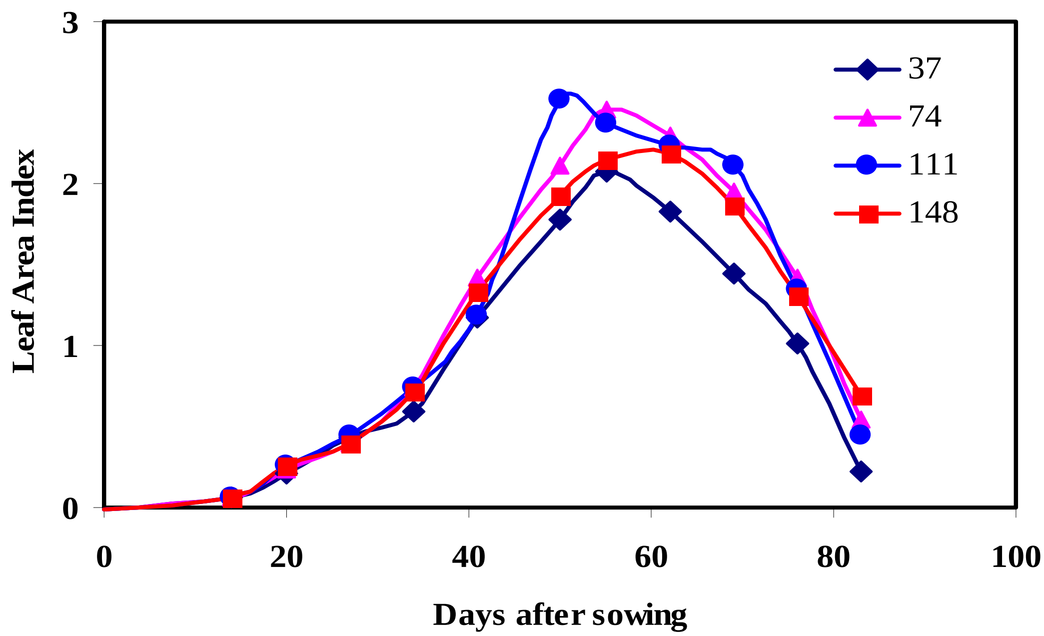


Figure 3-3. Leaf area index of snap bean over time as affected by four N fertilization rates in Gainesville FL during Spring 2007

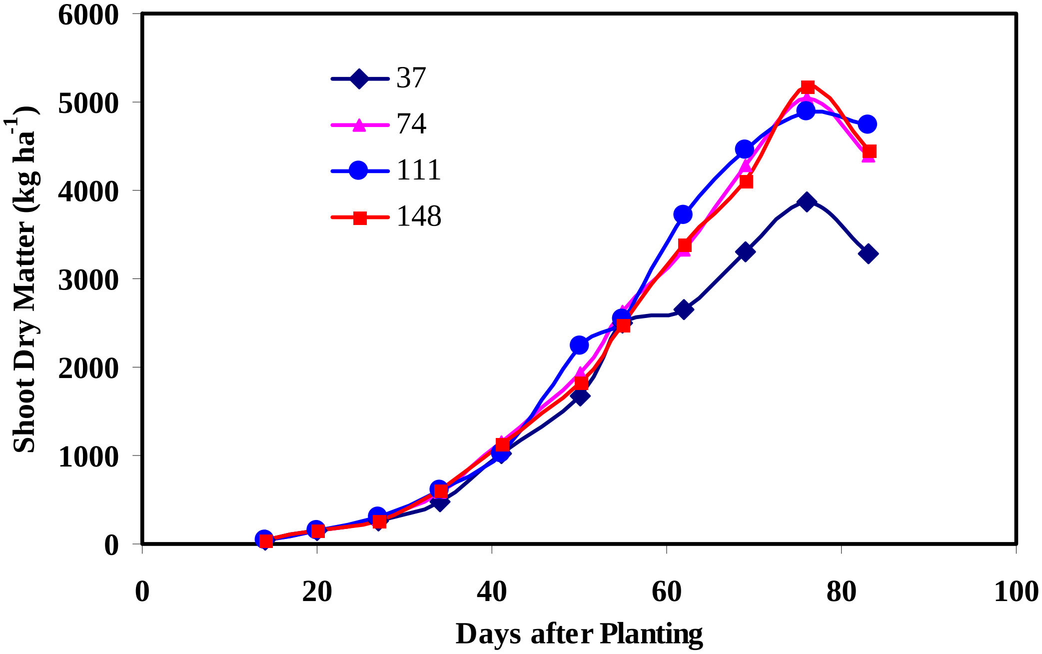


Figure 3-4. Shoot dry matter of snap bean over time as affected by four N fertilization rates in Gainesville FL during Spring 2007

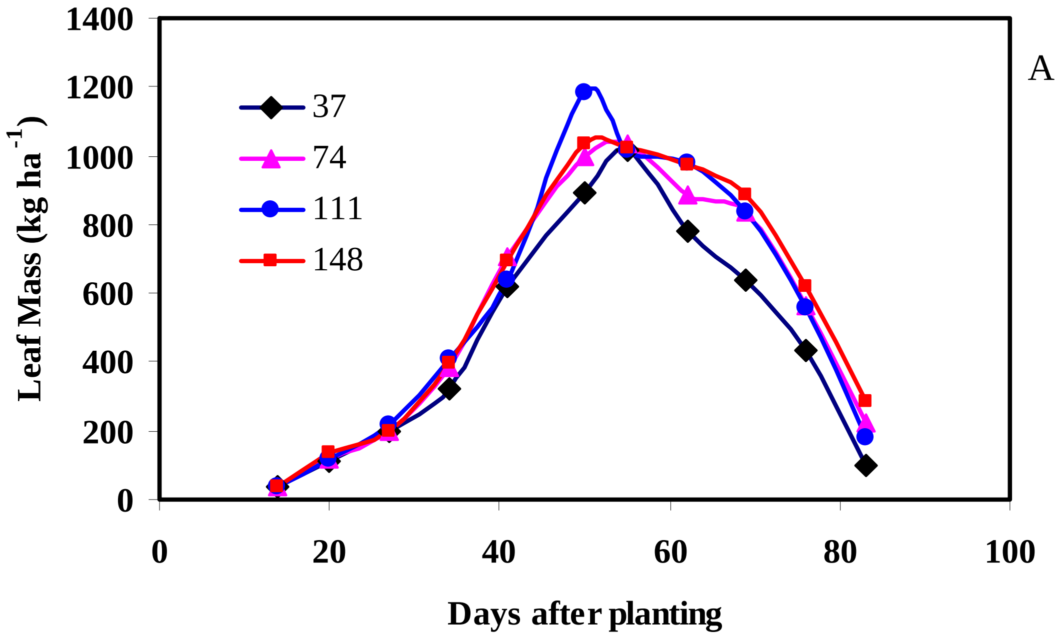
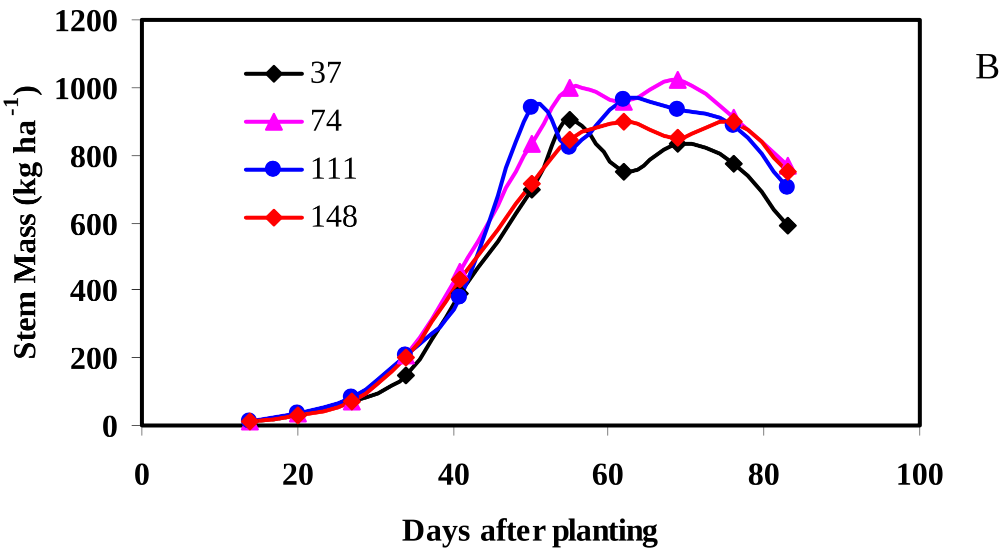


Figure 3-5. Plant dry matter of A) leaf, B) stem, C) pod, and D) seed of snap bean over time as affected by four N fertilization rates in Gainesville FL during Spring 2007



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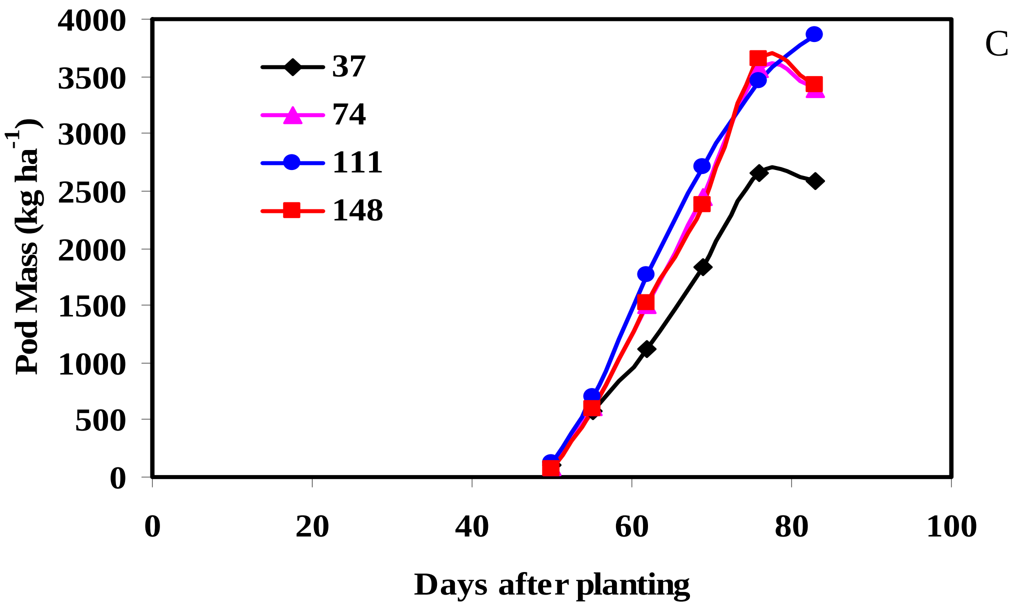

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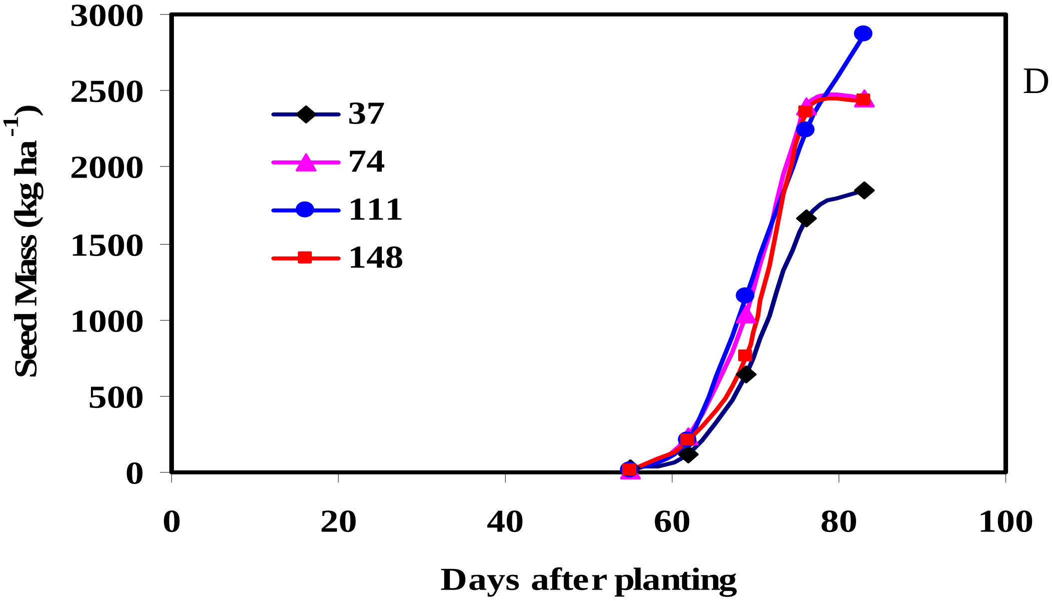

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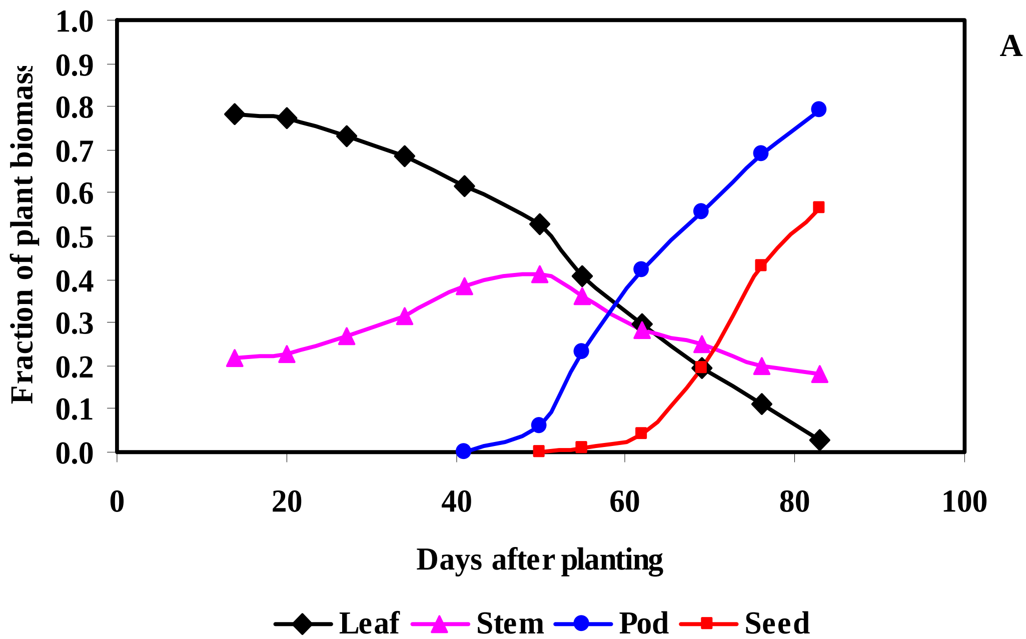
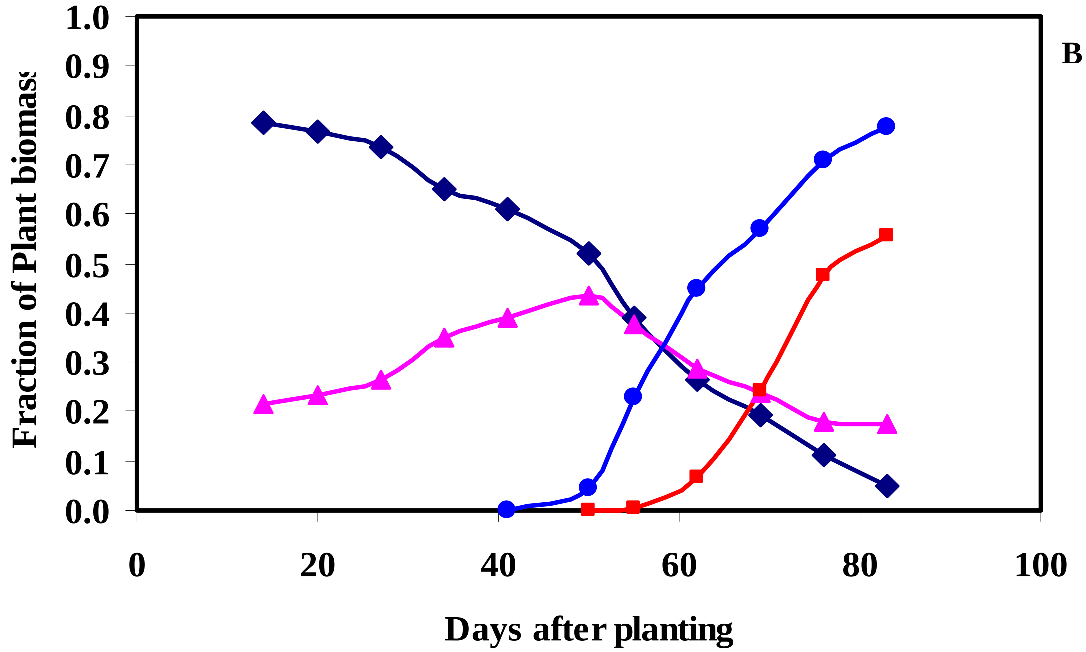


Figure 3-6. Percentage of total plant biomass found in leaf, stem, pod, and seed of snap bean over time as affected by A) 37 kg N ha^{-1}, B) 74 kg N ha^{-1}, C) 111 kg N ha^{-1} and D) 148 kg N ha^{-1}



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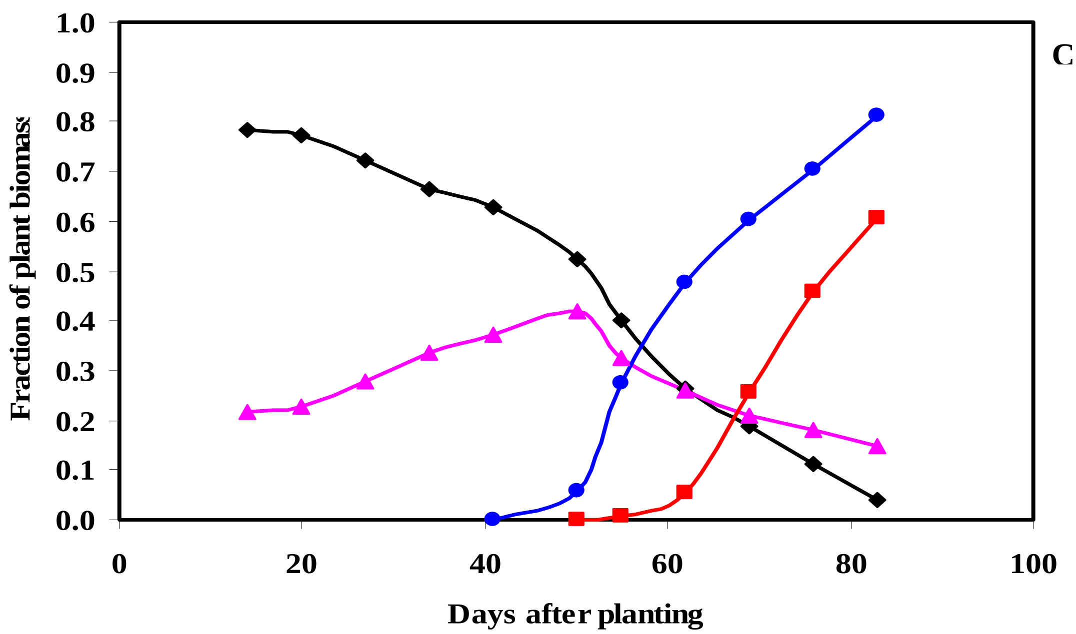

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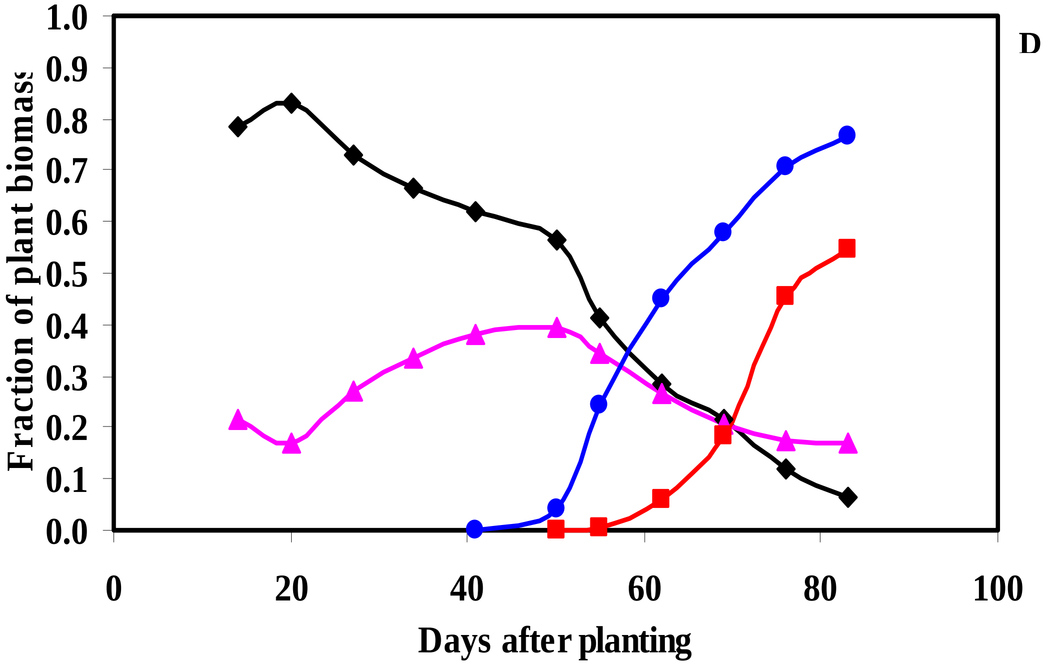

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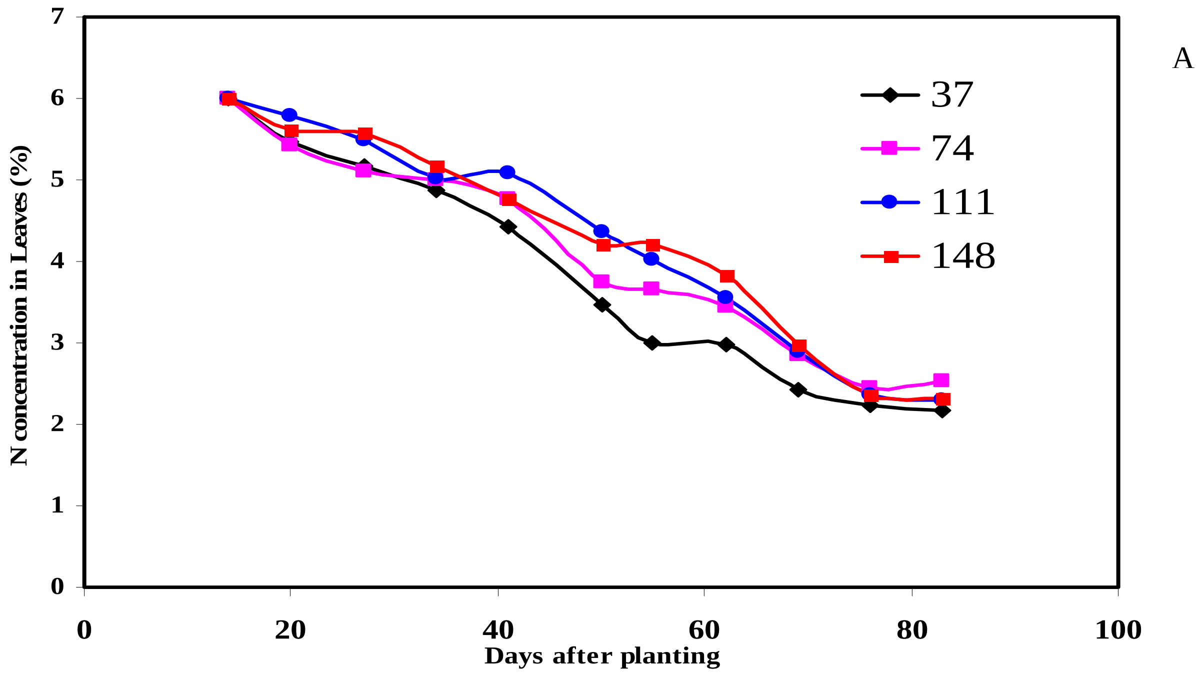
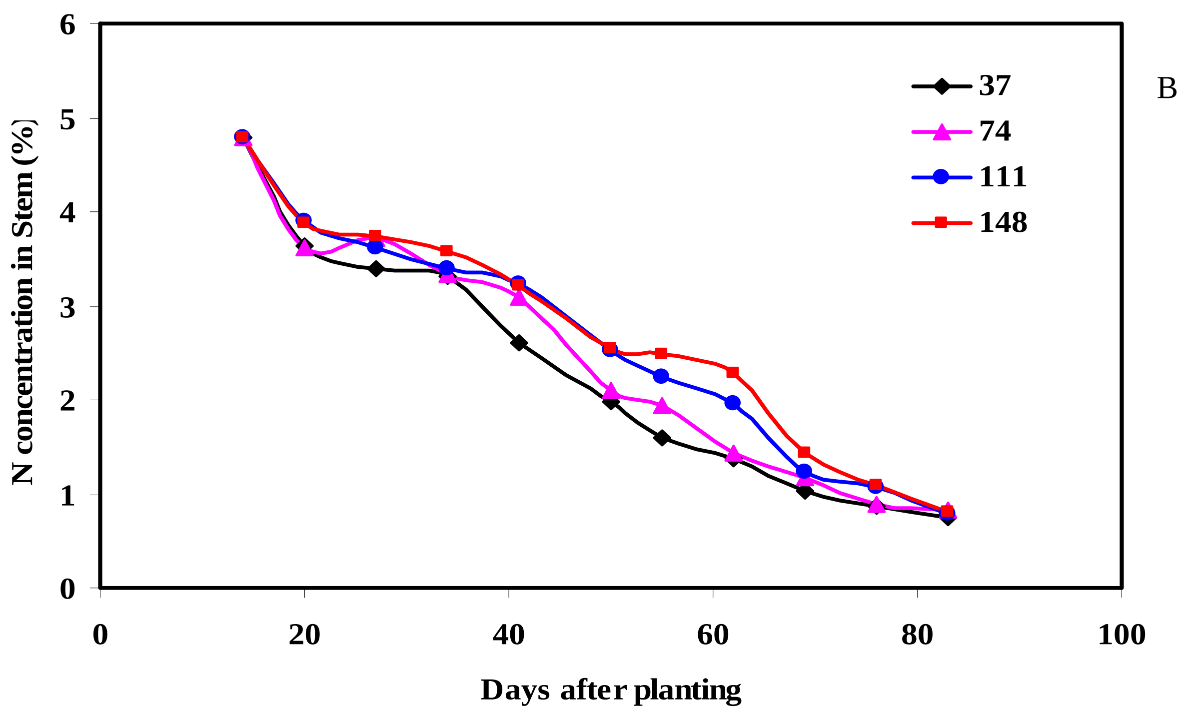


Figure 3-7. Effects of N-fertilizer rates on N concentration of A) leaf, B) stem, C) pod, and D) seed of snap bean grown in Gainesville FL in spring 2007



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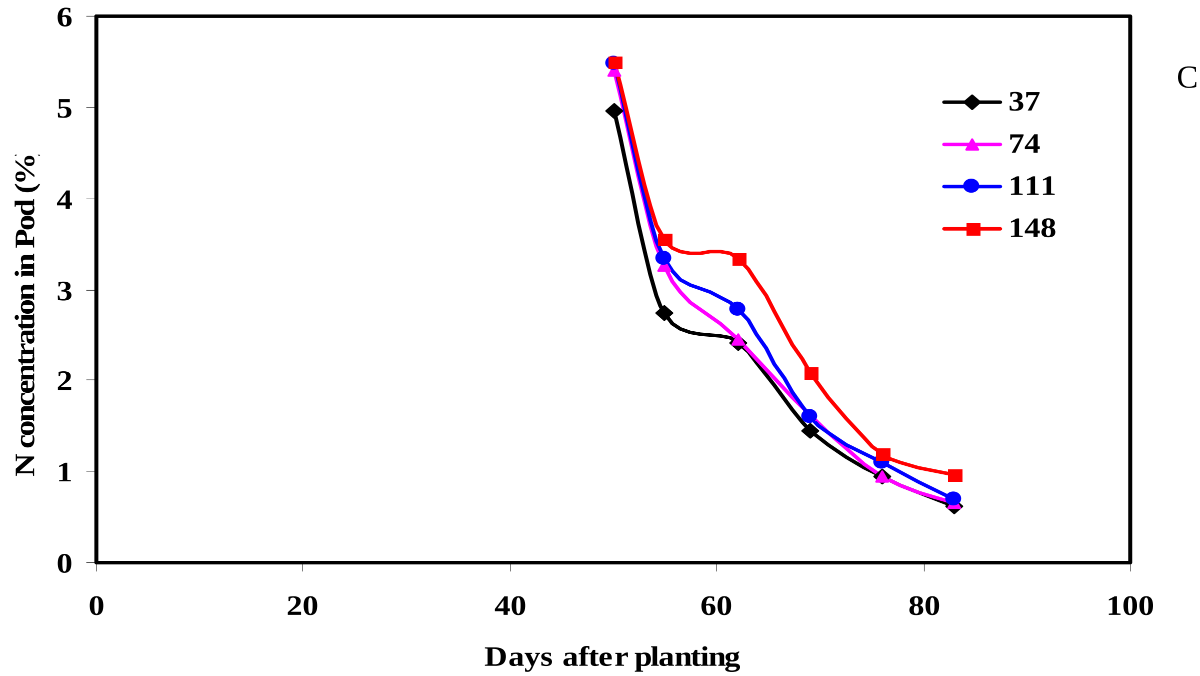

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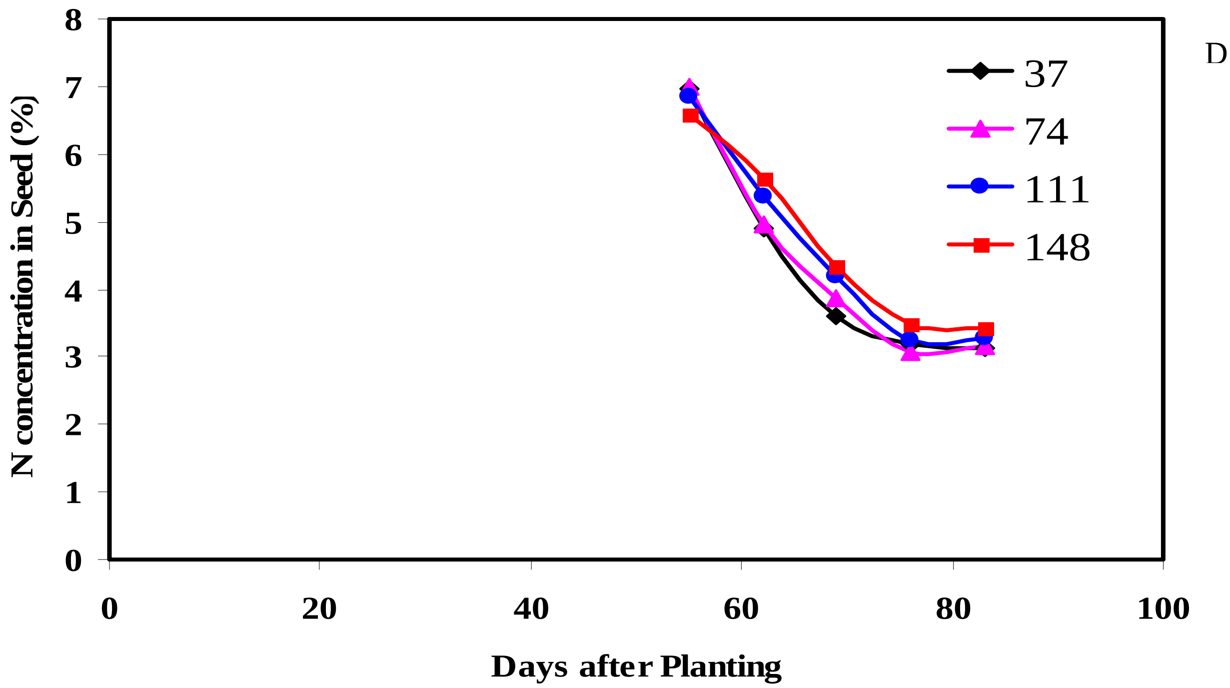

Figure 3-7. Continued

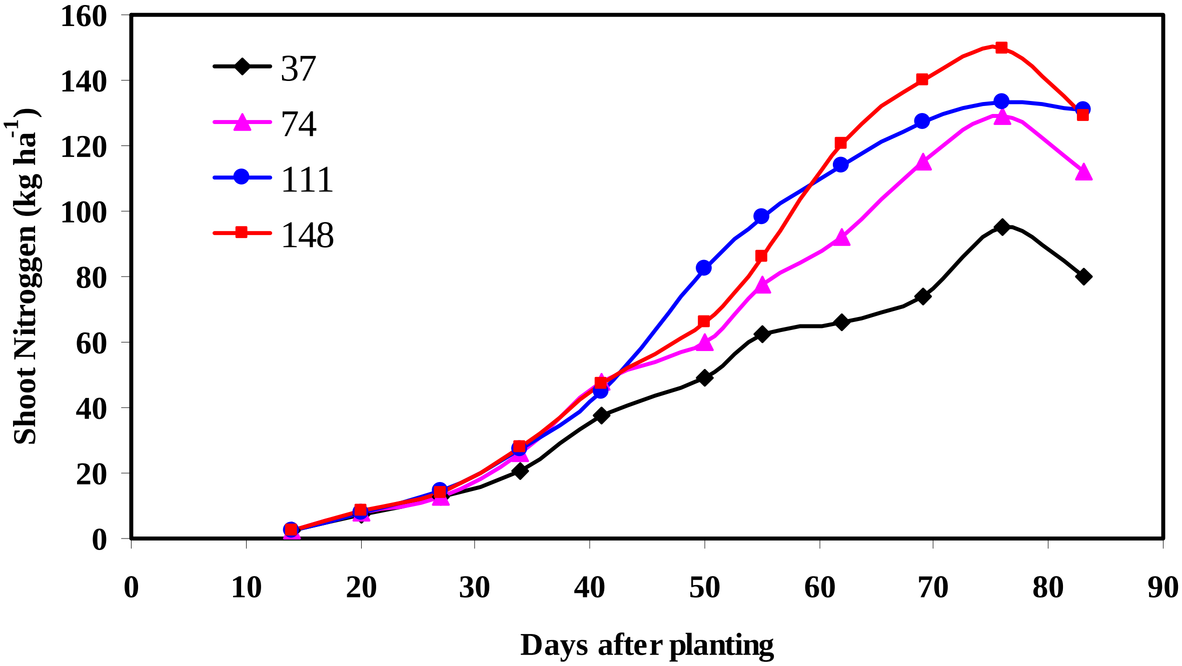

Figure 3-8. Shoot N of snap bean over time as affected by four N fertilization rates in Gainesville FL during Spring 2007

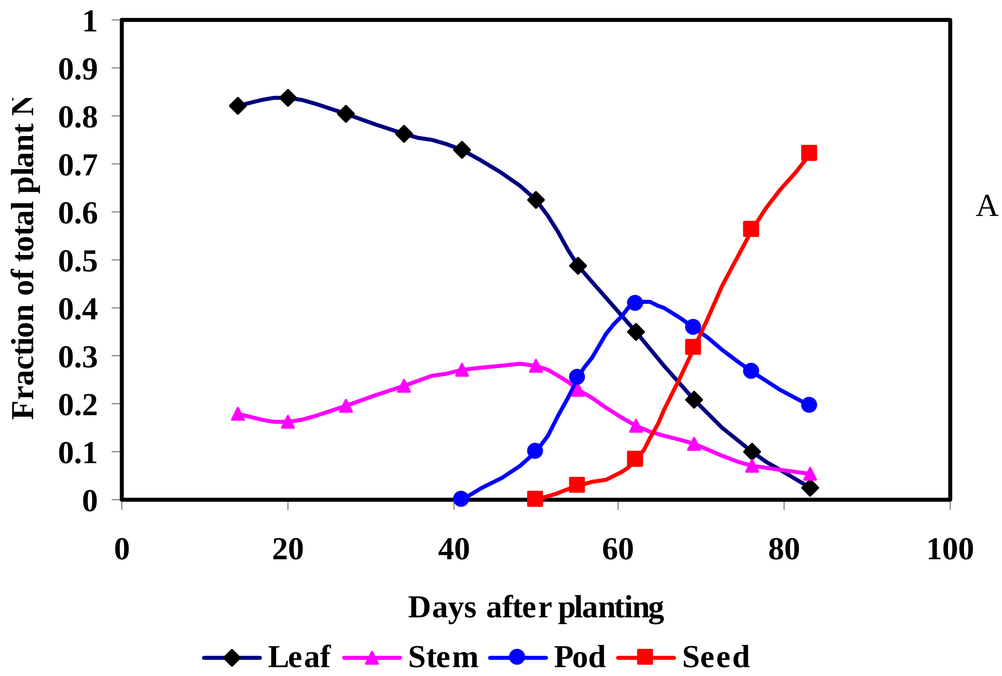

Figure 3-9. Effects of N-fertilizer rates on fraction of plant N found in plant components over time for: A) 37, B) 74, C) 111 and D) 148 kg ha^{-1} treatments of snap bean grown in Gainesville FL in spring 2007

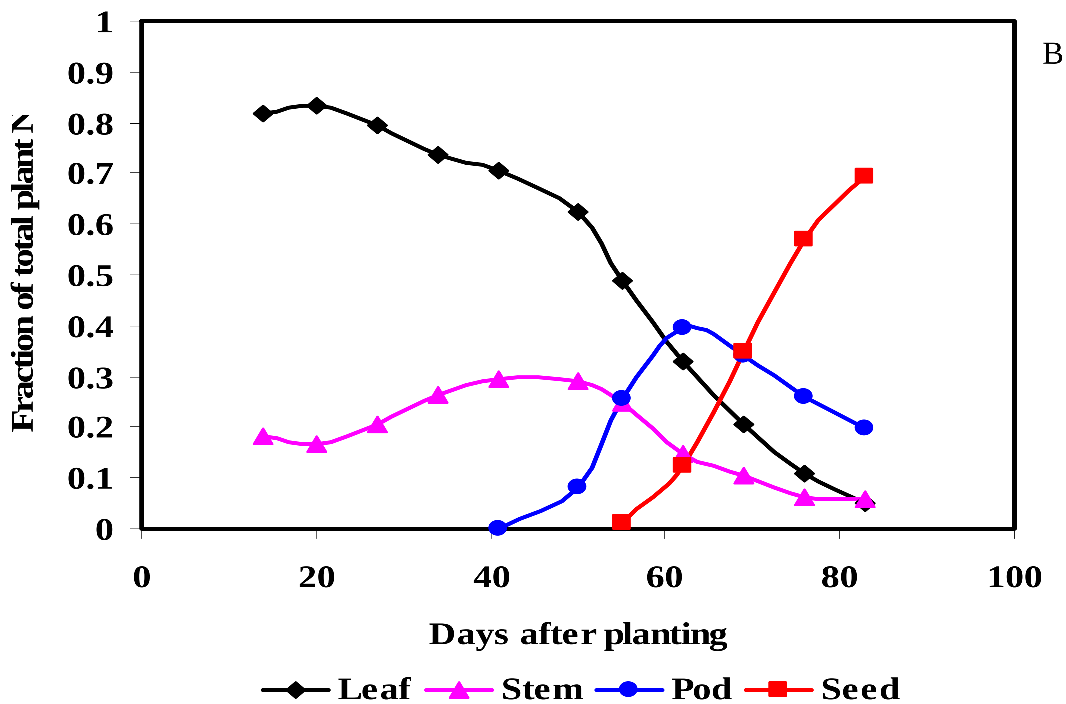

Figure 3-9. Continued

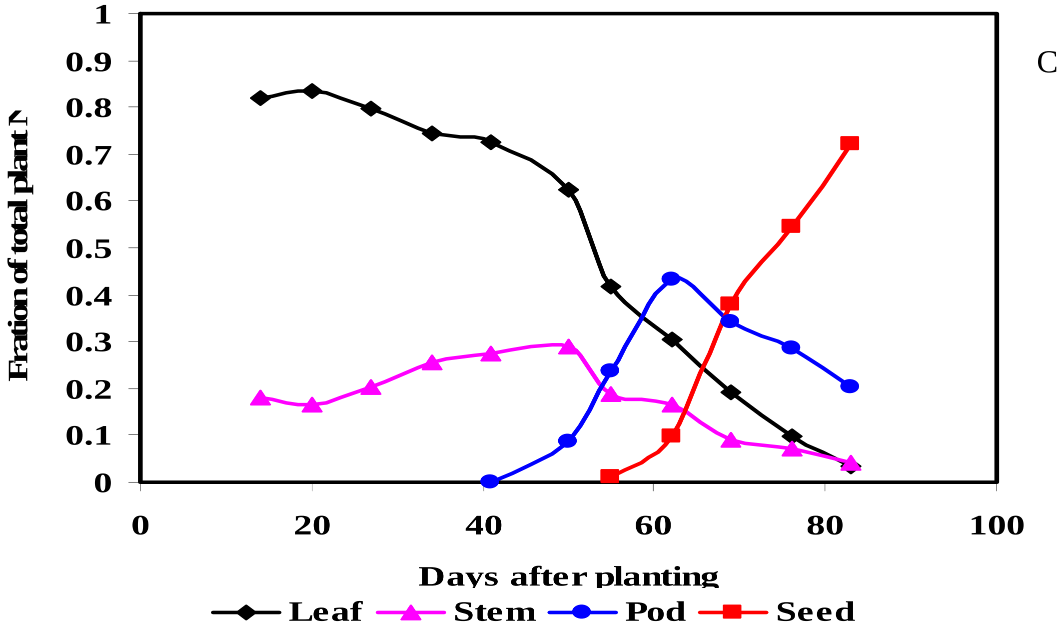

Figure 3-9. Continued

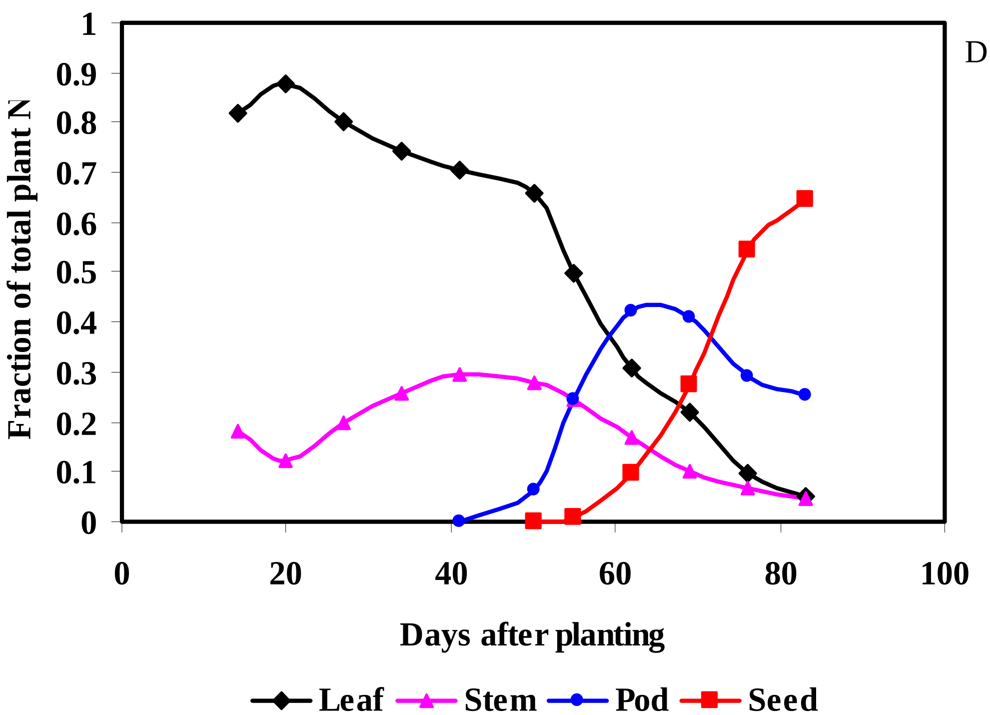

Figure 3-9. Continued

CHAPTER 4
RESPONSES OF SNAP BEAN TO INTERACTIVE EFFECTS OF IRRIGATION AND NITROGEN FERTILIZATION: YIELD, YIELD COMPONENTS AND QUALITY

Introduction

Yield is the integrated manifestation of various physiological processes occurring in plants and these processes influence the development of observed plant traits, which can be modified by imposed management practices (Gill and Narang, 1993). The management of water and fertilizers are among the management practices instrumental to crop performance and are vital to the high productivity of vegetable crops in the commercial production system. Achieving the correct rate of fertilizer application is an essential part of optimal fertilizer management. This however needs to be coupled with good irrigation practices as the application of fertilizer and water are interlinked. Indeed, a combination of optimal irrigation and N management is considered critical to improve crop N uptake efficiency, so as to maintain optimal crop yield, while minimizing NO_3^- leaching below the root zone (Quinones et al., 2007). Efficient use of water and fertilizers are thus highly critical for the sustainability of agriculture in increasingly competitive local and world markets, and in competition with urban environments for resources (Hebbar et al., 2004).

Several studies showed direct relationships between the addition of N in intensive agriculture and excessive soil N accumulation and losses to surface and ground water with potential long term environmental hazards (Paramasivam et al., 2001; Quinones et al., 2007; Zotarelli et al., 2007a). Like other vegetable crops in the commercial production system, snap bean production in Florida is intensively managed with relatively high inputs of fertilizers and irrigation water. Obtaining high fresh market snap bean yields in these production systems requires intensive sprinkler irrigation and fertilizer application. Zotarelli et al. (2007a) reported that excessive irrigation and/or N application rate combined with intense rainfall on excessively drained sandy soils with low water-holding capacity greatly enhances the potential risk of N leaching. Sustainability of these cropping systems requires developing management techniques that maintain or increase N and water use efficiency while sustaining environmental quality. Thus, this research was intended to: (i) determine the effects of interactions of irrigation amounts and N fertilization on snap bean fresh market yield, quality, N uptake, water use efficiency, nitrogen use efficiency, and (ii) evaluate the effect of irrigation regimes on the seasonal distribution of N in the soil profile.

Materials and Methods

Field Experiments

A detailed description of the field experiments (cultural practices and field treatments) is given in Chapter 3.

Final Yield Estimation

On 17 May (64 days after sowing), a sample area in the center of each sub-plot consisting of 2 rows of 2 m length was marked. First, canopy height and width was measured at two random sites in this area. Then, all plants within this harvest area were cut off at ground level and the number of plants recorded. A sub-sample of two median plants was taken and growth and development parameters (number of nodes, development stage, leaf area, and stem length) were recorded. Pods were picked from all plants. Pods were then sorted visually into the marketable pods (sieve sizes of 3 to 5) and unmarketable pods (culls made up with small pods less than 3 sieve size, plus damaged pods) and the fresh weight of each category was recorded. From the marketable pods, a sub-sample of 20 pods was taken and fresh weight of the 20 pods, and the sieve size, length, and diameter of each pod were recorded. Also, the total number of seed and the fresh weight of the seed from these 20 pods were recorded. Finally, the harvested plants (minus pods), marketable pods, unmarketable pods, and the podwall and the seeds of the 20-pod subsample were dried at 60^{o} C for at least 72 hours and their dry weights were recorded. From the two sub-sampled plants, the leaf and stem were dried and weighed. Leaf, stem, pod, and seed dry matter (DM) mass (kg DM ha^{-1}) were calculated from the combined sample and sub sample masses of leaf, stem, pod, and seed, respectively. Pod harvest index was calculated as pod to above ground biomass ratio on dry weight basis. Specific leaf area (SLA) (m^2 leaf kg^{-1} leaf) was calculated from the measured leaf area and leaf mass for the two sub-sample plants. Leaf area index (LAI) (m^2 leaf m^{-2} land) was then calculated by multiplying the SLA by the total leaf mass (g m^{-2}) from each sample.

Parameters such as size of seed, pod sieve size, pod length, pod diameter, number of seed, and average seed weight are important to appreciate the marketability of snap bean (Bonanno and Mack, 1983; Peck and MacDonald 1983). Interactive effects of irrigation and N rates were thus evaluated through computation of these parameters on the fresh market harvest date (64 days after sowing).

Plant Tissue Nitrogen Analyses

Oven-dried samples of component plant parts (leaf, stem, podwall, and seed) were ground in a Wiley mill to pass through a 2-mm screen. For nitrogen analysis, samples were digested using a modification of the aluminum block digestion procedure of Gallaher et al. (1975). Sample weight was 0.25 g, the catalyst used was 1.5 g of 9:1 K_2SO_4:$CuSO_4$, and digestion was conducted for at least 4 h at 375°C using 6 ml of H_2SO_4 and 2 ml H_2O_2. Nitrogen in the digestate was determined by semiautomated colorimetry (Hambleton, 1977).

Shoot N accumulation was computed by multiplying tissue weights of leaves, stem, pod and seed by the corresponding N concentrations.

Nitrogen in the Soil Profile

For monitoring N movement within the soil profile over time as affected by different irrigation regimes, soil cores (4cm diameter) were taken three times at 0.3 m depth increments to a depth of 1.20 m on the subplot treatment receiving the N rate of 111 kg ha^{-1} and refrigerated until further analysis. A 10-g sub sample was extracted with 100 mL of 1 M KCL and filtered by gravity with distilled water (Q8, Fisher Scientific Inc., Pittsburgh, PA). Soil core extracts were stored at -18^{o}C until they were analyzed for NO_3-N and NH_4-N using an air-segmented semi-automated colorimetric analysis (EPA Method 353.2) in the media extract with Technicon II Auto-Analyzer (Mylavarapu and Kennelley, 2002). Soil moisture was determined by drying a 30-g subsample at 105°C for 24 h in a forced-air oven. The soil bulk density was used to convert soil NO_3-N and NH_4-N to a mass-per-land-area basis.

Data Analysis

All the plant data were statistically analyzed as a split plot design with four replications using the General Linear Models program of SAS statistical software (SAS Institute Inc., 2000). Response variables tested included fresh marketable yield (Mg ha^{-1}), crop dry matter (DM) accumulation (kg ha^{-1}), crop N accumulation (kg N ha^{-1}), nitrogen use efficiency (NUE) (kg kg^{-1}), and water use efficiency (WUE) (kg ha^{-1} mm^{-1}). WUE was calculated as the ratio of the Fresh Marketable Yield (kg ha^{-1}) to the seasonal water use (effective amount of water applied in mm). Also, NUE was calculated as the ratio of fresh marketable yield to applied N. The main fixed effects used in the model were irrigation regime (I) and N-rate (N). Interaction effects included in the model were I*N-rate. Linear and quadratic trends of N and I treatments were also evaluated using orthogonal contrasts. Means among treatments were compared using Least Significant Difference (LSD) at $P \leq 0.05$ probability. Regression analyses between amounts of N applied and fresh marketable yield were performed.

Results and Discussion

Canopy Characteristics at Harvest Maturity

The canopy vegetative parameters of snap bean responded as expected to individual effects of irrigation levels and N rates and the interaction of these two factors (Table 4-1). The number of nodes formed on the main stem was approximately 7 at harvest maturity for all treatments, confirming that final node number on this very determinant snap bean is unresponsive (as expected) to the N-rates and irrigation levels in this study. Measured plant height and width were significantly responsive to the effects of irrigation regime. Plant height was not significantly responsive to the N rates but plant width was. The interactive effect of both irrigation levels and N rates was significant on the plant height response ($P < 0.05$) while plant width did not show any interaction. Further, the high irrigation treatments used in this study increased plant growth parameters such as the leaf area index (LAI). The increase in LAI would be expected to lead to a higher light interception and photosynthesis. Increasing irrigation rate would have increased water availability in the root zone resulting in improving plant water status and better stomatal conductance which eventually reflects in photo-assimilate production (Abdel-Mawgoud, 2006).

As can be seen in Table 4-1, response of leaf area index (LAI) showed no significant interactive effect of irrigation levels and N rates. Similar to plant height and width responses, only the lowest irrigation and N rates showed significant difference from the remaining higher treatments. The response of LAI to individual N or irrigation effects was linear.

Fresh Marketable Yield, Crop Biomass, and Pod Harvest Index at Harvest Maturity

Fresh marketable yield and shoot DM accumulation increased linearly with irrigation regimes and N-rates, while they showed a quadratic response to N rate (Table 4-2). Interactive effect of irrigation levels and N rates was significant on the fresh marketable yield ($P < 0.05$) while interaction effect on shoot DM was not significant. At the low irrigation regime (66% ET), fresh market yields were 8.5, 11.8, 15.7, and 10.6 Mg ha^{-1} for the 37, 74, 111, and 148 kg N ha^{-1} treatments, respectively. At the medium irrigation treatment (100% ET), yields were on the order of 10.1, 14.8, 17.5, and 17.1 Mg ha^{-1} and finally, at the high irrigation level (133% ET), they were 12.9, 16.3, 15.2 and 18.9 Mg ha^{-1}. Numerically, the incremental differences in fresh marketable yield among N rates for each irrigation regime were small at the low irrigation regime (3.3 versus 3.9 and 2.1 Mg ha^{-1} for N37 versus N74, N74 versus N111 and N37 versus N148, respectively) while they were larger at high irrigation regime (3.4 and 6 Mg ha^{-1} for N37 versus N74, and N37 versus N148, respectively). Results of fresh marketable yield to different N rates compared fairly well with yields reported by Hochmuth and Cordasco (2000) who found that marketable yields increased quadratically with average yield of 17 Mg ha^{-1} at N rates of 110 kg ha^{-1}. These authors also observed that there was no yield advantage from application of N in excess of recommended rates in experiments in north Florida. A similar conclusion was made by Dufault et al. (2000) who observed that snap bean fresh marketable yields were similar with 60 to 120 kg N ha^{-1}.

The higher irrigation (medium or high) enhanced the fresh market yield significantly compared to low irrigation levels (Table 4.2). These results illustrate the impact of irrigation regime on snap fresh market production and would suggest that irrigation is an important factor in snap bean production system and increased growth is expected with increased irrigation rate at recommended N application rates. This is in agreement with Abdel-Mawgood (2006) who quantified the interactive effects of irrigation level and compost application rate (as N source) on different plant growth parameters of snap bean. Additionally, in a sub-Saharan environment, Pandey et al. (2000) concluded that, generally, the greater the N supply, the more yield was reduced by deficit irrigation in maize production. High irrigation frequencies generally favored strong vegetative development and stimulated the generation of flowers and pods (Deproost *et al.,* 2004). Sezen et al. (2005) found that maximum fresh market yields (20,558 kg ha^{-1}) of snap bean were obtained from irrigation treatments consisting of 13-17 mm every 2 to 3 days with a crop pan coefficient (K_{cp}) of 1 as opposed to the treatments consisting of 58-62 mm every 10 to 12 days with a K_{cp} of 0.50 which yielded 12,243 kg ha^{-1}. This confirms again the positive effect of adequate soil water on N availability and the capacity that the plant has for a simultaneous uptake of water and N leading to their more effective use when both are at a satisfactory level (DiPaolo and Rinaldi, 2008). In this study, fresh marketable yield was increased 26% for High versus Low regime and only 6% for High versus Medium regime. As for the N rates, the response to N fertilizer level was less consistent. Fresh marketable yield increments were 35% for N111 versus N37 and only 4% for N148 versus N111.

Individual regression analysis for N rates at each irrigation regime was performed on the fresh marketable yield. Table 4-3 presents the quadratic model regression equations to N fertilization. Predicted N rates required to attain maximum yield under each irrigation regime condition were calculated and showed that across all three irrigation regimes, greater N rates were required to achieve the maximum yields, at successively higher irrigation regimes. Figure 4-1 shows the significant interaction of Irrigation x N on fresh market yield with a second order relationship, confirming that the soil water (irrigation regime) is the most fresh market yield limiting factor, followed by N effect. Values of Nmax could be used as a reference point for determining optimum N rate accounting for various production costs. With the coefficient of determination R^2 values of 0.52, 0.70 and 0.32 for Low, Medium and High irrigation regimes, respectively, it appeared that a relatively large fraction of the overall variability in yield could not be accounted for by N rates, most notably at high irrigation which showed the lowest coefficient of determination value.

While water and nitrogen availability had significant effects on fresh marketable yield and plant biomass, the response was not reflected on the pod harvest index which showed non-significant difference with respect to the individual effects of water and irrigation as well as the interaction. The observed harvest index for all treatments was within the range of 0.4 to 0.6 reported as typical by Fageria et al. (1997).

Yield Components and Pod Quality Parameters

Analysis of yield attributes in this study (number of pod and number of seed) showed that the pod number and seed number presented a linear response to the irrigation regimes while these variables both responded linearly and quadratically to the N rates. The interaction I*N-rate effect was not significant for these yield components (Table 4-4).

There were significant differences in pod diameter, pod length and number of seed per pod while other pod quality parameters such as percentage of seed weight per total pod weight on fresh weight basis and average weight per seed (mg) remained statistically unaffected by irrigation and N levels (Table 4-5). Pod quality parameters for fresh marketable yield such as pod diameter responded linearly to both irrigation and N rates while pod length and number of seed per pods were linearly responsive to the irrigation regimes and quadratically to the N rates. Overall, there was no interaction of irrigation and N rates on these pod quality parameters. Pod diameter decreased with increasing irrigation level while it increased with increasing N rates. Pod length increased with increasing irrigation regimes while it first increased with increasing N rate to the rate of 111 kg ha^{-1}, then it was reduced when N rate was further increased to 148 kg ha^{-1}. A similar trend was observed on the average number of seed per pod. Despite these small significant differences, it appeared from these results that pod quality parameters overall were not affected in a major way by irrigation and N effects. This is in line with Bonnano and Mack (1983) who concluded that pod quality in snap bean was less sensitive to water deficits than was pod yield. Findings of Sezen et al. (2005) suggested that higher Kcp coefficients with lower irrigation frequency (2 to 3 days interval) resulted in better quality green beans. The percentages of seed weight to the total pod weight on a fresh weight basis were in the range of 10 to 11%. This compared fairly well with Peck and MacDonald (1983) who indicated that unlike legumes harvested for seed, snap bean pods should have less than 10% seed in the pods on a fresh weight basis at optimum harvest time for processing for human consumption. Further analysis of the average weight per seed versus N rate revealed that increasing the N rate increased average weight per seed, but this may be a general statement of relative maturity, especially if seed growth and maturation is delayed by N deficit.

Quality in snap bean is defined in terms of sieve size. Sieve sizes, which are usually used as a primary measure of quality and therefore market price of snap bean pods, are actually based on the range of diameter of the pods. For this purpose, standard sieve size ranges were developed by USDA to grade snap bean fresh marketable quality. The U.S. standards for grades of fresh market snap bean separate pods into six main classes based mostly on pod diameter also called pod sieve size as follows: “Size 1” (diameter between 5.1 and 7.3 mm), “Size 2” (diameter between 7.3 and 8.3 mm), “Size 3 (diameter between 8.3 and 9.5 mm), “Size 4” (diameter between 9.5 and 10.7 mm) and “Size 5” (diameter greater than 10.7 mm). Of these five categories, “Size 3” and “Size 4” are considered appropriate for fresh market. Distributions of the pod sieve size at harvest are presented in Figures 4-2 A, B, and C. Analyses of these figures revealed that across all irrigation treatments, pods were between the sieve sizes 2 to 5 but the largest proportion of pods were in the sieve size 4 category. Regardless the N rate applied, relatively higher yield would then be expected as opposed to the case where most pods fall in the sieve size 3 for example because the bigger is the sieve size, the heavier is the pod. There was no difference among the four N rates with regards to pod sieve size distribution. At the low irrigation regime and the rate of 148 kg N ha^{-1}, 60% of pods were in sieve size 4. At the medium irrigation rate and the lowest N rate (N37), more than 60% of pods were in sieve size 4. Finally, at the highest irrigation regime with the optimum N rate of 111 kg N ha^{-1}, the sieve size 4 predominated. These results would indicate that that maturation was delayed under lower N (more categories 2 and 3, and less category 5 pods).

Total Nitrogen Accumulated and Analysis of Water and Nitrogen Use Efficiency for Snap Bean at Harvest

Nitrogen accumulated in the snap bean crop did not respond significantly to the individual effect of irrigation regimes but did respond linearly to N rate. Increasing N rates significantly increased the total N accumulated in the plants. The N-rate*Irrigation regime interaction effect was not significant for total N accumulated (Table 4-6). Apparent N recovery (ANR) is defined as the amount of N taken up by the crop in a given N treatment minus the amount taken up in the zero N treatment divided by the amount of N applied. If we consider the lowest N rate (N-37) as a zero N treatment, values of ANR averaged over all the irrigation levels were 30, 34 and 31% for 74, 111, 148 kg ha^{-1}, respectively. These values of fertilizer N recovery by snap bean could have been affected by such factors as various sources of N such as nitrogen fixation, mineralization of residues and soil organic matter and also initial soil ammonium and nitrate; irrigation, precipitation and even soil type.

The NUE values, expressed as kg of fresh marketable yield per kg of N applied, are also reported in Table 4-6. Analysis of these values revealed that the N use efficiency was linearly increased with irrigation, but linearly decreased with higher N rate. There was no interaction of these two factors on the efficiency of N use. In line with Peck and McDonald (1985), these results showed that NUE increased linearly with soil water availability and decreased with applied N. The NUE of the two higher irrigation regimes were similar, with 15% lower value at the low irrigation. On the contrary, the NUE of the first three N rates (N37, N74 and N111) were also similar, with a 19% lower NUE at the highest N rate.

There was a quadratic response of water use efficiency to the irrigation regimes and WUE responded both linearly and quadratically to the N rates. Water use efficiency was overall greater at higher N rates and under medium irrigation regimes. With the use of SDI (sub-drip irrigation) as irrigation technique, Gencoglan et al (2006) observed in the Mediterranean region that increasing applied irrigation water increased irrigation water use efficiency. On the other hand, Stansel and Smittle (1980) reported that in general, WUE values decreased with increasing irrigation interval and listed WUE value of 4-6 kg m^{-3} for green bean in Georgia, USA.

Seasonal Variations of Nitrate and Ammonium Contents in the Soil Profile

In this study, the effect of the three different irrigation regimes was assessed under the IFAS recommended N rate (N111 kg N ha^{-1}) on NO_3-N and NH_4-N distribution at different soil depths at various times during the snap bean growing season. It is of interest to note that the snap bean root system is a relatively shallow, well-branched lateral forming system with extensive fibrous roots (Rubatzky and Yamaguchi, 1997). Nitrate concentration in soil in the upper 60 cm of the soil profile was thus considered the potential N available for root uptake while NO_3-N concentration detected below 60 cm depth was an indication of potential NO_3-N leaching into groundwater. Contents of NO_3-N and NH_4-N in the soil profile at each soil sampling date (18, 49 and 87 days after preplant fertilization or 13, 44 and 82 days after sowing) are presented in Tables 4-7 and 4-8, respectively. Analyzing these values revealed that 18 days after the first fertilizer application, there was no effect of irrigation on soil NO_3-N and NH_4-N content at any soil depth but there was a significant depth effect on the amount of NO_3-N and NH_4-N. Irrespective of the irrigation regimes, higher values of NO_3-N and NH_4-N were observed in the rooting zone (0-60 cm) and were potentially available for plant uptake compared to below the rooting zone (60-120 cm) which could be susceptible to leaching. About 10 kg ha^{-1} of NO_3-N was observed in these deeper soil profile layers (60-120) in addition to about 27 kg ha^{-1} in that zone as NH_4-N. Nitrification is a microbial process by which reduced N compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate. Therefore, the bulk of the NH_4-N present in the profile is expected to undergo nitrification to result into NO_3-N which may be available for plant uptake or readily leach out from the soil profile. Indeed, results from different experiments suggest that approximately half of the applied ammonium has been reported to be converted to NO_3-N in sandy soils in Florida and Turkey (Sato and Morgan, 2007; Unlu et al., 1999). At 18 days after preplant fertilization, values of mineral N (NO_3-N + NH_4-N) below the root zone (60-120 cm), thus potentially leachable, were 37, 31 and 34 kg ha^{-1} for the Low, Medium and High irrigation regimes, respectively. At the same period, cumulative irrigation water and precipitation received by the crop were about 54 mm for all three irrigation regimes (Figure 4-4). The similar amounts of mineral N found in deeper soils layer at this stage may be explained in part by the relatively low amount of water applied in this period which did not induce any significant N leaching.

By 49 days after first fertilizer application (31 days after the second application), nitrate and ammonium in the soil profile followed a non-uniform distribution across the soil depths similar to the trend observed at the first soil sampling. It appeared that irrigation effect on nitrate in the soil profile was not significant but this effect was significant on NH_4-N content in the soil profile. Depth effects were significant for both nitrate and ammonium. However, there is more

NO_3-N available in the rooting zone of the soil profile (0-60 cm) compared to what was available at the first sampling while values of NH_4-N appeared to be relatively similar to the first sampling. The result would suggest that a proportion of the NH_4-N from applied fertilizer was nitrified into nitrate and the plant uptake rate would be expected to be higher during this period which coincided to the period of active growth and plant N uptake. From the second fertilizer application to the second soil sampling (31 days after fertilizer application), amounts of water (irrigation plus precipitations) applied to the plants were 73, 86 and 125 mm for Low, Medium and High irrigation regimes, respectively (Figure 4-4). Within the same period, amount of mineral N (NO_3-N + NH_4-N) below the root zone (60-120 cm) was 32, 50 and 31 kg ha^{-1} for the Low, Medium and High irrigation regimes, respectively. This movement of mineral N below the rooting zone shows that relatively more mineral N was observed below the rooting zone in the medium irrigation regime than in the high irrigation. This difference in mineral nitrogen may be due to the surplus in amount of water received in high irrigation which may have induced much of the N to leach into the deepest depth before soil samples were taken given the high mobility of nitrate in sandy soil.

Examining values of the downward movement of mineral N in the soil at the end of the growing season (82 days after sowing or 38 days after the last fertilizer application) revealed that there was a relatively large amount of NO_3-N and NH_4-N below the root-zone (60-120 cm) compared to within the root-zone (0-60 cm), irrespective of irrigation treatment. This would imply that potential nitrate and ammonium was leached below the snap bean root-zone (Figure 4-6). However, there was no significant difference in the amount of NO_3-N and NH_4-N remaining in the entire soil profile due to irrigation treatment implying that all irrigation treatments most likely had leached NO_3-N essentially equally. This confirmed our hypothesis and common assumption that as more water is applied, more N is expected to be leached out from the soil profile. Similarly, in a mass balance approach to model the annual N cycle under soybean, Gibson et al. (2007) found that average residual soil NO_3–N to a depth of 120 cm was in the range of 70 to 80 kg ha^{-1} after soybean grown at two locations in Iowa.

Although there was no significant difference between the residual nitrate and ammonium due to the irrigation regimes, an overview of the time course of the mineral N (NO_3-N + NH_4-N) across the soil profile presented in Figure 4-6, showed greater reductions in residual soil NO_3–N and NH_4-N in soil profile at the end of growing season for the highest irrigation regime (133% Et) as opposed to the two other irrigation regimes, indicating that increasing the irrigation rate enhanced N movement to soil layers below 120 cm. Therefore, management practices that increase downward water flux increases the risk of loss of NO_3-N below the crop root-zone.

Conclusion

This chapter examined how management of irrigation regimes and N rates influenced snap bean growth, fresh marketable yield production and quality, and movement of nitrate and ammonium in the soil profile. According to these results, fresh marketable yield of snap bean, crop biomass, and N uptake were all significantly increased with irrigation regime or N rates (each individual factor) but the interaction of both factors was only significant for the fresh marketable yield. Analyzing more closely this interaction revealed that at the low Irrigation regime, increasing N rates did not increase linearly the fresh marketable yield; there was no yield benefit with N-rates over 111 kg ha^{-1}. Additionally, application of N in excess of that recommended in medium irrigation regime did not significantly increase the fresh marketable yield. The result at medium irrigation regime showed that 74 kg N ha^{-1} was enough to provide statistically acceptable fresh marketable yield quantity close to the rate observed under the N rate of 148 kg N ha^{-1}.

Analyzing the temporal and spatial distribution of both nitrate and ammonium contents in the soil profile showed that nitrate and ammonium were higher in the deepest layers (90-120 cm) at the end of the season irrespective of irrigation regimes, implying that accumulation of these nutrients leading to possible leaching into ground water.

Results presented in this chapter may help improve irrigation and nitrogen management within whole farm level and also assist efforts towards development of Best Management Practices for snap bean in particular and Florida vegetable crops in general.

Table 4-1. Effects of irrigation and N fertilizer on canopy characteristics of snap bean grown in Gainesville during spring 2007 at 64 DAS.

Treatments	# Nodes	Height (cm)	Width (cm)	LAI
Irrigation				
Low	7.0 A	35.8 B	44.4 B	1.8 B
Medium	7.0 A	39.7 A	50.5 A	2.1 A
High	7.0 A	41.2 A	53.0 A	2.2 A
Significance	ns	L***	L***	L***
N Rates				
N-37	7.0 A	37.9 A	44.8 B	1.7 B
N-74	7.0 A	40.0 A	50.5 A	1.9 A
N-111	7.0 A	39.5 A	51.6 A	2.3 A
N-148	7.0 A	38.1 A	50.1 A	2.2 A
Significance	ns	Q*	L*** Q**	L***
''Water x N''	ns	*	ns	ns

NS,*,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively, and linear (L), quadratic (Q) for each effect (Irrigation regime and N-rate). Means followed by identical lower case letters in the same column are not significantly different according to Tukey's test (p<0.05), "a", "b", "c" denote higher to lower ranking. Irrigation treatment Low, Medium and High are 66%, 100% and 133% of crop evapotranspiration rates (ETc), respectively.

Table 4-2. Effects of irrigation and N fertilizer on fresh marketable yield, crop biomass and pod harvest index of snap bean grown in Gainesville during spring 2007 at 64 DAS.

Treatments	Fresh marketable yield ($Mg\ ha^{-1}$)	Total dry matter ($kg\ ha^{-1}$)	Pod harvest index
Irrigation			
Low	11.7 B	2.7 B	0.42 A
Medium	14.9 A	3.3 A	0.44 A
High	15.9 A	3.4 A	0.45 A
Significance	L***	L***	ns
N Rates			
N-37	10.5B	2.5 B	0.41 A
N-74	14.3A	3.2A	0.45 A
N-111	16.2 A	3.5A	0.45 A
N-148	15.6A	3.3A	0.45 A
Significance	L***Q**	L***Q**	ns
'Water x N"	*	ns	ns
Low x 37	8.5C		
Low x 74	11.8B		
Low x 111	15.7A		
Low x 148	10.6BC		
Med x 37	10.1B		
Med x 74	14.8A		
Med x 111	17.5A		
Med x 148	17.1A		
High x 37	12.9B		
High x 74	16.3AB		
High x 111	15.2AB		
High x 148	18.9A		

NS,*,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively, and linear (L), quadratic (Q) for each effect (Irrigation regime and N-rate). Means followed by identical lower case letters in the same column are not significantly different according to Tukey's test (p<0.05), "a", "b", "c" denote higher to lower ranking. Irrigation treatment Low, Medium and High are 66%, 100% and 133% of crop evapotranspiration rates (ETc), respectively.

Table 4-3. Quadratic model regression equations for snap bean fresh marketable yield response (y, Mg ha^{-1}) to fertilizer N rates (x, kg ha^{-1}) under different irrigation regimes in Gainesville in spring 2007.

Irrigation regime	N-response curve	*N*max	*Y*max	R^2
Low	$y = -1421.61 + 312.26x - 1.53x^2$	103	14.5	0.52
Medium	$y = 2380.89 + 241.39x - 0.95x^2$	120	16.78	0.70
High	$y = 12194 + 31.20x – 0.077x^2$	200	22.0	0.32

Table 4-4. Effects of irrigation and N fertilizer on yield components of snap bean grown in Gainesville during spring 2007 at 64 DAS.

Treatments	Pod Number	Seed Number
Irrigation		
Low	191 B	891 B
Medium	235 A	1226 A
High	248 A	1331 A
Significance	L***	L***
N Rates		
N-37	178 B	907 B
N-74	236 A	1222 A
N-111	249 A	1291 A
N-148	236 A	1176 A
Significance	L*** Q*	L*** Q***
"Water x N"	ns	ns

NS,*,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively, and linear (L), quadratic (Q) for each effect (Irrigation regime and N-rate). Means followed by identical lower case letters in the same column are not significantly different according to Tukey's test (p<0.05), "a", "b", "c" denote higher to lower ranking. Irrigation treatment Low, Medium and High are 66%, 100% and 133% of crop evapotranspiration rates (ETc), respectively.

Table 4-5. Effects of irrigation and N fertilizer on fresh market pod quality of snap bean grown in Gainesville during spring 2007.

Treatments	Pod Diameter (mm)	Pod Length (cm)	# Seed/Pod	% Seed Fwt/total Pod	Avg Fwt/seed (mg)
Irrigation					
Low	9.2 A	13.8 B	4.9 B	10.9 A	131.5 A
Medium	9.1 AB	14.5 A	5.5 A	10.7 A	119.7 A
High	8.9 B	14.7 A	5.7 A	11.1 A	119.9 A
Significance	L*	L***	L***	ns	ns
N Rates					
N-37	8.9 B	14.1 B	5.3 A	10.5 A	115.3 A
N-74	9.0 AB	14.3 AB	5.5 A	10.8 A	118.8 A
N-111	9.1 AB	14.7 A	5.6 A	11.2 A	127.7 A
N-148	9.3 A	14.3 AB	5.2 B	11.1 A	133.1 A
Significance	L*	Q*	Q*	ns	**
"Water x N"	ns	ns	ns	ns	ns

NS,*,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively, and linear (L), quadratic (Q) for each effect (Irrigation regime and N-rate). Means followed by identical lower case letters in the same column are not significantly different according to Tukey’s test (p<0.05), “a”, “b”, “c” denote higher to lower ranking. Irrigation treatment Low, Medium and High are 66%, 100% and 133% of crop evapotranspiration rates (ETc), respectively.

Table 4-6. Effects of irrigation and N fertilizer on total crop N uptake, pod WUE and pod NUE of snap bean grown in Gainesville during spring 2007

Treatments	Accumulated N (kg ha^{-1})	Pod WUE (kg ha^{-1} mm^{-1})	Pod NUE (kg kg^{-1})
Irrigation			
Low	81.5 A	46.4 B	147.1 B
Medium	88.4 A	52.7 A	173.7 A
High	92.8 A	43.8 B	173.5 A
Significance	ns	Q**	L**
N Rates			
N-37	60.8 C	35.1 C	173.1 A
N-74	82.9 B	48.2 B	177.7 A
N-111	98.8 A	55.5 A	164.9 A
N-148	107.7 A	51.8 AB	143.4 B
Significance	L***	L***Q**	L**
'Water x N"	ns	*	ns

NS,*,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively, and linear (L), quadratic (Q) for each effect (Irrigation regime and N-rate). Means followed by identical lower case letters in the same column are not significantly different according to Tukey’s test (p<0.05), “a”, “b”, “c” denote higher to lower ranking. Irrigation treatment Low, Medium and High are 66%, 100% and 133% of crop evapotranspiration rates (ETc), respectively.

Table 4-7. Irrigation effects on nitrate movement in the soil profile for snap bean grown in Gainesville during spring 2007

Treatments	Days after First Fertilization		
	18	49	87
	N-NO_3 (kg ha^{-1})		
Irrigation			
Low	15.6 AB	24.5 A	15.6 A
Medium	17.1 A	21.9 A	10.8 A
Over	11.7 B	23.8 A	8.0 A
Depth (cm)			
0-30	34.7 A	57.0 A	11.6 A
30-60	13.5 B	24.4 B	3.5 B
60-90	6.3C	7.7 C	9.4 B
90-120	4.6 C	4.4 C	21.4 A
Irrigation (I)	ns	ns	ns
Depth (D)	***	***	***
I x D	ns	**	ns

NS,**,*** Non-significant or significant at the p<0.05, 0.01, 0.001 level, respectively. Means within columns followed by the same lowercase letters are not significantly different (p < 0.05) according to Least Significant Difference test.

Table 4-8. Irrigation effects on ammonium presence in the soil profile for snap bean grown in Gainesville during spring 2007

Treatments	Days after First Fertilization		
	18	49	87
	N-NH_4 (kg ha^{-1})		
Irrigation			
Low	19.5 A	12.9 B	28.5 A
Medium	17.3 A	19.8 A	25.5 A
Over	17.6 A	13.9 B	19.1 A
Depth (cm)			
0-30	27.5 A	24.5 A	24.7 A
30-60	18.1 B	11.8 B	18.6 A
60-90	13.9 B	13.2 B	19.9 A
90-120	13.1 B	12.6 B	34.2 A
Irrigation (I)	ns	*	ns
Depth (D)	***	***	ns
I x D	ns	ns	ns

NS,*,*** Non-significant or significant at the p<0.05, 0.001 level, respectively. Means within columns followed by the same lowercase letters are not significantly different (p < 0.05) according to Least Significant Difference test.

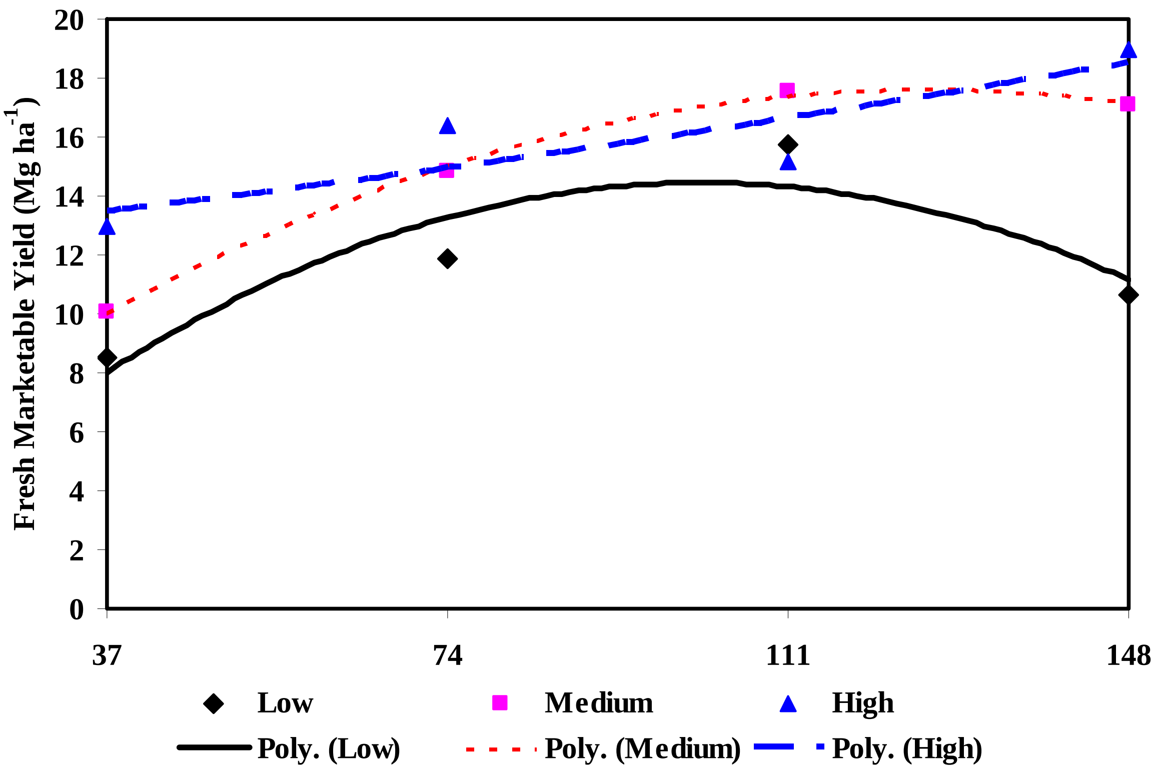

Figure 4-1. Response (quadratic polynomial) for fresh marketable yield of snap bean as affected by N rate under different irrigation regimes in Gainesville FL during spring 2007

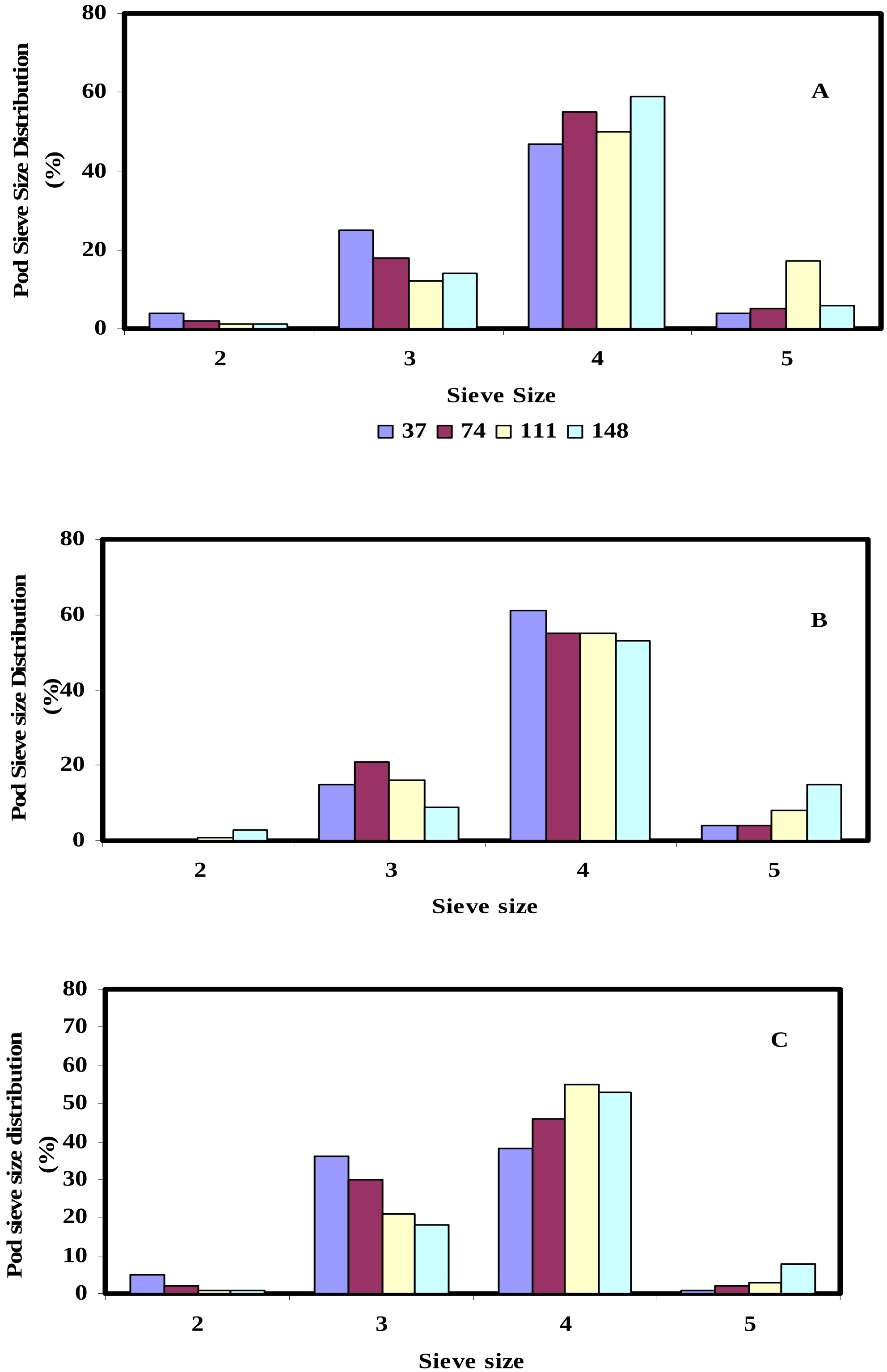

Figure 4-2. Distribution of sieve size of snap bean at harvest as affected by four N rates in A) Low, B) Medium and C) High irrigation regimes in Gainesville during spring 2007

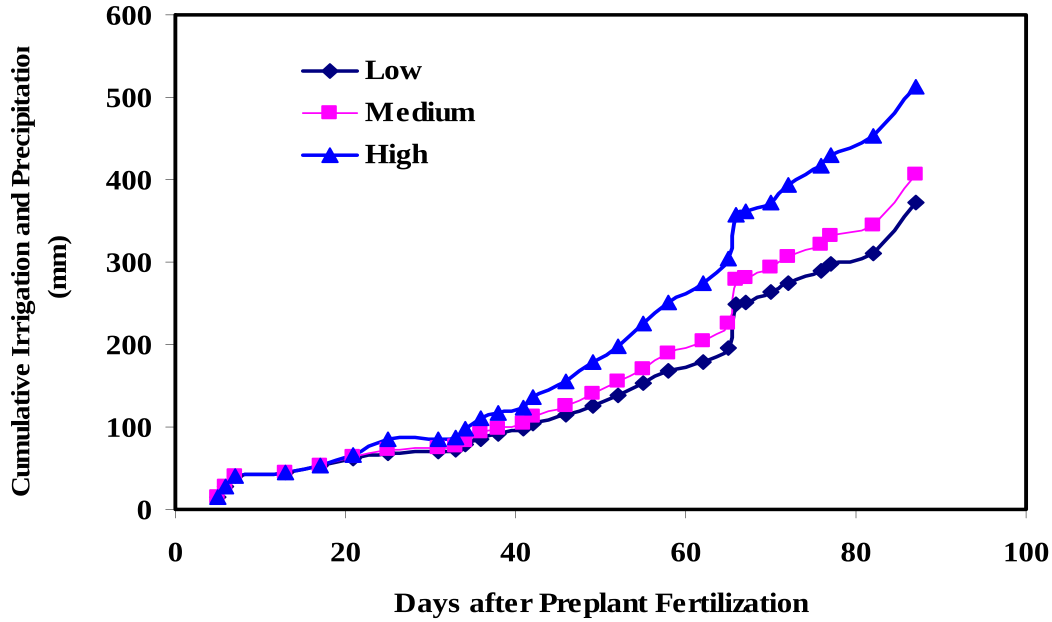

Figure 4-3. Cumulative irrigation and precipitation during the growing season of snap bean in Gainesville in spring 2007

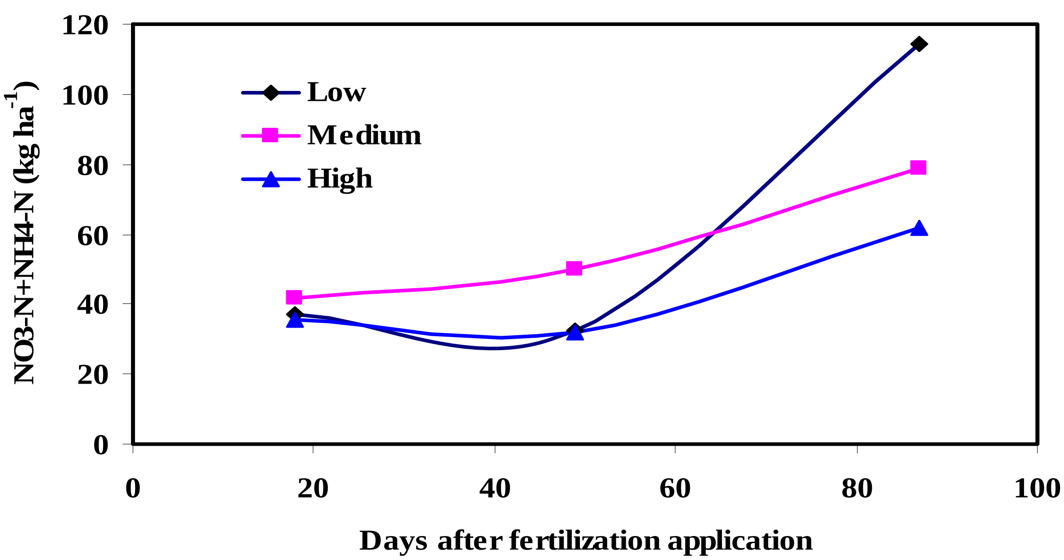

Figure 4-4. Movement of mineral N (NO3-N + NH4-N) below the root zone (in 60-120 cm depth) over time as affected by irrigation regimes on snap bean grown in Gainesville in spring 2007

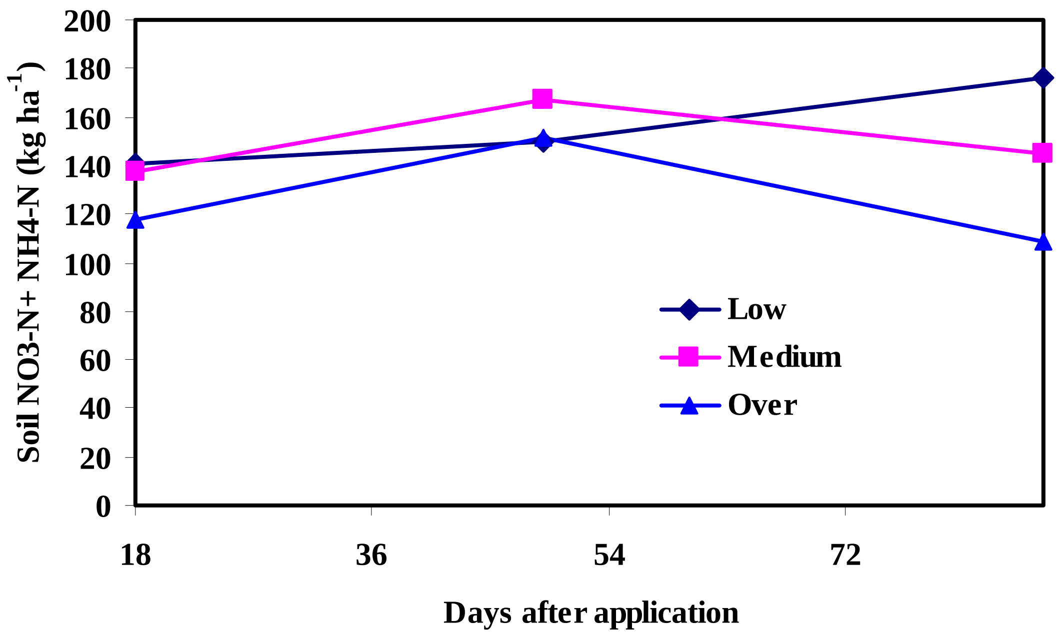

Figure 4-5. Cumulative mineral N (NO_3-N + NH_4-N) in the soil profile (0-120 cm) over time as affected by irrigation regimes on snap bean grown in Gainesville in spring 2007

CHAPTER 5
ADAPTING THE CROPGRO-DRY BEAN MODEL TO SIMULATE THE GROWTH AND DEVELOPMENT OF SNAP BEAN (*PHASEOLUS VULGARIS* L)

Introduction

Crop simulation models are mathematical representations of plant growth processes as influenced by interactions among genotype, environment, and crop management (Yang et al., 2004). A wide array of crop simulation models are increasingly used to assess crop performance in various environments and management strategies, and to assist decision-making processes such as crop timing, irrigation, fertilization, crop protection, and to facilitate optimization of the crop and its management strategies.

The CROPGRO model (Hoogenboom et al., 1994; Boote et al., 1998ab), embedded in the Decision Support System for Agrotechnology Transfer Cropping System Model (DSSAT-CSM), is a process-oriented, dynamic, and generic crop simulation model. It is designed to simulate the effects of weather, soils, and agronomic management (including planting, nitrogen, residues and irrigation) on daily crop growth and development, carbon balance, crop and soil N balance, and soil water balance. Its generic, process-oriented design has allowed it to be adapted to model a variety of different species including tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997), faba bean (*Vicia faba* L.) (Boote et *al.,* 2002), velvet bean (*Mucuna pruriens)* (Hartkamp et *al*., 2002), (chickpea (*Cicer arietinum* L.) (Singh and Vermani, 1994), and bahiagrass (*Paspalum notatum)* (Rymph, 2004). This versatility is achieved through three input files that define species traits, ecotypes and cultivars, along with code improvement in the basic model (Boote et al., 2002). The species file contains information on base temperatures (Tb) and optimum temperatures (Topt) for developmental processes (rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity) and growth processes (photosynthesis, nodule growth, N_2-fixation, leaf expansion, pod addition, seed growth, N mobilization, etc.). These parameters are set during model development and are not generally changed by the user. The ecotype file contains information that describes broad groups of cultivars, such as determinate vs. indeterminate growth habit groups. Cultivar differences are represented in a file containing 15 coefficients (Boote et al., 2003; Hartkamp et al., 2002) that allows users to specify how cultivars differ in life cycle progression, daylength sensitivity, canopy and fruit growth characteristics.

Knowledge of bean genetics suggests that snap beans were derived from dry beans because more genetic changes would be required to derive snap beans from the wild bean than from dry beans (Myers and Baggett, 1999). Moreover, growth habit and plant architecture in snap bean fall into a range similar to that found in dry beans. Most cultivars, especially for fresh market and processing, have determinate bush (type I) growth habit (Fernandez et al., 1986). It could thus be hypothesized that the CROPGRO-Dry bean model is a good starting point for the development of a snap bean growth and development simulation model.

Consequently, the objective of this chapter was to adapt the CROPGRO-Dry bean model to simulate the growth and development of snap bean.

Materials and Methods

Snap Bean Field Experiments

The adjustment of the parameters in mechanistic crop models requires measured data. In this study, the experimental data used for calibration of the CROPGRO Dry bean model were collected from field experiments presented in Chapter 3. In order to assure relatively good precision in the parameters calibrated, field data used in the species, ecotype, and cultivar calibration procedure should generally be collected under optimal water and nitrogen supply and in absence of pests and diseases. Thus, we calibrated the species, ecotype, and cultivar parameters, with growth analysis data collected from the Medium (100 % crop ET) irrigation regime and High nitrogen rate (N-148 kg N ha^{-1}) treatment. Subsequently, in order to enable the model to respond accurately to various nitrogen fertilization rates, field data collected from the two lower nitrogen treatment (37 and 74 kg N ha^{-1}) were used to calibrate parameters (soil-related, as well as some plant-related N balance parameters) which influenced nitrogen uptake.

Model Calibration

Soil profile properties calibration

The CROPGRO simulation model uses a soil file which describes the soil profile properties and is created based on measured values or information gathered in the literature. The soil in our experimental site is classified as a Millhopper fine sand, a member of the loamy, hyperthermic family of Grossarenic Paleudults. Carstille et *al.* (1981) presented some soil physical characteristics such as soil texture (fractions of the clay, silt, and sand) which influence the soil water balance traits and soil water holding capacity. The soil file in CROPGRO-DSSAT also lists information of each layer which includes the drained upper limit (DUL) or field capacity, the lower limit (LL) or permanent wilting point, and the saturated soil water content (SAT). Default values of these parameters were available for Millhopper sand soil in the SOIL.SOL file in DSSAT and were used during this calibration process. Also, in our calibration procedure of soil parameter values, we varied the soil organic matter fractions (SOM1, SOM2 and SOM3) to minimize the Root Mean Square Error (RMSE) of the plant nitrogen uptake for the two low N treatments (37 and 74 kg N ha^{-1}). Based on the RMSE-plant N uptake, we selected the appropriate values of the soil organic matter fractions which were then used in the overall model calibration procedure. In the soil layer (0-30 cm), the default initial ratio of soil organic matter fractions (SOM1:SOM2:SOM3) were adjusted from 0.02:0.54:0.44 to 0.01:0.70:0.29, respectively, and in the soil layer (30-150 cm), these values were set from 0.02, 0.64, and 0.34 to 0.01, 0.60, and 0.39, respectively (Table 5-1). It is of interest to note that the soil organic matter is a changeable nutrient reservoir that may function both as source and sink for N through the competing effects of mineralization and immobilization (Boone, 1990).

Additionally, the CROPGRO model in the DSSAT requires information on the initial status of mineral N in the soil profile before planting. Measurements were not made to evaluate initial soil nitrate and ammonium values in our field before planting. Therefore, these initial values were set from data found in the technical report produced by Graetz (2007) on a study of similar soils conducted at the North Florida REC. Table 5-1 presents profile characteristics of a Millhopper fine sand, (hyperthermic family of Grossarenic Paleudults) used during our calibration process, which includes these initial soil nitrate and ammonium values for respective layers.

It should be noted that the model was run with symbiotic nitrogen fixation routines turned off given that snap bean has poor N fixation capability and no rhizobium treatment was provided in this experiment, and the soil was not known to have bean rhizobium applied previously.

Furthermore, the CROPGRO model requires weather data as inputs. The weather file contains daily maximum and minimum air temperature, solar radiation collected from the Florida Automatic Weather Network (FAWN) web page from Citra site. Data on precipitation were based on a rain gauge placed in the field experiment.

Approach for genetic coefficients calibration

The CROPGRO dry bean model requires genetic coefficients that describe durations of phases of the crop life cycle, vegetative growth traits, and reproductive traits unique to a given cultivar. The calibration of the CROPGRO-dry bean model to accurately simulate snap bean growth was carried out using the systematic approach described by Boote (1999) and led to the development of the required cultivar and ecotype files. In essence, this approach starts off with the life cycle by adjusting the appropriate genetic coefficients in the cultivar file in order to match the date of flowering, and the date of physiological maturity (first mature pod stage). Indeed, variation in life cycle and duration of different phases are among the most important genetic variations contributing to yield potential of different cultivars (Boote et al. 2003). Then, the dry matter accumulation (biomass and leaf area index) was adjusted and finally yield and the yield components parameters were calibrated. The generic "Andean Habit" cultivar with generic "Andean" ecotype present in the CROPGRO-dry bean model version 4.5 was used as our initial starting point to define the appropriate cultivar and ecotype files for our snap bean cultivar Ambra. It was anticipated that the species file would not require much modification in this adaptation process because dry bean and snap bean are both in the same species *Phaseolus vulgaris* and therefore developmental processes in relation to cardinal temperatures and growth processes (photosynthesis, nodule growth, N_2 fixation, pod addition, and seed growth, etc.), which characterize the species files, would fundamentally not change. However, some parameters in the species files which define the relative carbon and nitrogen mobilization rates of vegetative tissues (CMOBMX, NMOBMX, NVSMOB) were modified to minimize computed N stress, and the rate of N uptake per unit root length (RTNO3 and RTNH4) were modified to optimize N uptake for the two low N fertilization treatments. Coefficients CMOBMX, NMOBMX, NVSMOB were increased from 0.03, 0.10 and 0.36 to 0.07, 0.16 and 0.70, respectively. Additionally, $RTNO_3$ and $RTNH_4$ were set from their initial default values 0.006, and 0.006 to 0.015 and 0.015, respectively. Values of these parameters are presented in Table 5-

2. In addition, as the CO_2 level is no longer at 330 ppm CO_2 value used for the default model; the CO_2 level was increased from 330 to 383 ppm which is the current CO_2 level.

Crop life cycle

Photothermal day (PD) threshold values were adjusted to accurately predict crop life cycle, anthesis and maturity dates, each in sequence. First the EM-FL parameter (photothermal days between plant emergence and flower appearance) was adjusted until the simulated date of flowering matched the observed date. Then, the SD-PM (photothermal days between first seed and physiological maturity) was adjusted until the simulated date of maturity was correct. Calibration of phenology was conducted by minimizing the error between observed and simulated flowering and maturity dates.

Dry matter accumulation and LAI

Genetic coefficients calibrated in order to minimize the error between observed and simulated dry matter accumulation and LAI included specific leaf area (SLAVR), time to cessation of leaf area expansion (FL-LF), light-saturated leaf photosynthesis (LFMAX) and the specific leaf weight at which standard leaf photosynthesis is defined (SLWREF in species file). More specifically, SLWREF was increased from 0.030 to 0.033 g cm^{-2} and LFMAX was reduced from 1 to 0.95 mg CO_2 m^{-2} s^{-1} in order to compensate for the increase in the CO_2 level from 330 to 383 ppm, and/or because snap bean is somewhat less productive than the previously modeled dry bean cultivars. In addition, the timing of pod formation and seed formation influence LAI, but those traits are listed below.

Yield and yield components

The seed size, seeds per pod, and single-seed growth duration (SFDUR) were adjusted to reproduce observed seed size and seed growth duration. The threshing percentage (THRESH) was not changed. Parameters accounted for in this step included WTPSD (maximum weight per seed), SDPDV (average seeds per pod), SFDUR (seed filling duration for pod cohort), PODUR (duration of pod addition), time to onset of pod addition (FL-SH), and time to onset of seed growth (FL-SD). The latter three (PODUR, FL-SH, and FL-SD) also influence onset of pod and seed growth. There was iteration between this procedure and the prior procedures relative to dry matter accumulation.

Two statistical indices were used to compare observed and model-simulated values: the Root Mean Square Error (RMSE) and the Willmott's index of agreement (*d*). The RMSE was calculated as:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (S_i - O_i)^2 \right]^{0.5} \qquad (5\text{-}1)$$

where S_i and O_i are a corresponding pair of simulated and observed values, respectively, and n is the number of observations included in the evaluation. The parameter *d* or Willmott's index was calculated as:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (|S'_i| + |O'_i|)^2} \right] \qquad (5\text{-}2)$$

where $S'_i = S_i - \overline{O}$ and $O'_i = O_i = \overline{O}$. Parameter *d* lies within the range 0 to 1 with higher values indicating more accurate simulations.

Results and Discussion

Predictions with Unmodified Model Parameters

The model was run with the default genetic coefficient values (generic “Andean Habit” cultivar with generic “Andean” ecotype and default V4.0 species traits) and initial soil profiles and the outcomes were compared with data collected on the N treatment of 148 kg ha^{-1}. The default version slightly over-predicted the anthesis date (43 versus 41) and the physiological maturity date (82 versus 76). Figure 5-1 presents the default model performance in simulating the time course of leaf area index. The default model slightly over-predicted the leaf area index during the exponential phase, but the over-prediction was more pronounced during later stages, when the maximum leaf area index value was reached, caused in part because reproductive onset and maturity were predicted to occur too late. These high simulated values of LAI were resolved in the calibrated model, by the simulated earlier onset of reproductive growth, as well as by reducing the coefficient SLAVAR as shown in Table 5-2. For LAI, the Root Mean Square Error (RMSE) values of the default model were 0.82, 0.54, 0.74 and 0.53 m^2 m^{-2} and the d-statistic was 0.79, 0.91, 0.93 and 0.91, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1} indicating relatively poor prediction of LAI especially at the lowest N rate.

On the contrary, the default model showed relatively good ability in predicting the accumulation of shoot dry matter over time. Indeed, Figure 5-2 reveals that the simulation had good agreement with observed shoot biomass irrespective of N rates until about 60 DAS, and thereafter, the model consistently over-predicted the shoot dry matter accumulation, more so at the lowest N rate. The Root Mean Square Error (RMSE) values of the default model were 1000, 652, 532 and 563 kg $ha^{-1}$and the d-statistic was 0.91, 0.97, 0.98 and 0.98, respectively, for the N rates of 37, 74, 111, and 148 kg ha^{-1}. The RMSE values were increased at decreasing N rates, implying that the model performed relatively poorly at low N rate. Additionally, simulation of the time course of pod dry weight grown under four different N rates is illustrated on Figure 5-3. In general, the model consistently under-predicted the time-course of pod dry weights irrespective of N rates, in part because of incorrect phenological timing, and partly because of inadequate pod growth at lower N rates. The Root Mean Square Error (RMSE) values of the default model were 728, 957, 907 and 708 kg ha^{-1}and the d-statistic was 0.83, 0.83, 0.87 and 0.92, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. Seasonal patterns of simulated and observed total plant N accumulated with the default model under the different N rates are shown in the Figure 5-4. The simulated N accumulation closely matched with the observed values during the lag phase (about 35 DAS) but onwards, the model under-predicted N accumulation. The Root Mean Square Error (RMSE) values of the default model were 12.26, 19.66, 17.18 and 12.26 kg N ha^{-1} and the d-statistic was 0.95, 0.93, 0.96 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. These results, while reasonably close, showed insufficient N uptake in late season, especially under low N rates, which illustrate the need to modify parameters that influence N uptake in the model.

In essence, with the default values of genetic, ecotype and species coefficients in the CROPGRO Dry bean model, the life cycle was longer (late to set pods and late to reach physiological maturity), the leaf area index and the shoot dry matter were too high, but the pod dry matter was consistently too low irrespective of N rates and the total plant N accumulation was relatively lower than the observed values. These results with the default dry bean model justify various calibrations of the genetic coefficients described above in order to accurately mimic the simulated and observed values of different crop variables for snap bean.

Life Cycle and Canopy Growth

The calibration process involved changes and adjustments of different ecotype and cultivar coefficients which govern the life cycle duration, dry matter accumulation and partitioning. Table 5-2 presents the adjusted values of these coefficients which were used for the subsequent simulations. Photothermal day requirements presented in Table 5-2 are equivalent to calendar days, if the temperature is at the optimum 28^{o}C for the entire 24-h day, where snap bean's base and optimum temperatures are 5 and 27^{o}C, respectively. Calibration of phenology to accurately simulate the life cycle and duration of development phases is important as these genetic variations lead to yield potential of different cultivars. It should be noted that the module of life cycle simulation in the CROPGRO model was not intrinsically built to be sensitive to different nitrogen rates. Therefore, discussions in this section relative to reproductive and vegetative phenology stage apply to all the N rates. The model predictions of flowering (anthesis) and maturity dates accurately agreed with the observed measurements. Under the weather conditions prevailing in our study area (Gainesville), this snap bean cultivar (Ambra) flowered 41 days after sowing and the physiological maturity was reached 77 days after sowing, and there was no observed effect of N rates. Days from emergence to anthesis and days from first seed to maturity are controlled in CROPGRO by EM-FL and SD-PM which were set respectively to 21 and 14 photothermal days (PD). It is of interest to note that snap bean, like many dry bean cultivars, has a day-neutral response to photoperiod. Therefore setting the daylength sensitivity coefficient and thresholds determining flowering and maturity for this cultivar was not necessary. The slope of the relative response of development to photothermal period (PP-SEN) and the critical short daylength (CSDL) (not listed in Table 5-2) for this cultivar were maintained to their respective default value of 0.0 and 12.17 h (0.0 meaning no sensitivity).

Snap bean has relatively slow growth upon seedling emergence. Using the calibrated coefficients, the number of leaves on main stem (expressed as the number of nodes on the main stem) during early season was slightly overestimated at all four N rates. Subsequently, the rate of main stem leaf appearance was also slightly too rapid, as noted by 45 days after planting (Figure 5-5). The Root Mean Square Error (RMSE) values of calibration were 0.59, 0.48, 0.55 and 0.57 and the d-statistic values were 0.96, 0.97, 0.96 and 0.97, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. These coefficients values indicated a good prediction of this variable and no meaningful response to N fertilization rate was observed.

Several parameters controlling canopy width and height such as RWIDTH and RHIGHT, ecotype coefficients for relative canopy width and height, and internode length (in species) were changed even though the default dry bean cultivar values used for the calibration procedure were selected from the growth habit type I (determinate). These adjustments were made in order to more accurately mimic the simulated and observed canopy height and width, basically increasing height and width about 10% more over time compared to initial default simulations. Observed and simulated canopy heights exponentially increased to a maximum at 50 days after sowing and were maintained constant thereafter (Figure 5-6). The end of the exponential phase coincided with time to end of main stem appearance, time of flowering and early pod development. During this phase, the simulated height closely agreed with the measured values of heights, but also when the maximum plant height was reached (plateau phase), the simulation was accurate except at the end of growing season where the model seemed not to capture the slight decrease in plant height which may be caused by canopy loss due to senescence. The average maximum height of the simulated canopy height was 0.30 m versus 0.36 m for the measured one. The Root Mean Square Error (RMSE) values of the canopy height calibration were 0.02, 0.02, 0.0.03 and 0.02 m and the d-statistic values were 0.99, 0.99, 0.99 and 0.99, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. Similarly, the time-course of canopy width followed the same time trend as the canopy height, and reached a maximum width at the time of end of main stem node appearance and onset of pod formation (Figure 5-7).

Biomass Accumulation and LAI

Upon successfully calibrating anthesis and maturity parameters and the plant N uptake parameters as presented above, the model was run to simulate the biomass accumulation. The temporal changes in observed crop canopy dry matter along with the predicted values are presented in Figure 5-8. Simulated changes in dry matter accumulation globally matched well with observed measurements. Comparisons showed that the slope of dry matter accumulation rose smoothly after a short lag phase early in the vegetative growth period. Both the simulation and the observations for the high N treatment used for calibration indicated a peak of vegetative dry weight above 5000 kg ha^{-1}. The Root Mean Square Error (RMSE) values of calibration data were 390, 129, 164 and 196 kg ha^{-1} and the d-statistic was 0.98, 0.99, 0.99 and 0.99, respectively, for the N rates of 37, 74, and 111 and 148 kg ha^{-1} indicating good prediction of this variable. A somewhat higher RMSE value was observed at the lowest N level indicating that N stress resulted in relatively poor prediction of crop dry matter accumulation at low N.

Comparison of the seasonal patterns of simulated biomass accumulation among the N treatments did not show any difference until about 60 days after sowing. Thereafter, the simulated dry matter accumulation at the lowest N treatment showed lower dry matter accumulation as opposed to the three higher N treatments. On the contrary, plants at the three higher N treatments maintained dry matter accumulation longer into pod filling, suggesting that the higher N rates enhanced the photosynthetic apparatus, thus maintaining longer the source of plant structural dry matter.

The temporal changes in LAI are presented in Figure 5-9. Analysis of these plots showed that the CROPGRO model performed well in predicting the time courses of LAI especially during the initial exponential increasing phase and slightly under-predicting LAI near the end of season. Simulated maximum value of LAI under lowest N treatment was reached around 50 days after sowing whereas under the three higher N treatments, maximum value occurred after 55 days after sowing. The peak in the LAI probably marked the end of the leaf expansion development and thereafter, the CROPGRO model predicted a reduction in LAI due to natural senescence. Gutierrez et *al.* (1994) observed that maximum LAI occurred when pod filling began in their study on development of a simulation model for beans. Leaf senescence in the model is dependent on the mobilization of protein (C and N) from vegetative tissues to reproductive tissues and is closely related to predictions of onset of pod initiation during reproductive development in other legumes (Alagarswamy et *al.,* 2000). Plants at the three higher N treatments started showing leaf senescence later in the season (about 5 days difference) suggesting that a smaller fraction of N might be mobilized from older leaves during the vegetative phase. The Root Mean Square Error (RMSE) values of calibration data were 0.16, 0.31, 0.28 and 0.21 m^2 m^{-2} and the d-statistic was 0.98, 0.96, 0.97 and 0.98, respectively, for the N rates of 37, 74, and 111 and 148 kg ha^{-1} indicating that the model performed well in simulating this variable irrespective of N rates.

Timing of Pod Growth

The CROPGRO model begins to add pods at the beginning pod stage (R3) which occurred at 4 photothermal days (PD) from first flower to first pod (FL-SH) for snap bean (Table 5-

2). The coefficients SFDUR (seed filling duration for one cohort of pods) and PODUR (time required for cultivar from first to final pod load) were also set to 18 and 6 photothermal days, respectively. After these adjustments of appropriate genetic coefficients defining reproductive behavior of the plant, the CROPGRO model showed relatively good performance in predicting pod and grain dry matter at various N treatments (Figure 5-10). The RMSE and d-statistic of pod weight for the calibration were 150, 191, 224 and 315 kg ha^{-1} and 0.99, 0.99, 0.99 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}.

Time between first flower and first seed (R5) was set to 13 photothermal days (PD) and the time between first seed (R5) and physiological maturity (R7) (first pods beginning to mature, color turning brown) was set to 14 PD. Based on these adjustments, seed growth initiated at 64 days after sowing. Similar to the prediction of pod dry matter growth pattern, the simulated grain weight time course was in good agreement with observed values, irrespectively of the nitrogen levels (Figure not shown).

Pod harvest index is the ratio of pod mass to total aboveground mass and illustrates the onset and degree of partitioning to reproductive organs. The comparison of simulated vs. observed pod harvest index (Figure 5-11) showed relatively good prediction of this variable at high N rate (148 kg N ha^{-1}) used for the model calibration and for the model evaluation under other N treatments as well. The RMSE and d-statistic of pod harvest index for the calibration were 0.10, 0.06, 0.06 and 0.06 and 0.96, 0.98, 0.98 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. While these values are relatively close, it appears that the model showed relatively poorer prediction capability of pod harvest index at low N due to a concept deficiency revealed in the model code in simulating shoot biomass at low N. The CROPGRO model, under N stress, accumulates non-structural carbohydrates in stems mainly, but also in leaves, which causes dry matter accumulation in vegetative organs that appears to be more than observed in the real crop. The result is the incorrect appearance of sustained dry matter growth, and a lower (than observed) pod harvest index, for the low N treatment.

The calibration of seed characteristics (seed size, threshing percentage and seed fill duration) involved adjustment of different genetic coefficients controlling these variables. To mimic the final mass per seed at harvest, the coefficient maximum weight per seed (WTPSD) was set to 0.255 g seed^{-1}. Also, the threshing percentage (seed divided by pod wall plus seed) was set to 78% (same as default value) and the individual seed-filling duration (SFDUR) was increased from 14 to 18 PD. With these different adjustments, the model seemed to well estimate the weight per seed during early seed growth period but under-estimated it near the end of the growing season (Figure 5-12). Also, analysis of the time-courses of the threshing percentage presented in the Figure 5-13 showed a trend similar to the weight per seed simulation. However, as opposed to the weight per seed simulation at the end of growing season, the model performed better in simulating the threshing percentage at the end of growing season. The RMSE and d-statistic of threshing percentage for the calibration were 8.12, 3.77, 3.55 and 5.16 and 0.97, 0.99, 0.99 and 0.99, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}.

Distribution of Dry Matter to Leaf, Stem, Pod, and Seed

Evaluation of distribution of dry matter among different aboveground organs was achieved by comparing simulated vs. observed fraction leaf, fraction stem, fraction pod, and fraction seed. The model performance in simulating plant biomass distribution among plant organs is presented in Figure 5-14A, B, C, D. Across all the N rates, simulation of the time courses of dry matter distribution was in general in accordance with the pattern of distribution of measured dry matter partitioning. Inspection of the figures indicated that snap bean partitions more assimilates to vegetative growth (leaf and stem) early in the life cycle until the onset of reproductive organs which become potential sink strength, thus decreased the partitioning intensity to vegetative organs. Indeed, Boote and Scholberg (2006) mentioned that partitioning of dry matter to leaf, stem, and root in CROPGRO initially varies as a function of main-axis leaf appearance (related to photothermal time), but then dry matter allocation begins to be reduced in a transition after anthesis, controlled by the fact that reproductive sinks are given first priority once they are added. Assimilate allocation to vegetative growth progressively declines and will cease if full fruit load is attained, depending on the fruit assimilate allocation coefficient (XFRT). Leaves accounted for a very low fraction of the total dry matter accumulation at the end of the growing season due to the natural senescence. Intermediate amounts were allocated to the stem, slightly higher than leaf dry matter accumulation. The switch in dry matter allocation from vegetative growth to pod and seed growth is expressed as a plateau in root and stem growth according the bean model developed by Gutierrez et al. (1994). The simulation of plant dry matter allocation to plant components was reasonably well predicted across all four N rates. This is a direct consequence of a relatively good prediction of shoot and organs mass described above.

Simulation of Nitrogen Accumulation in the Plant

After calibration of parameters which influence plant N uptake as described in the Methods (calibrated to the two low N treatments) and calibration of cultivar, ecotype, and species parameters to the high N treatment, the following seasonal patterns of simulated and observed total plant N accumulation for the different N treatments resulted (Figure 5-15). After a short lag phase, a rapid and linear N accumulation was observed between 35 to 60 days after sowing under the different N treatments. During this period, the data indicate relatively close agreement between predicted and measured values, with differences among N treatments becoming apparent around 45 days after sowing. The model simulations captured the decrease in N uptake as a result of low N conditions fairly well after calibration. After 45 days after sowing, increase in N uptake was less rapid under the lowest N treatments, with peak values reached at 55 days after sowing, followed by a "plateau" phase until the end of season suggesting that the crop accumulated almost all its N prior to 55 days after sowing for the low N treatments. Accordingly, N allocated to the reproductive tissues (pod and seed) during this phase had to be remobilized from vegetative tissues, mainly stems and leaves. Similar patterns were observed under the three higher N treatments, but respective peak values were reached differently. Analysis of model performance with different N treatments showed that the N uptake was accurately predicted under these N treatments. More closely, the Root Mean Square Error (RMSE) values were 9.80, 15.10, 13.16 and 9.56 kg N ha^{-1} and the d-statistic values were 0.97, 0.97, 0.98 and 0.99, respectively, for the N rates of 37, 74, and 111, and 148 kg ha^{-1}. Thus, with the adjustments of parameters controlling plant N uptake and the fractions of soil organic matter (SOM), the CROPGRO simulation model was able to accurately capture the dynamics of plant N uptake over the growing season. Indeed, availability of N in the soil is determined by the balance between N supply and mineralization, and between N immobilization and losses.

Figure 5-16 shows the simulated and measured time course of total N accumulated in the vegetative parts (leaf and stem). Nitrogen accumulated in these vegetative parts increased exponentially for the first 40 days and the peaks for leaf and stem were reached at 50 and 58 days after sowing, respectively for the lowest (37) and highest (148 kg N ha^{-1}) with progressively greater N accumulation with increasing N fertilizer rates. The model slightly under-predicted the N uptake notably at higher N treatments. The RMSE values were 3.5, 8.8, 9.5 and 9.7 kg ha^{-1}. N accumulated in vegetative parts declined sharply after the peak towards the end of the growing season and the decline was more apparent at the three higher N treatments. The decline phase observed is ontogenic and corresponded to the setting of reproductive organs (pod and seed namely) which became sinks for N. Nitrogen mobilization from vegetative parts to reproductive tissues is expected to be higher during this period. Figure 5-17 illustrates the simulated and measured time course of N accumulated in the grain. The overall trend was relatively well simulated except an under-prediction was observed at later stages.

Conclusion

This study illustrates the adaptation of the CROPGRO dry bean model to simulate the growth, development and dry matter accumulation of snap bean. With the calibration of several coefficients in the ecotype file and genetic coefficients in cultivar file, CROPGRO Dry Bean model was able to capture most of the patterns of growth and development in snap bean. In addition, N mobilization aspects in the species file were modified (accelerated) to minimize computed N stress and improve simulations of N balance under low soil N supply. We suspect that these modifications may also be necessary for the dry bean model as well, as it has not been tested under low N supply and non-nodulation. The model has adequate capabilities to predict the life cycle (anthesis and maturity dates) and biomass accumulation irrespective of different N rates. Furthermore, with adjustments of parameters defining N uptake and mobilization, the simulated yield and yield components were generally in good agreement with the data obtained under different N supply conditions.

Additional model components such as fruit fresh weight, fruit size distribution, fruit quality, and fruit maturity can be included into the structure of this calibrated CROPGRO dry bean model in order to simulate the fresh marketable yield and quality of snap bean.

Table 5-1. Soil profile characteristics of the Millhopper fine sand, (hyperthermic family of Grossarenic Paleudults) used during the calibration process

SLB	SLLL	SDUL	SSAT	SBDM	SLOC	SH_2O	SNH_4	SNO_3	SOM1	SOM2	SOM3
5	0.023	0.086	0.23	1.47	0.9	0.086	1.03	0.7	0.01	0.70	0.29
15	0.023	0.086	0.23	1.47	0.69	0.086	1.03	0.7	0.01	0.70	0.29
30	0.023	0.086	0.23	1.41	0.28	0.086	1.03	0.7	0.01	0.70	0.29
45	0.023	0.086	0.23	1.43	0.2	0.086	1.30	0.95	0.01	0.60	0.39
60	0.023	0.086	0.23	1.43	0.2	0.086	1.30	0.95	0.01	0.60	0.39
90	0.021	0.076	0.23	1.52	0.09	0.076	1.40	1.4	0.01	0.60	0.39
120	0.02	0.076	0.23	1.52	0.03	0.076	1.10	0.8	0.01	0.60	0.39
150	0.027	0.13	0.23	1.46	0.03	0.13	1.10	0.8	0.01	0.60	0.39
180	0.07	0.258	0.36	1.46	0.03	0.258	1.10	0.8	0.01	0.60	0.39

SLB, depth to base of soil layer (cm); SLLL, soil lower limit (cm^3 cm^{-3}); SDUL, soil drained upper limit (cm^3 cm^{-3}); SSAT, soil saturated upper limit (cm^3 cm^{-3}); SBDM, soil bulk density, moist (g cm^3), SLOC, soil organic carbon (%); SH_2O, Initial soil water content, (cm^3 cm^{-3}); SNH_4, Initial ammonium, (g elemental N Mg^{-1} soil); SNO_3, Initial soil nitrate, (g elemental N Mg^{-1} soil); SOM1, Initial microbial soil organic matter fractional composition (unitless); SOM2, Initial intermediate soil organic matter fractional composition (unitless); SOM3, Initial passive soil organic matter fractional composition (unitless); SOM1 + SOM2 + SOM3 = 1.0. (Compiled from Carstile et al., 1981 and Graetz, 2007)

Table 5-2. Genetic coefficients of cultivar Ambra for the CROPGRO model, after the calibration process, compared to generic "Andean" dry bean cultivar

Genetic Coefficients	Abbreviation	Andean	Ambra
Photothermal days from emergence to flower appearance	EM-FL	22.6	21
Photothermal days from first flower to first pod	FL-SH	3	4
Photothermal days from first flower to first seed	FL-SD	12	13
Photothermal days from first seed to physiological maturity	SD-PM	18.40	14.00
Photothermal days from first flower (R1) and end of leaf expansion	FL-LF	10	16
Maximum leaf photosynthesis rate, mg CO_2 m^{-2} s^{-1}	LFMAX	1	0.95
Specific leaf area of cultivar under standard growth conditions cm^{-2} g^{-1}	SLAVR	305	210
Maximum size of full leaf, cm-2	SIZELF	133	135
Maximum fraction of daily growth partitioned to seed + shell	XFRUIT	1	1
Maximum weight per seed, g	WTPSD	0.600	0.255
Photothermal days for seed filling for pod cohort at standard growth conditions	SFDUR	15	18
Average seed per pod under standard growing conditions no. pod^{-1}	SDPDV	3.50	5.60
Photothermal days to reach final pod load	PODUR	10	6
Ecotype Coefficients			
Photothermal days from first flower to main stem termination	FL-VS	0	1.50
Weight percentage of seeds in pods (shelling percentage)	THRESH	78	78
Fraction protein in seeds (g(protein)/g(seed))	SDPRO	0.235	0.200
Fraction oil in seeds (g(oil)/g(seed))	SDLIP	0.030	0.030
Photothermal days required for growth of individual shells	LNGSH	8	11.3
Species Coefficients			
Maximum rate of mobilization of carbohydrate from veg. tissues (Fraction of pool/day)	CMOBMX	0.03	0.07
Maximum rate of mobilization of protein from veg. tissues during reproductive growth (Fraction of available protein pool/day)	NMOBMX	0.10	0.16
Relative rate of mobilization of protein from veg. tissues (compared to rate in reproductive phase)	NVSMOB	0.36	0.70
Specific leaf weight at which LFMAX is defined (g dry weight cm^{-2})	SLWREF	0.0030	0.0033
Maximum uptake of NO3 per unit root length (mg N per cm root length)	RTNO3	0.006	0.015
Maximum uptake of NH4 per unit root length (mg N per cm root length)	RTNH4	0.006	0.015

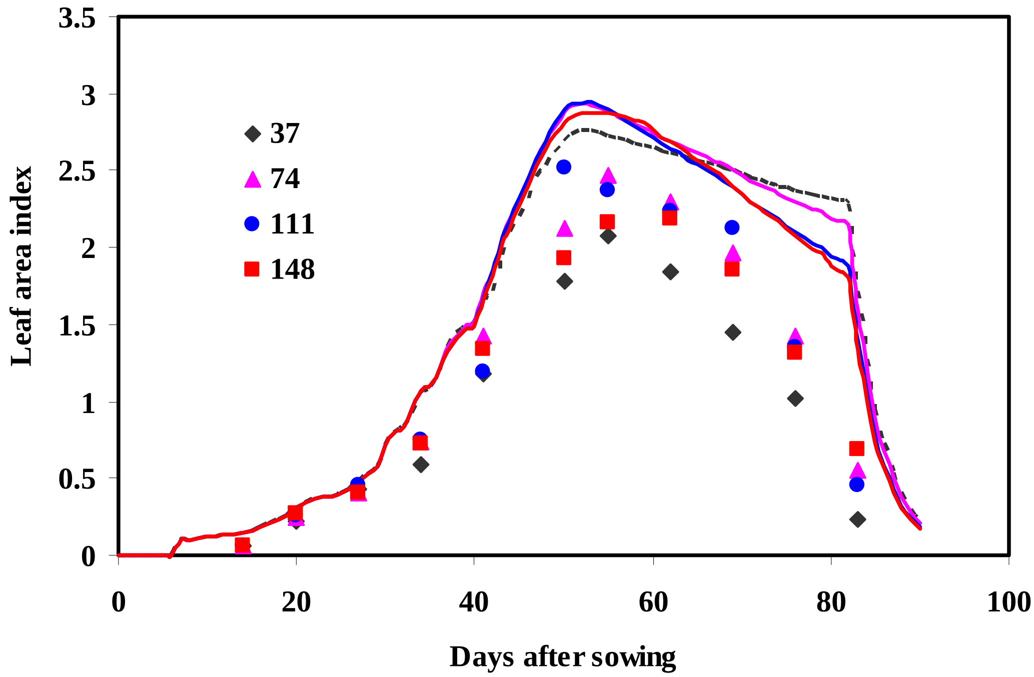

Figure 5-1. Default model simulated (lines) and observed (symbols) leaf area index as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

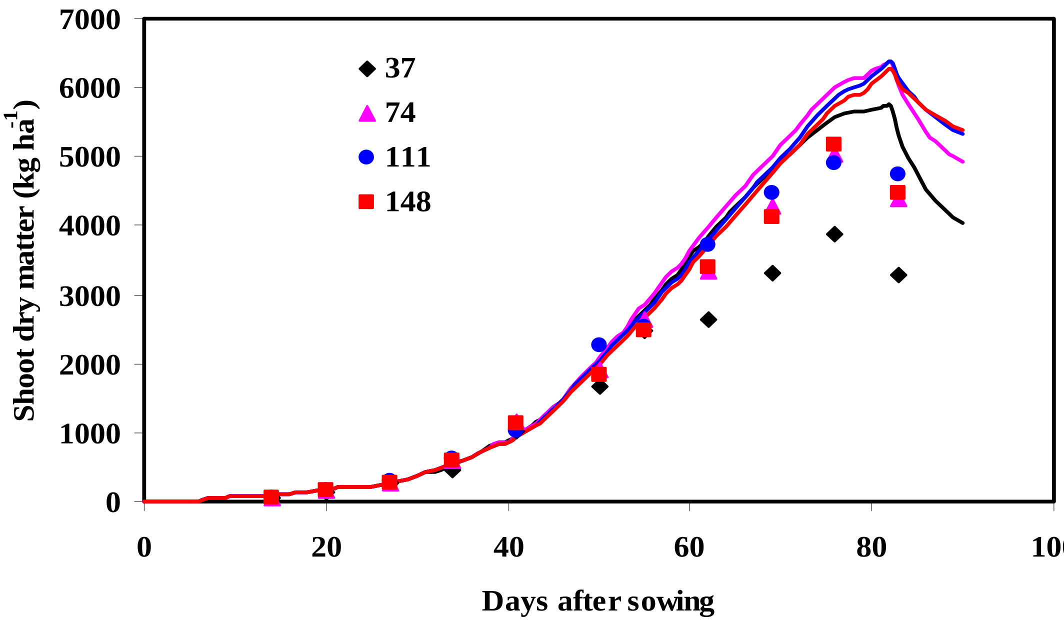

Figure 5-2. Default model simulated (lines) and observed (symbols) shoot dry matter as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

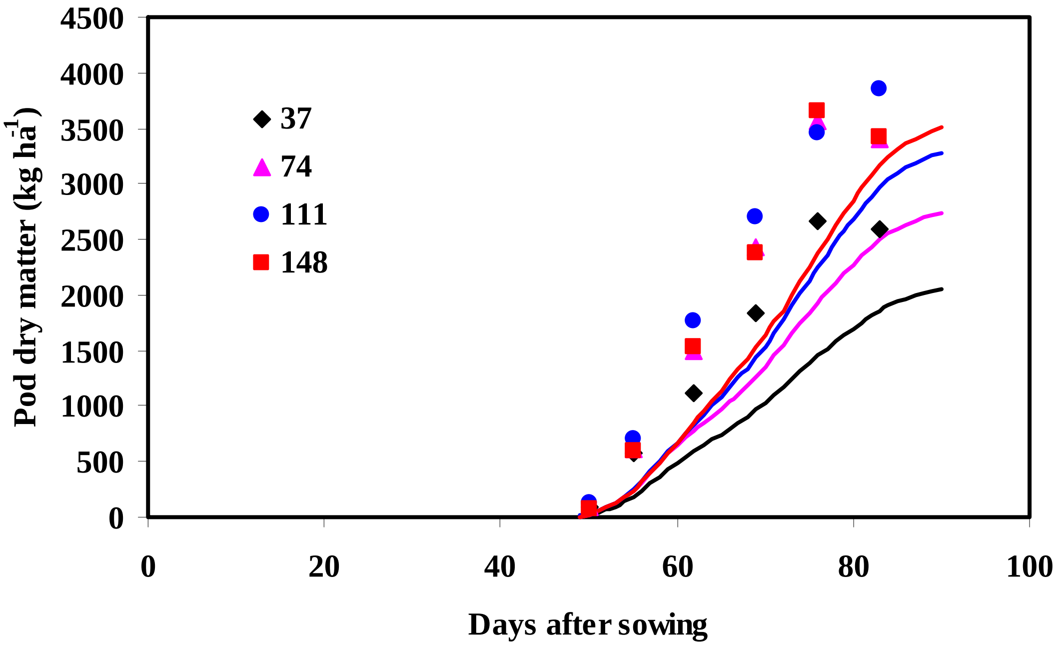

Figure 5-3. Default model simulated (lines) and observed (symbols) pod dry matter as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

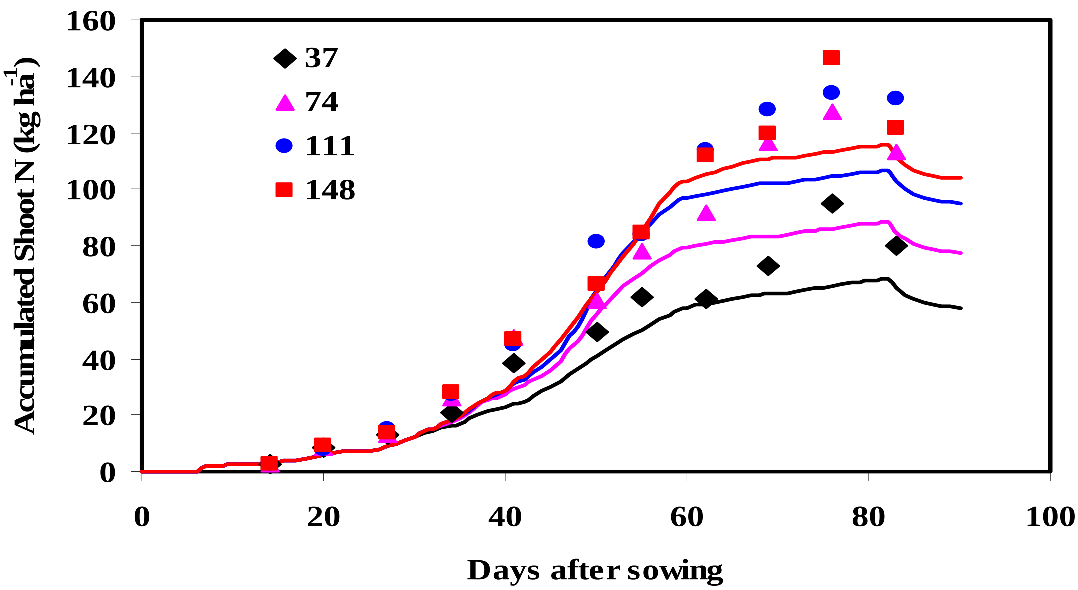

Figure 5-4. Default model simulated (lines) and observed (symbols) accumulated shoot N as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

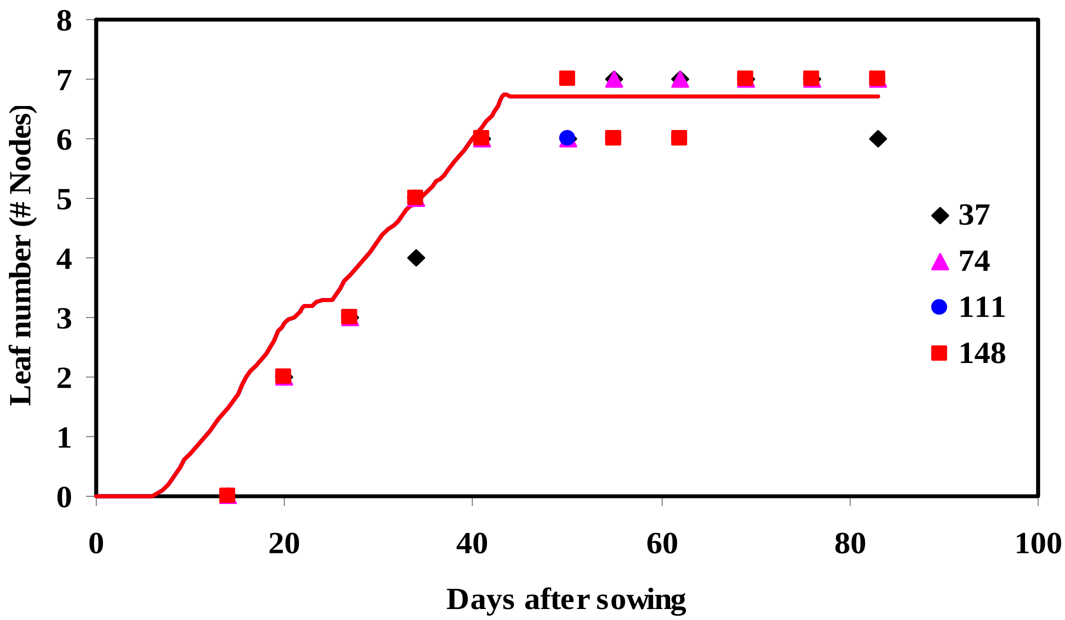

Figure 5-5. Simulated (lines) and observed (symbols) main stem node number as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

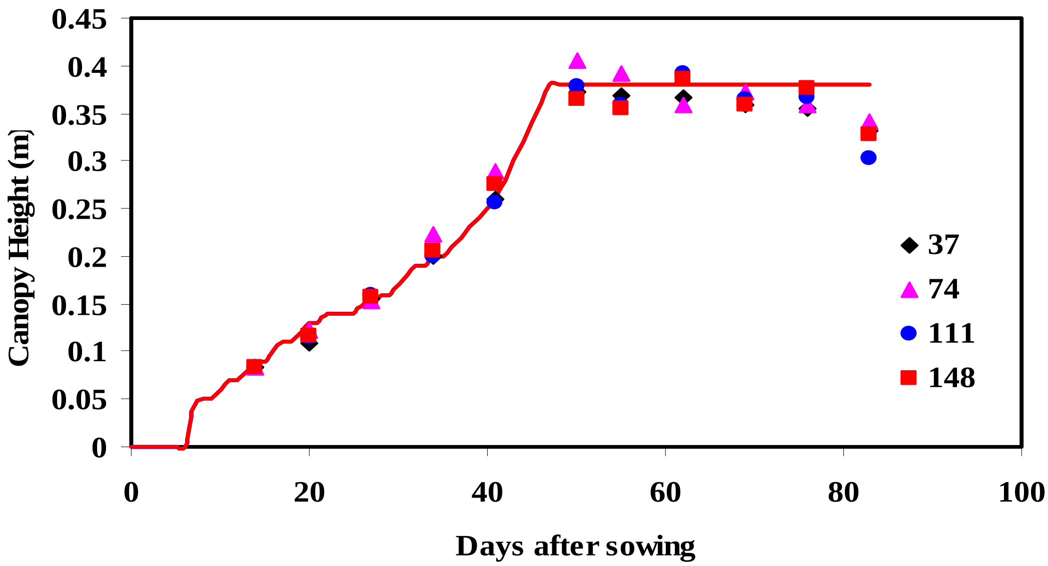

Figure 5-6. Simulated (lines) and observed (symbols) canopy height as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

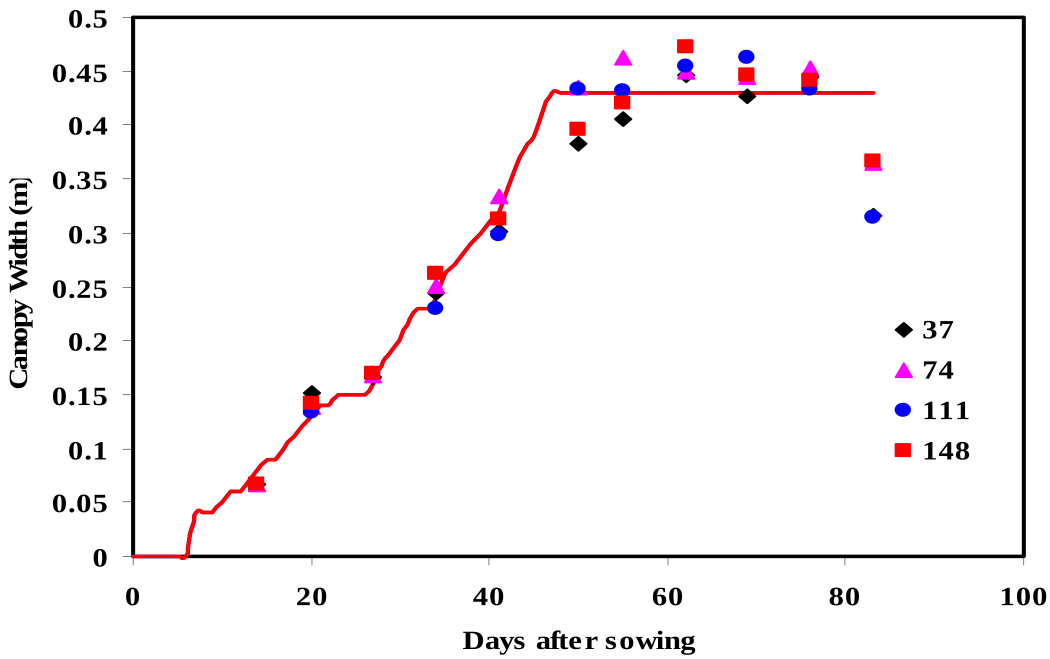

Figure 5-7. Simulated (lines) and observed (symbols) canopy width as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

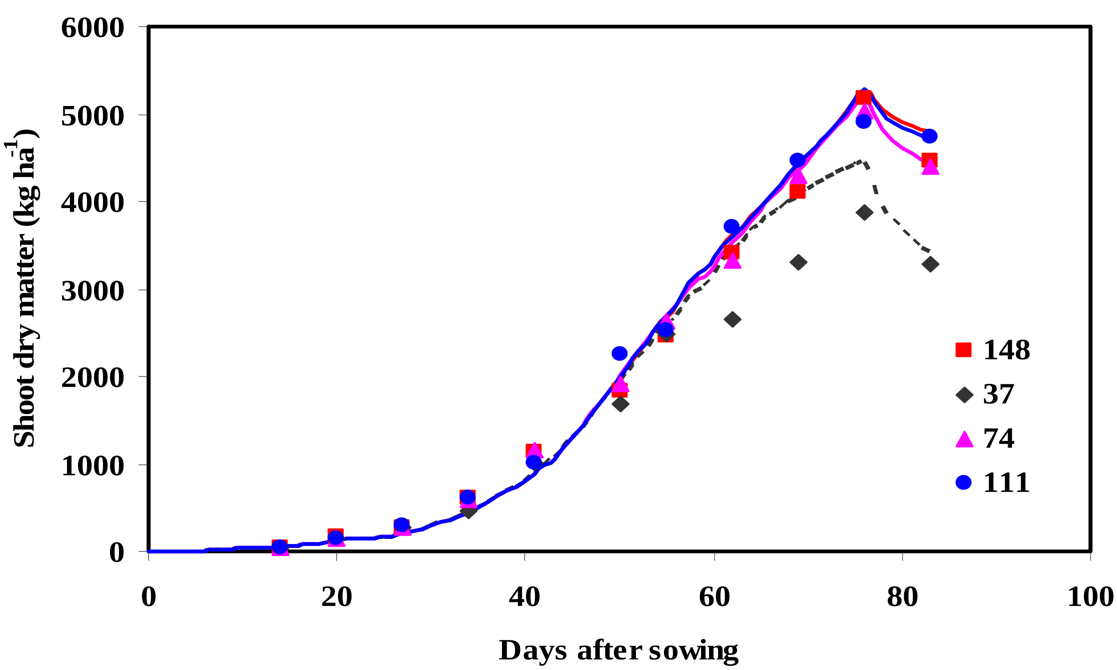

Figure 5-8. Simulated (lines) and observed (symbols) shoot dry matter as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

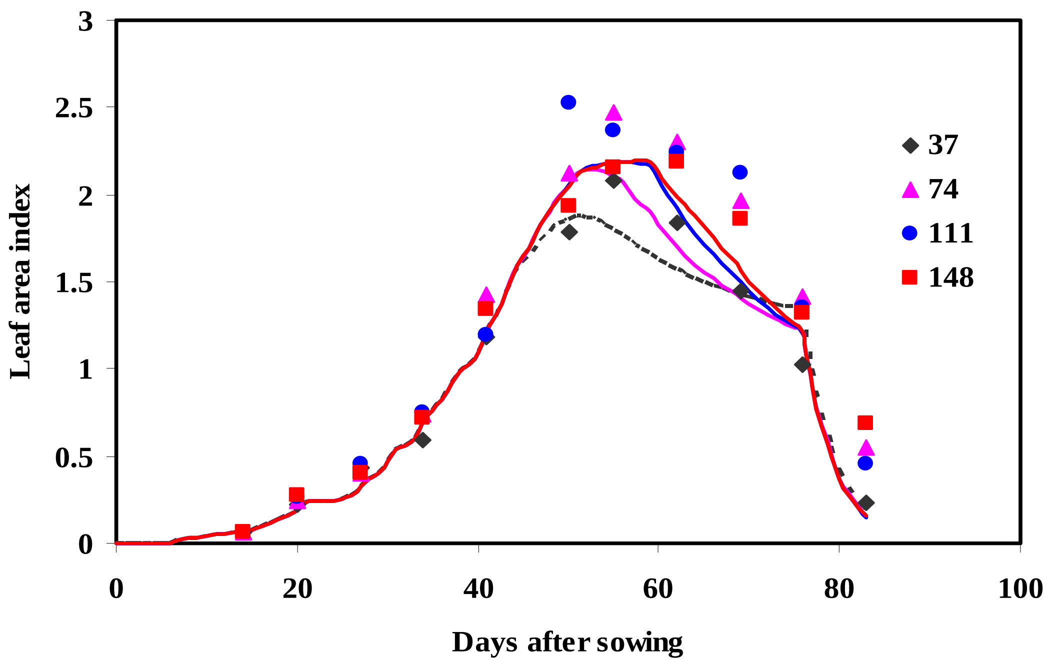

Figure 5-9. Simulated (lines) and observed (symbols) leaf area index as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

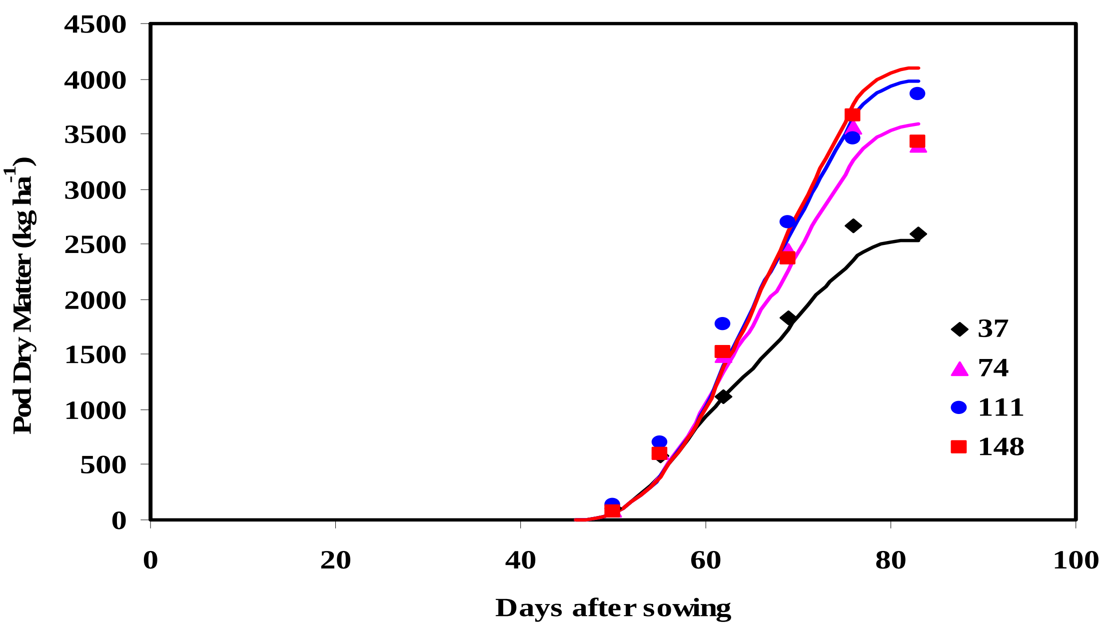

Figure 5-10. Simulated (lines) and observed (symbols) pod dry matter as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

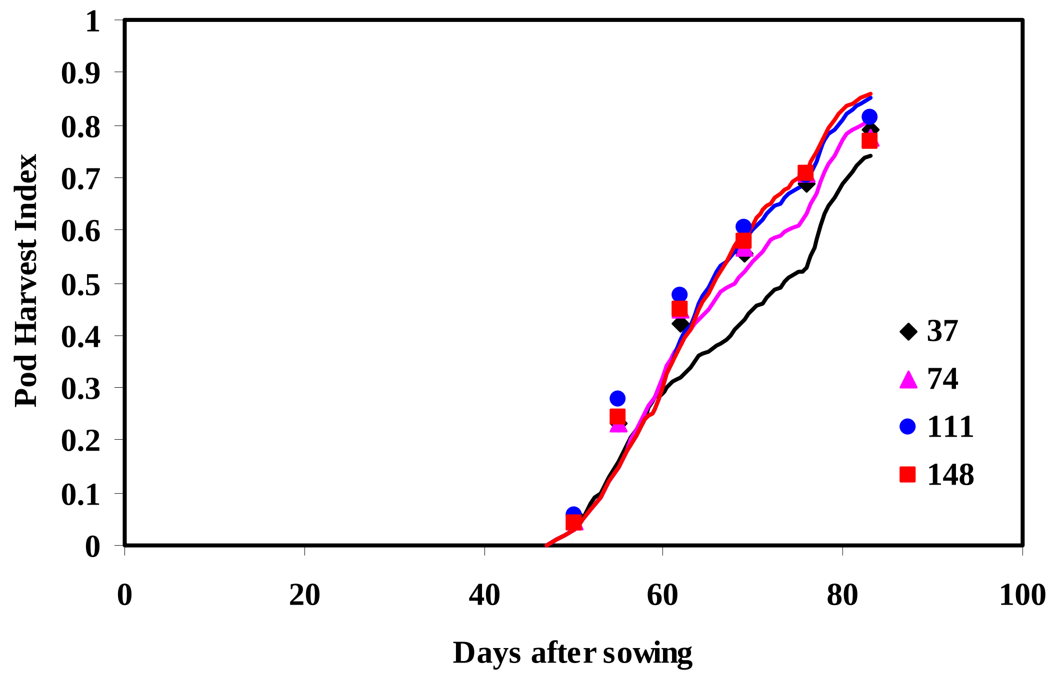

Figure 5-11. Simulated (lines) and observed (symbols) pod harvest index as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

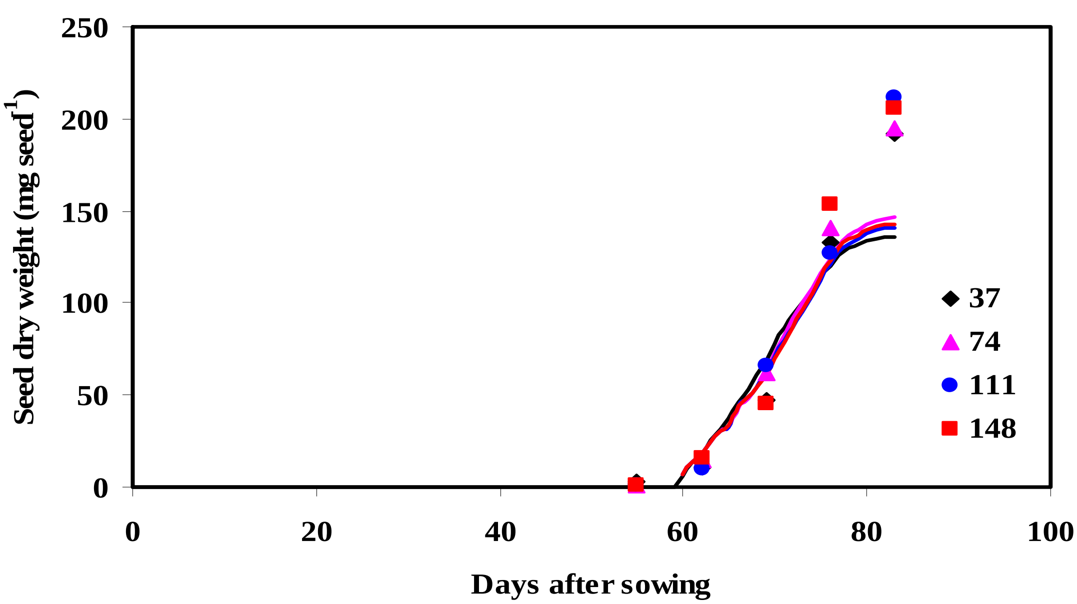

Figure 5-12. Simulated (lines) and observed (symbols) weight per seed as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

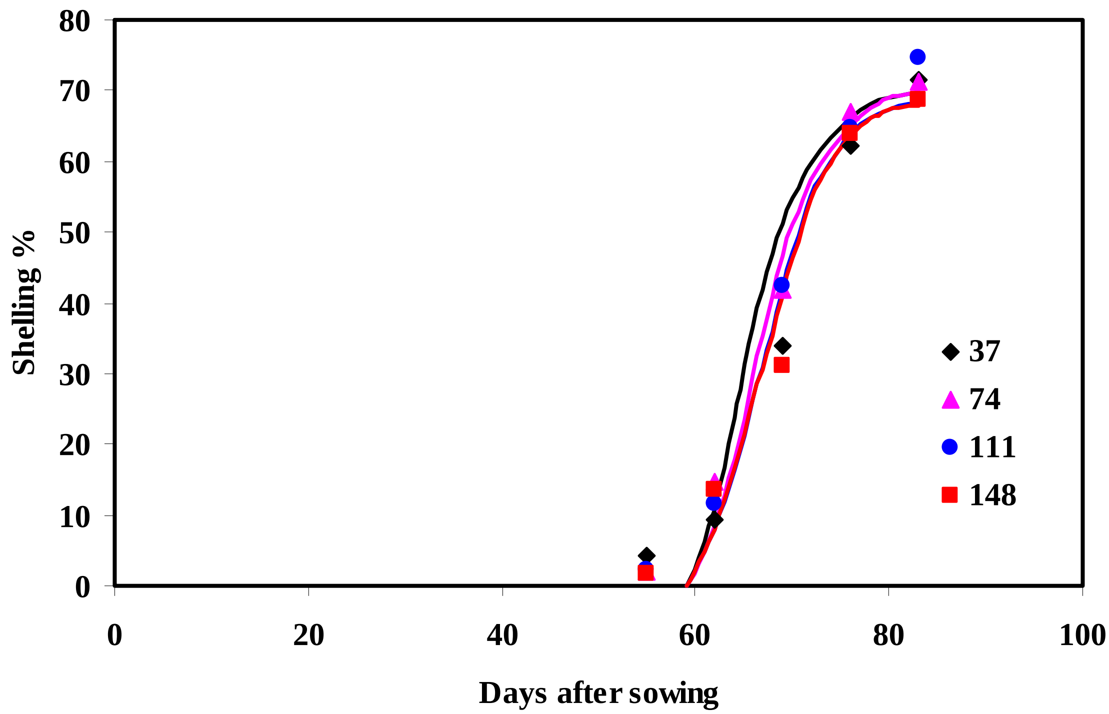

Figure 5-13. Simulated (lines) and observed (symbols) shelling percentage as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

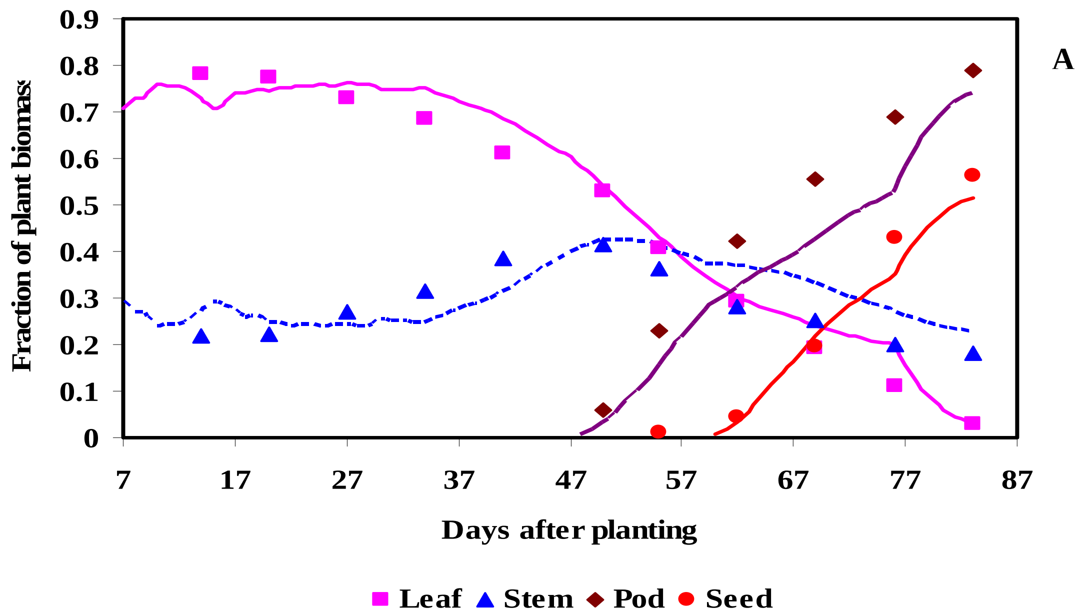

Figure 5-14. Simulated (lines) and observed (symbols) fraction of biomass in plant organs as a function of days after sowing for snap bean cultivar Ambra grown under (A) 37, (B) 74, (C) 111, and (D) 148 kg N ha^{-1} rates in Gainesville FL during spring 2007

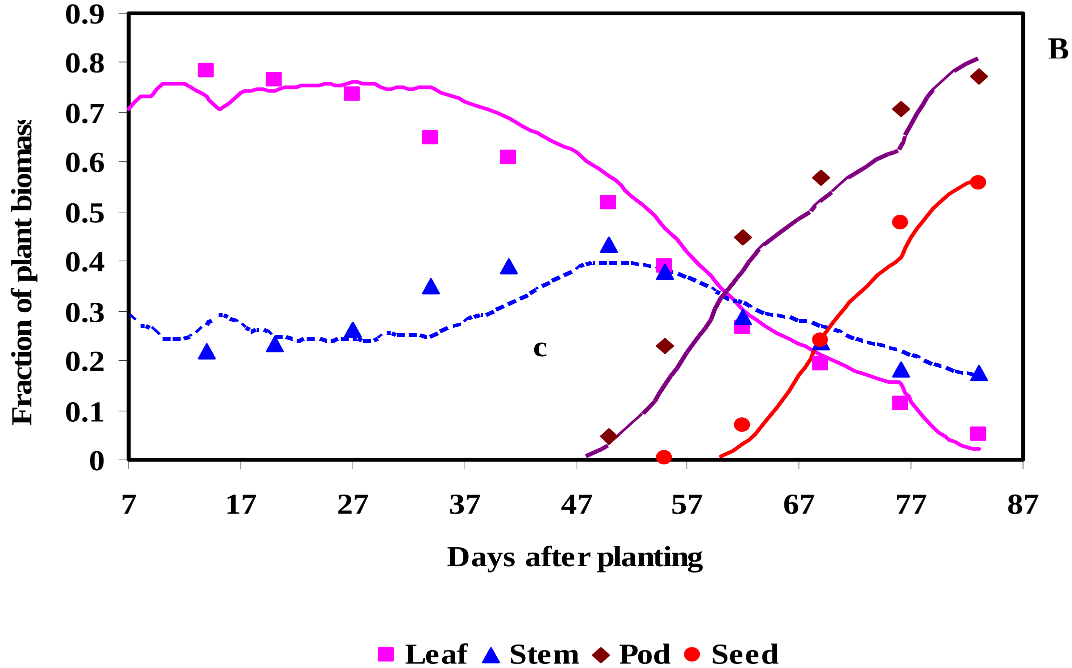

Figure 5-14 Continued

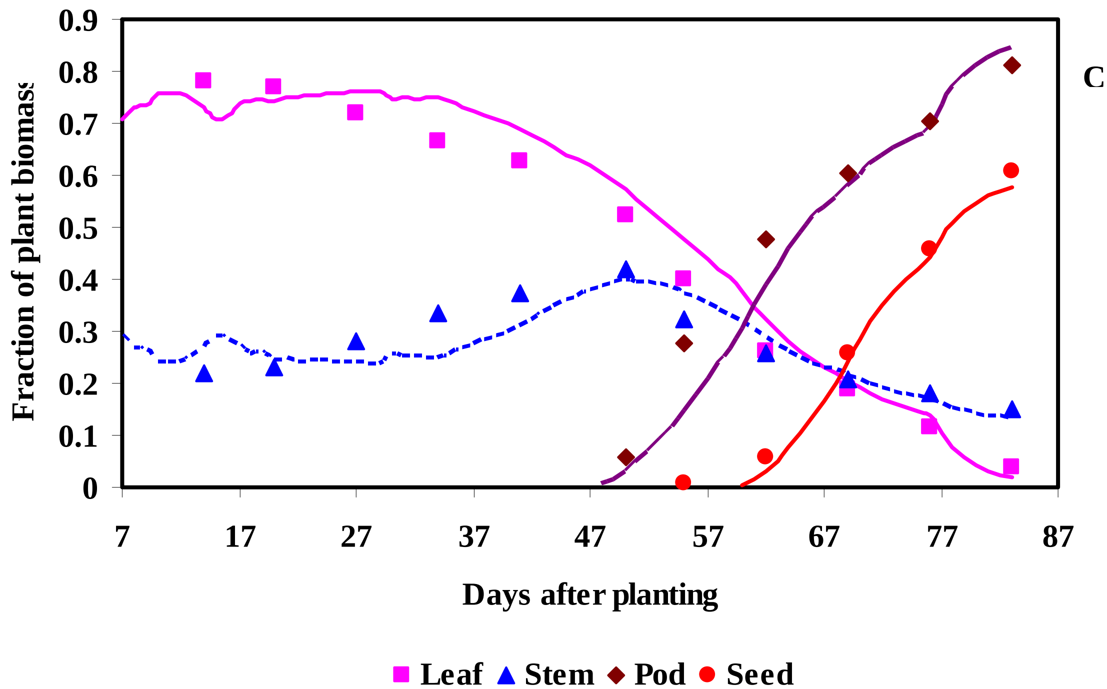

Figure 5-14 Continued

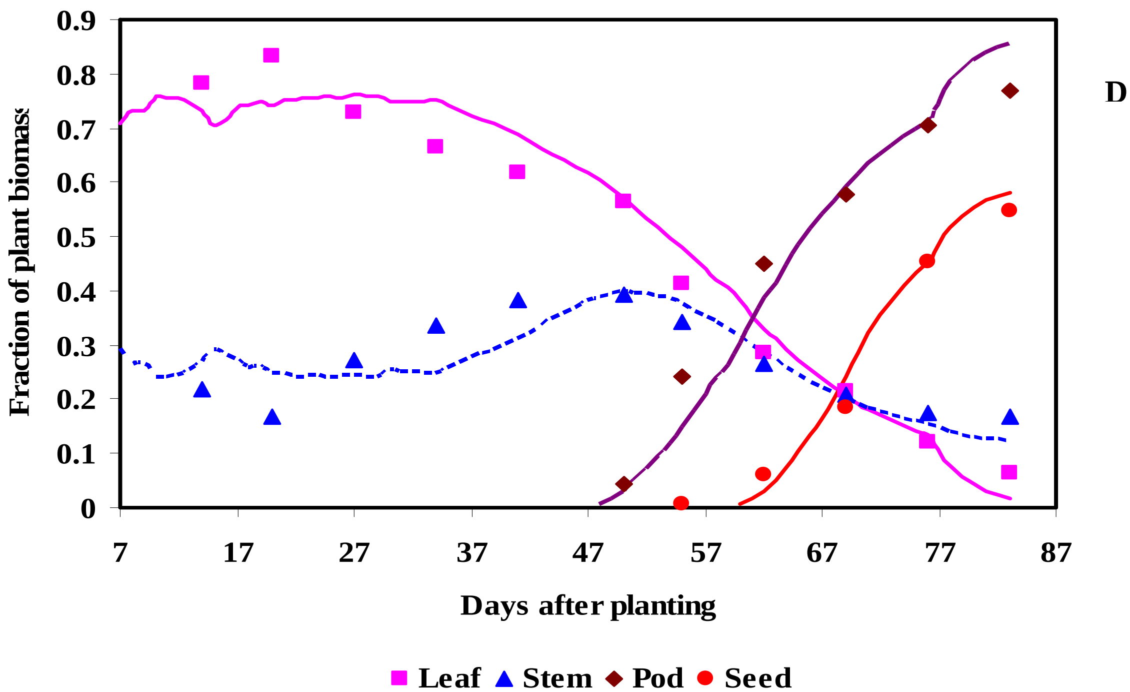

Figure 5-14 Continued

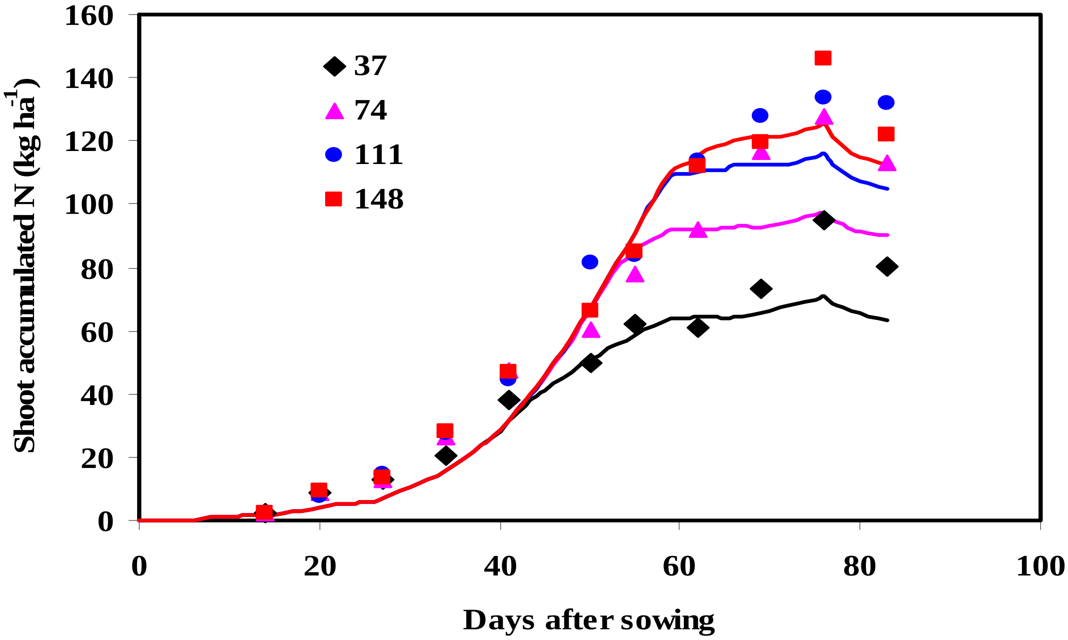

Figure 5-15. Simulated (lines) and observed (symbols) total plant N accumulation as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

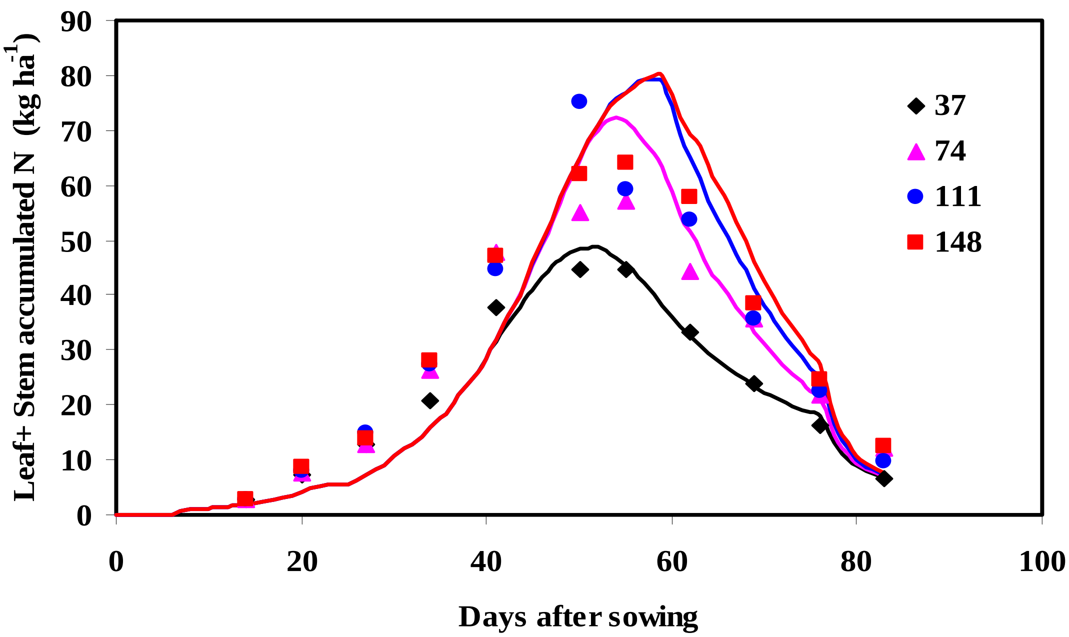

Figure 5-16. Simulated (lines) and observed (symbols) N in vegetative parts (leaf and stem) as a function of days after sowing for snap bean cultivar Ambra grown under under four N rates in Gainesville FL during spring 2007

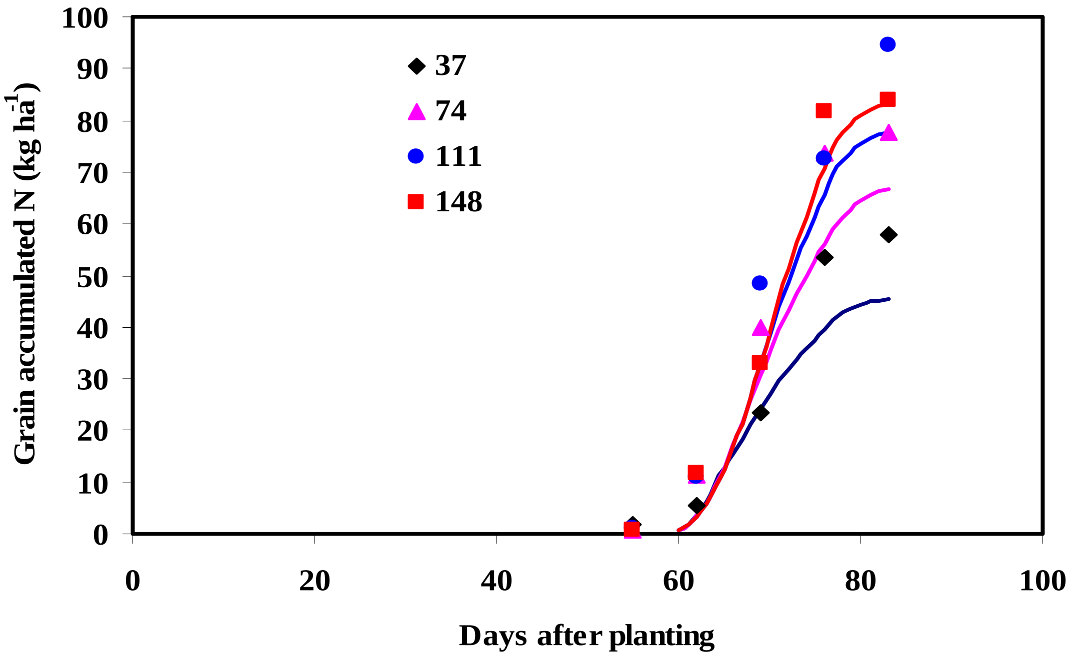

Figure 5-17. Simulated (lines) and observed (symbols) grain N as a function of days after sowing for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

CHAPTER 6
DEVELOPING A SNAP BEAN SIMULATION MODEL TO PREDICT FRESH MARKET YIELD AND QUALITY OF PODS

Introduction

Snap bean (*Phaseolus vulgaris* L.) is an economically important vegetable with a U.S. fresh market crop value of more than 390 million (USDA, 2007). Florida is the largest snap bean producing state in the United States. In 2007, Florida accounted for 35% of the total harvested U.S. fresh market snap bean and 55% of the overall U.S. crop value (USDA, 2007). Like production of most vegetables, snap bean production faces different challenges with respect to crop management and decision-making throughout the growing season. As a vegetable grown for fresh market, managing snap bean production to meet market standards is a complex trade-off between yield and quality; growers select a time for harvest that produces the highest possible yield and the optimum quality parameters before quality deteriorates to an unacceptable level.

Several process-oriented crop growth models have been extensively developed and used for predicting crop growth, development and yield in relation to the weather, pests, soil, and management practices. In the case of snap bean, Ferreira et al. (1997) attempted to predict phasic development of green beans using a model with thermal time accumulation concept, but their work did not predict fresh market quality. Also, Ferreira et al. (2006) accounted for some internal as well as external quality variables such as alcohol-insoluble solids, dry matter concentration, seed: pod ratio, fiber concentration, length of 10 seeds, Kramer shear press, color, lipid concentration and mineral composition. They determined regression analyses between these variables versus thermal time in order to evaluate quality and maturity of snap bean pods. These empirical approaches based on statistical analyses to model snap bean may not be of great interest for growers and researchers in that they did not account for underlying causes and mechanisms which regulate the temporal changes and distribution of fresh weight and pod quality in relation to environmental factors and management practices (water and nitrogen influence). For modeling results to be meaningful or useful for producers or extension agents, additional modules including fruit fresh weight, fruit size distribution, fruit quality, and fruit maturity should be incorporated into existing crop simulation models which predict crop production on a dry matter basis as affected by crop management strategies and environmental factors. For such crops, Marcelis et *al.* (1998) suggested that model-predicted fruit dry matter needs to be converted to fresh weight and/or fruit size as yield is predominantly determined by the water concentration.

The CROPGRO model is a process-oriented model that uses daily weather and management inputs to predict daily changes in plant growth to the point of final yield on dry matter basis. Boote and Scholberg (2006) envisioned that since the CROPGRO model predicts explicit fruit addition and fruit growth rates over time for specific cohorts, this model ability could be valuable for predicting fresh market yields over time. Achieving these processes required modification and new algorithms in the existing CROPGRO code. Therefore, our objective in this study was to add a new module to the calibrated CROPGRO model to simulate the fresh market production and quality of snap bean. It is of interest to note that to a grower or processor, quality in snap bean is defined in terms of sieve size, percent seed by weight of total pod weight, pod fiber content, pod smoothness and straightness, pod color, and flavor. This study was only interested in pod sieve size distribution to simulate the snap bean pod quality.

Materials and Methods

Model Structure

Figure 6-1 illustrates a conceptual model for simulating snap bean fresh marketable yield and quality useful to understand how temporal patterns of pod distribution and quality aspects (dry matter concentration, pod diameter) are impacted by environment factors and management practices. This conceptual model diagram is designed based on previous visuals of Jones and Luyten (1998), and Marcelis et *al*. (1998).

In essence, the model is photosynthesis-based, and first calculates the interception of light by the leaf area and then simulates the production of photosynthates. Subsequently, the use of photosynthates for respiration, conversion into structural dry matter (DM), the partitioning of assimilates or DM among the different plant organs is calculated. Finally, the fresh weight can be estimated from the dry weight based on the dry matter concentration algorithm.

In this model, plant biomass production is mainly driven by climatic factors (CO_2, solar radiation, and temperature) and is affected by growth reduction factors, namely nitrogen and water stress (not represented on the diagram).

Model Development

In Chapter 5, the CSM-CROPGRO-Dry bean Model was calibrated to simulate the growth and development of snap bean under optimum water and nitrogen conditions. The calibrated model resulting from this process was modified to simulate the fresh market production and quality of snap bean. For this purpose, additional source code was incorporated into the general model structure and was focused on two components: pod fresh weight and pod quality.

Model development data

Data used to develop this model were collected in the same field experiment presented in Chapter 2. More specifically, data for this chapter relate to single pod growth, fresh market weight and quality. For this purpose, 50 small pods (about 2-cm length) were tagged all on the same day per replicate from the four N treatments receiving the medium irrigation (100% Et). Subsequently, at interval of 3 days, 4 pods per replicate (4 replicates total) were randomly harvested from the tagged pods and the following data were measured on a “per pod” basis: pod diameter (mm), pod fresh weight (g), pod wall dry weight, number of seed, seed fresh weight and seed dry weight. Also, pod sizes were determined with the green snap bean sieve size grader. These data were used to develop functional relationships between fresh weight and dry weights versus thermal time and also pod size (diameter) versus fresh weight with the use of the software package Microcal ™ Origin Version 6.0 which provided the best fit and equations of our numerical data.

Dry matter concentration (DMC) and pod fresh weight

Fresh weight and dry weight of pods and seeds measured were used to develop a Dry Matter Concentration algorithm (DMC) as a function of thermal time as follows:

$$DMC = 0.0465 + 0.0116 * \exp(0.161 * PAGE) \tag{6-1}$$

The model simulates the increase in Pod Dry Matter Concentration *(DMC)*, following an exponential pattern with thermal time (physiological days) (Figure 6-2). It should be noted that the thermal time values in this function were derived from the thermal time module in CROPGRO which accounts for the cardinal temperatures (base temperature, optimum temperature and maximum temperature) to calculate values of physiological days accumulated by a given observation date.

Fresh weight of pods [FWpod (grams per pod)] is thus calculated as follows:

$$FWpod = \frac{DWpod}{DMC} \tag{6-2}$$

where *DWpod* is the pod dry weight (grams per pod). Doing this for all pod cohorts on the crop for which *DWpod* is positive and integrating the resulting *FWpod* over all pods, the model calculates total fresh weight yield of pods [*TotFW* (kilograms per hectare)].

Pod quality

Upon developing the fresh weight relationship, a functional relationship between measured pod diameter (which defines pod quality) and measured pod fresh weight was developed, which subsequently allows predicting the U.S. standard grades of fresh market of snap bean (USDA, 1997). The pod diameter versus *FWpod* relationship is described as follows:

$$PodDiam = 9.737 * (1 - \exp(-0.460 * FWPod + 0.48)) \quad (6\text{-}3)$$

This is a monomolecular growth relationship of the pod fresh weight with a sharp increase of pod diameter early in the pod growth period up to the point where the pod diameter follows a steady and constant plateau phase (Figure 6-3). The U.S. standards for grades of fresh market snap bean separate snap bean into six main classes based on pod diameter also called pod sieve size as follows: “Size 1” (diameter between 5.1 and 7.3 mm), “Size 2” (diameter between 7.3 and 8.3 mm), “Size 3” (diameter between 8.3 and 9.5 mm), “Size 4” (diameter between 9.5 and 10.7 mm) and “Size 5” (diameter greater than 10.7 mm). Of these five categories, “Size 3” and “Size 4” are considered appropriate for fresh market.

A new module to simulate the aggregated time-courses of fresh market yield (kg ha^{-1}) and pod quality was developed through introduction of the different algorithms and code added to the CROPGRO simulation model structure. Therefore, the model outputs daily pod dry matter concentration, pod fresh weight (kg ha^{-1}) and individual pod dry and fresh weight (g pod^{-1}), pod diameter (mm) and pod sieve size. An aggregating function in that module integrates over all single pod cohorts, to compute total fresh market yield falling into respective pod size classes.

Results and Discussion

Tagged Pod and Seed Dry Mass Simulation

In the CROPGRO simulation model, the time step of the modules for simulation of assimilate partitioning, dry matter production, pod growth, dry matter concentration and pod fresh mass is 1 day. The numbers of pods, seeds and flowers that are initiated within a given day are stored in arrays that allow knowing not only the numbers of pods, etc., on the plants, but also the calendar time ages of the pods and their physiological ages (Boote, 1999). The model predicts pods formed on each day, and a specific day's pods can thus be identified. The function for individual pod growth rate (which affects final pod size) depends on maximum weight per seed (g) (WTPSD), the maximum ratio of (seed/(seed+shell)) at maturity (THRSH), and the average seed per pod under standard growing conditions (SDPDV), as well as the duration of shell growth (LNGSH), which is also sensitive to temperature. Seasonal dry weight progression of individual pods formed "in the model" on the same day as the observed tagged pods (10 days after anthesis) are compared in Figure 6-4. The single pod dry weight simulations were reasonably close, but these also required some calibration of the length of shell growth period (LNGSH) which was increased from 8 to 11.3 PD. Analyzing these plots show a linear increase in single pod dry weight up to 23 days after anthesis and thereafter, the trend shows a more rapid increase in pod dry weight which is related to the accumulation of dry weight in seed within the pods, as can be seen in Figure 6-5. Simulations of single seed growth under the different N treatments indicated that the CROPGRO snap bean model has a general tendency to set seed within the pod a little late, but gives relatively good prediction of seed dry weight during the initial growth of seed but under-predicts them later. A similar trend was also observed with respect to the single pod dry weight simulations. The RMSE of pod dry weight prediction and the corresponding d-statistic values were 0.21, 0.12, 0.14 and 0.08 g pod^{-1} and 0.93, 0.98, 0.97 and 0.99 for the N treatments of 37, 74, 111 and 148 kg ha^{-1}.

Tagged Pod DMC Simulation

Figure 6-6 shows the time course of dry matter concentration of individual pods as a function of days after anthesis. After an initial lag-period phase of approximately 5 days, the pod showed a steady almost linear increase (linear growth phase) of pod dry matter concentration over time. The DMC was relatively constant at about 0.06 during the initial lag phase period.

Based on these plots, it appears that the model performed relatively well in simulating the dry matter concentration of individual pods. Simulation was relatively accurate with RMSE being 0.039, 0.029, 0.044 and 0.027 and the d statistic was 0.98, 0.98, 0.97 and 0.99 for the N treatments of 37, 74, 111 and 148 kg ha^{-1}, respectively.

Tagged Pod Fresh Weight Simulation

Fresh weight of fruit is calculated from the dry weight and dry matter concentration relationship. The ability of the snap bean model to simulate seasonal progression of single pod growth is shown in Figure 6-7. Analysis of the accumulation of single pod fresh weight showed a linear increase during the initial pod development (from onset of pod growth at about 10 days lasting until about 20 days after anthesis). From day 20 after anthesis onwards, the simulation quickly approached a peak pod fresh weight followed by a slow decline phase. The peak illustrates attainment of full pod size, also characterized by accumulation of assimilates into the growing seed inside the pod. The period of rapid pod fresh weight growth is indicative of the intense growth activity associated with cell division and elongation. The RMSE values of pod fresh weight predictions were 1.04, 0.94, 0.97 and 0.955 g pod^{-1} and the d-statistic values were 0.78, 0.88, 0.87 and 0.87 for the N treatments 37, 74, 111 and 148 kg ha^{-1}, respectively. Based on these model evaluation coefficients, it is concluded that the model performed relatively poorly in simulating the individual pod fresh weights, which could possibly be improved with better single pod DM growth algorithms and possibly improved DMC algorithms.

Total Pod Dry Matter Concentration Simulation

Implementation of the single pod dry matter concentration algorithm described above is used in the model to simulate the aggregated pod dry matter concentration. The CROPGRO Snap bean model exhibited good performance in simulating the seasonal pod dry matter concentration (Figure 6-8). Indeed, the simulated dry matter concentration matched well with the observed values, irrespective of the N rates. This result indicates therefore that dry matter concentration of snap bean pods appears to be relatively unaffected by N stress. However, Scholberg (1997) suggested that increased N supply may result in a reduction in dry matter percentage, due to increased plant growth and a dilution of dry matter concentration of tomato fruit. Similar to our results, Kenig et al. (1993) observed that pod DMC for soybean increased exponentially over time, with the later rapid phase caused by the drying of pods during seed maturation.

Harvest for the fresh market occurred at 23 days after anthesis (indicated on figure by the arrow). At this time, the pod dry matter concentration was around 10% regardless the N rates. As many horticultural crops grown for fresh market are characterized by a low DM concentration, this compares well with values reported by Gardiner and Prendiville (1970) and Ferreira et al. (2006). Based on this pod quality variable, it can be concluded that in our experiments and the model prediction, the harvest for fresh market occurred at the appropriate period. It is of interest to note that Marcelis et al. (1998) observed that the relationship between growth in fresh matter and DM, which determines the DM concentration, is still poorly understood and reported that to some extent the accumulation of water might be independent of the accumulation of DM and suggested that a model in which carbon production and partitioning are combined with water uptake and transpiration may be the first step in direction of a more mechanistic model for DM concentration.

Total Pod Fresh Weight Simulation

Simulation of the time course of total aggregated pod fresh weight of snap bean grown under four N rates is illustrated on Figure 6-9. At high N rate, the model predicted well the accumulation of pod fresh weight, but slightly under-predicted this variable as the N supply was reduced. During the initial expolinear phase, the model showed good prediction ability for the progression of pod fresh mass for the three highest N treatments, but for the low N treatment, it began to under-predict the pod fresh weight from 20 days after anthesis until the end of growing season, although this may not be important after that time. To place this analysis into perspective, consider that harvest for fresh market production in this study occurred 23 days after anthesis or 64 days after sowing. Data observations after this period are irrelevant to fresh market harvest because pods are already too mature and beginning to dry out. Therefore, when analysis accounts for only the period up to fresh market yield production, the model shows good prediction capability irrespective of N treatments. The simulated maximum pod fresh weights were reached slightly later than the observed maximum value. The Root Mean Square Error (RMSE) values of pod fresh weight prediction were 1673, 1814, 1948 and 1365 kg ha^{-1} and the d-statistic values were 0.95, 0.97, 0.97 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}. Data on simulation of pod dry matter presented in Chapter 5 were relatively consistent with this analysis showing relatively good prediction capability of the model. Given that the fresh market pod yield is derived from the pod dry matter concentration functional relationship, good prediction of pod dry matter should also ultimately result in good prediction of pod fresh weight, if the environmental conditions and management practices remain equal.

Pod Size Simulation

Pod sieve size is considered an important quality aspect of snap bean grown for fresh market. Snap bean pods are marketed based on the U.S. grade standards defined in terms of the pod sieve size which itself is related to the pod diameter. Figures 6-10 and 6-11 illustrate the time courses of simulated and measured individual pod diameter and pod sieve size, respectively. In essence, simulations of single pod diameter and sieve size progression over time appeared to relatively follow the general trend of the measured values under different N treatments. However, it appears that the model was initially too rapid in predicting the growth pattern of fresh pod diameter but later consistently matched the dynamics of measured pod diameter. The simulated pod diameter during this initial growth phase appeared not to be affected by different N treatments, but showed slight differences during later stages. The RMSE values of pod diameter simulation were 1.55, 1.41, 1.39 and 1.32 and the d-statistic values were 0.73, 0.79, 0.80 and 0.82 for N treatments 37, 74, 111 and 148 kg ha^{-1}. These values suggest that the model slightly under-estimated the pod diameter when N application was low. Simulation of fresh weight of individual pod presented in Figure 6-7 above is consistent with this analysis which showed relatively poor prediction of pod fresh weight at low nitrogen. Accordingly, given the functional relationship between pod diameter and pod fresh weight, poor prediction of pod diameter was just a direct consequence of poor performance of the model in simulating the pod fresh weight notably at low N rate.

After the linear increase phase of pod diameter from 10 to 20 days after anthesis, the time course of pod diameter showed a steady plateau phase which indicates that the pod had reached its full size. The subsequent calculated decrease phase of diameter is related to pod drying and loss of fresh weight, and is thus not as important to predicting pod quality. The linear growth phase of the pods corresponds to the period of cell enlargement and higher water import and assimilates which leads to the maximum diameter (pod size) when seed development may still be insignificant. When a pod reaches its full size, the import of water into the pod ceases and subsequently pod DMC continues to increase.

The temporal distribution patterns of pod sieve size presented in Figure 6-11 show step increases in pod size similar to, and triggered by, pod diameter with short plateau phases which indicates the time for passage from one sieve size to another one. The increase in pod size corresponds to the period of intense accumulation of water and assimilates into the pods; implying that assimilates and water import play a dominant role in snap bean quality aspects.

The model did not show any differential response to N treatments relative to the time course of pod size until 15 days after anthesis. Thereafter, the lowest N treatment (N-37 kg ha-1) showed a steady plateau phase at the pod sieve size 3 while the three higher N treatments followed an increase in sieve size up to 4. A steady plateau phase shown on the plots at 20 days after anthesis illustrates that pod reached the full size which is according to the results. The decline phase observed later in the season explains a decrease in pod diameter as a result of pod drying and loss of water.

The prediction of appropriate harvest date of snap bean for fresh market is important to guarantee both optimum yield and quality of bean. Figure 6-12 illustrates concurrently the simulated progression of snap bean total fresh market yield and fresh yield in pod sieve sizes 3 and 4 over time. The arrow in the figure indicates the date of harvest for higher yield and higher bean quality which occurred around 23 days after anthesis. Our harvest was 23 days after anthesis, but optimum harvest could be 1 to 2 days earlier. After this period, fresh yield decreases rapidly (due to increase in dry matter concentration) and quality declines rapidly (pods with higher fiber). Therefore, the optimum harvest date is a compromise between two opposing components: optimum yield and optimum quality.

Simulation of the Interactive Effect of Irrigation and Nitrogen Rates on Different Crop Variables

The capability of the CROPGRO Snap bean simulation model to predict various snap bean crop variables under different irrigation regimes was evaluated through prediction of total shoot dry weight, pod dry weight, pod fresh weight and average pod diameter. Figure 6-13 illustrates the effect of irrigation and N treatments on snap bean total shoot dry weight at fresh market harvest date. In general, the model appears to slightly over-predict the shoot biomass irrespective of different irrigation regimes, but it did not show any difference among irrigation treatments notably at the three higher N rates.

On the other hand, analysis of the simulated pod dry weights versus measured pod dry weights at harvest shows a discrepancy in the model performance with respect to irrigation regimes effects. Irrespective of the N treatments, the simulated pod dry weight under low irrigation regime was higher than the simulated pod dry weight under high irrigation. Additionally, when these simulated pod dry weights were compared with observed pod dry weights under the respective irrigation conditions, it appears that the model over-predicted pod dry weight under low irrigation while under-predicting it at high irrigation, notably at the lower nitrogen rates (37 and 74 kg ha^{-1}). This simulated result could be related to more N being available for uptake under low irrigation than high irrigation. Results of simulated N uptake from the soil under low and high irrigation regimes at the N rate of 148 kg N ha^{-1} show that total simulated N uptake from the soil was higher in low irrigation than high irrigation (160.0 versus 125.9 kg ha^{-1}). Less N uptake simulated in the high irrigation treatment can also be a result of higher simulated N leaching from the root zone. Analysis of the amount of simulated N leached at the N rate of 148 kg ha^{-1} shows that the model is predicting higher N leaching at high irrigation (99.8 versus 27.6 kg ha^{-1}). The differential performance of the model with regard to the irrigation regimes may be due to a combination of deficiencies in model inputs or parameters which influence water uptake and ET in the model. It is important to highlight that our initial model calibration was performed under medium irrigation regime (100% ET) and initial soil N and soil organic matter fractions and N uptake rates per unit root length were the only N-related variables adjusted during the calibration procedure. Therefore, it appears that further modification and adjustment of parameters are still needed to better capture N uptake and transpiration parameters in the model.

With no surprise, the trend for pod dry weights was similar to that observed for the pod fresh weights with the simulation in low irrigation performing better that the high irrigation treatment (Figure 6-15). Given the functional relationship between pod dry weight and pod fresh weight, this deficiency in pod fresh weight simulation resulted from the discrepancy in pod dry weight reported previously.

Finally, Figure 6-16 illustrates the interactive effect of simulated and observed fresh pod diameter at fresh market harvest. Inspection of these plots did not reveal any meaningful difference in response to the interactive effect of irrigation and N treatments on the simulated versus observed pod diameter.

Conclusion

To simulate fresh market production and pod quality of snap bean under different N and irrigation regimes, new algorithms of pod dry matter concentration and pod diameter were developed and incorporated into the CROPGRO dry bean model calibrated for snap bean. Although the proposed model for snap bean fresh market production and quality is still in its initial development stage, preliminary modeling results appear to be encouraging. Indeed, the pod dry matter concentration was well predicted and appeared to be unaffected by differential N rates. In this model, single pod fresh weight was derived from dry matter concentration function and the total fresh market pod production was computed on the land area basis. Results of simulation indicate that at high N rate, the model predicted well the accumulation of total pod fresh weight, but slightly under-predicted it at low N treatment. Further, simulation of pod sieve size and pod diameter, important snap bean quality aspects, were also acceptable and were not significantly affected by various N treatments.

Simulating the seasonal changes in crop production variables under different irrigation regimes and nitrogen rates helped to evaluate the model stability and performance. An analysis of the influence of interactive effect of irrigation regimes and N rates on fresh weight pod indicated that the model predicted too high under low irrigation regime and predicted too low under high irrigation regime in simulating pod fresh weight at fresh harvest date. This finding was attributed to relatively higher prediction of N leaching in high irrigation regime and consequently lower available N for uptake as opposed to low irrigation. This discrepancy is associated in part to deficiency and inaccuracy of parameters and inputs in the model which influence water balance and N uptake. Therefore, further model improvements are thus still needed for a better understanding of some underlying processes in order to overcome limitations and to enhance the accuracy of our model predictions, notably under differential irrigation conditions.

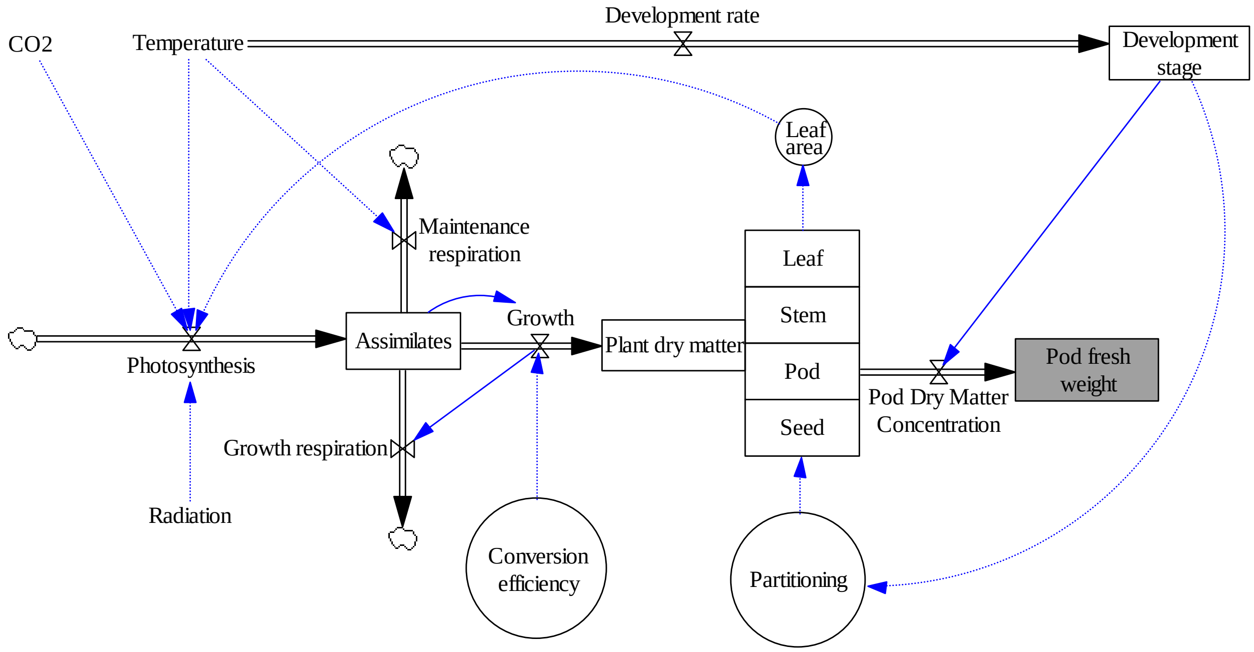

Figure 6-1. A relationship diagram of the crop model used in the present study. Boxes are state variables, valves are rate variables, circles are parameters, solid lines represent carbon flow, and dashed lines represent information flow. Adapted from Jones and Luyten (1998) and Marcellis et al. (1998).

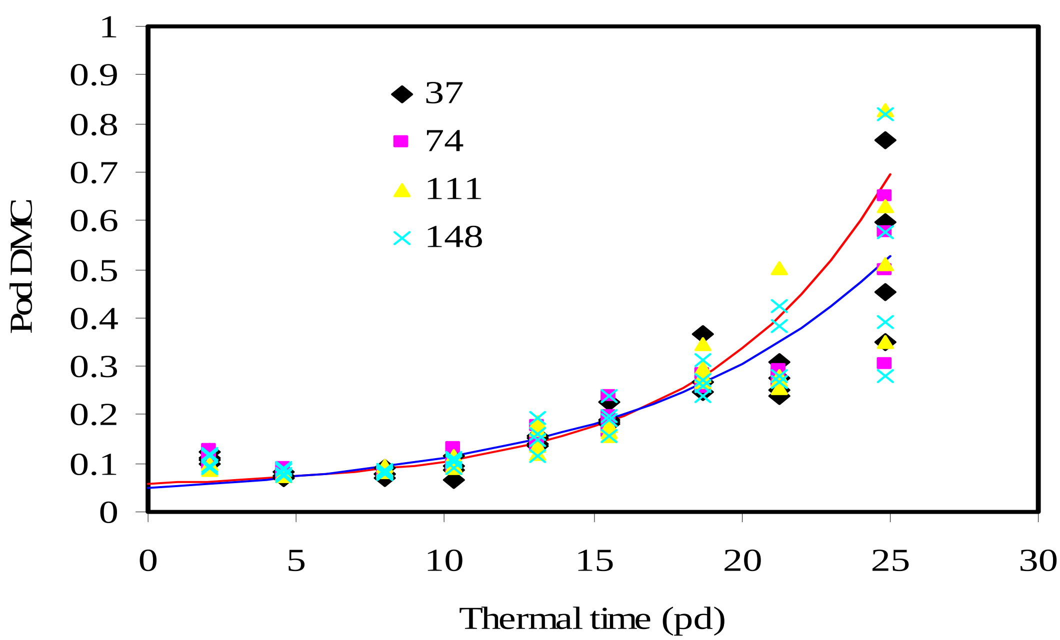

Figure 6-2. Progression of single pod dry matter concentration versus thermal time (photothermal days) for pods tagged 10 Days After Anthesis (DAA) on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

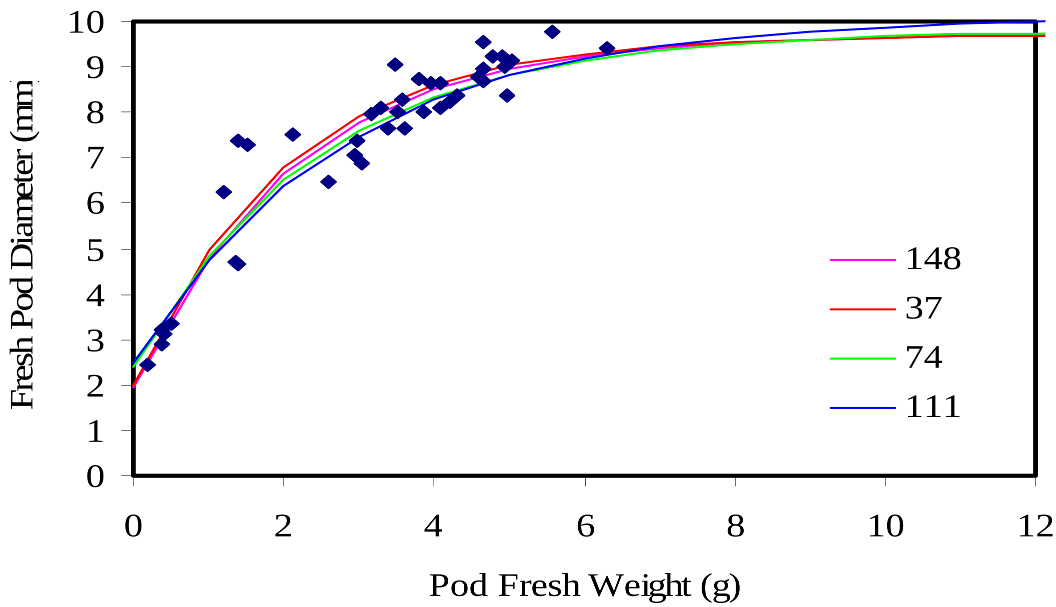

Figure 6-3. Pod diameter versus single pod fresh weight for pods tagged 10 DAA on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

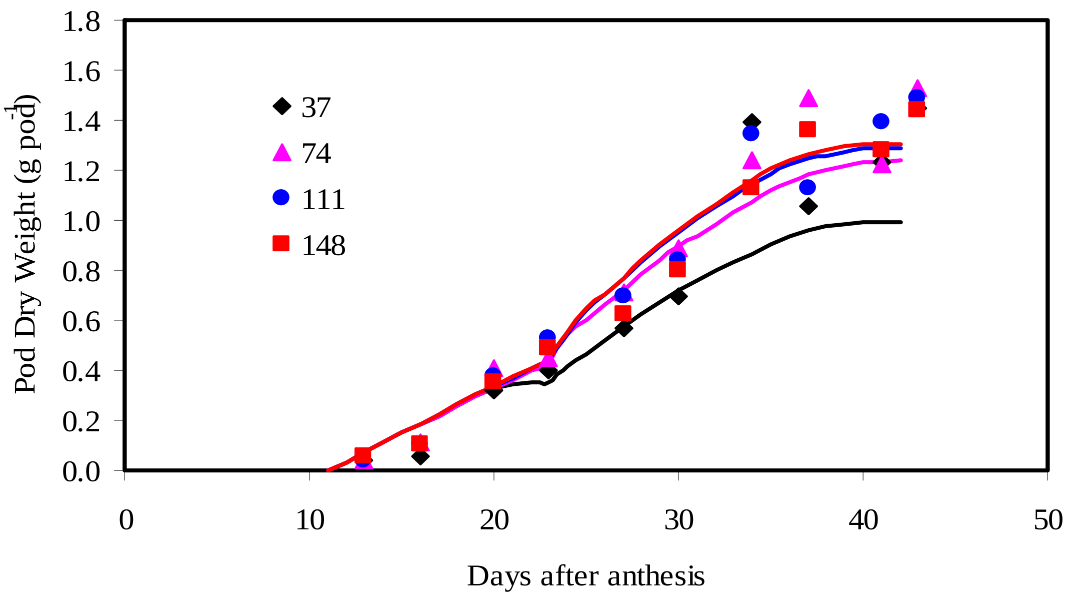

Figure 6-4. Model simulated (lines) and observed (symbols) average pod dry weight per pod as a function of days after anthesis for pods tagged 10 days after anthesis (DAA) on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

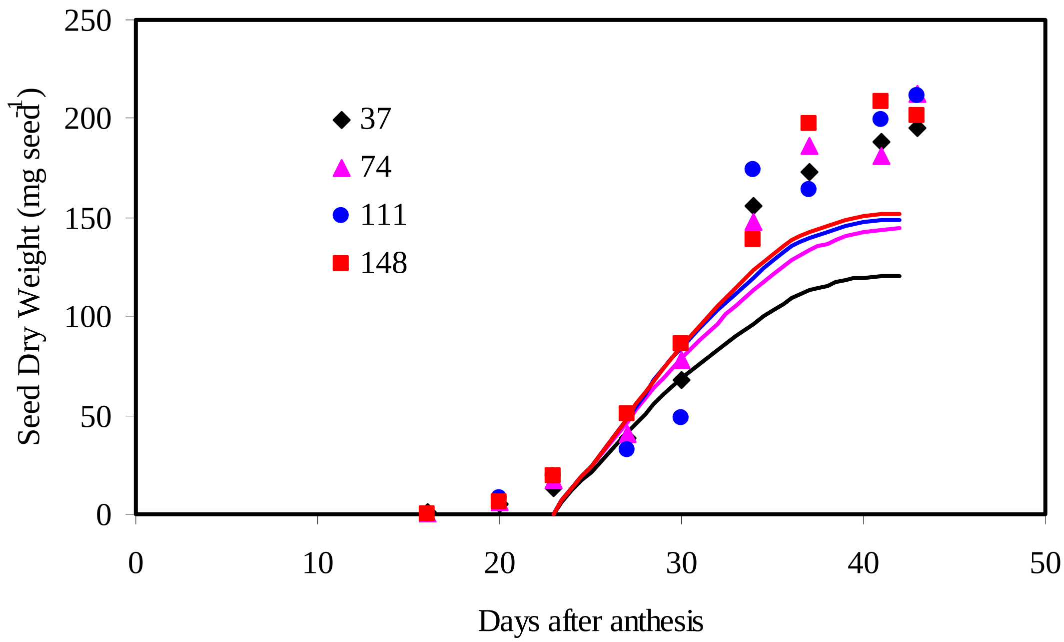

Figure 6-5. Model simulated (lines) and observed (symbols) average seed dry matter per seed as a function of days after anthesis for pods tagged 10 DAA on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

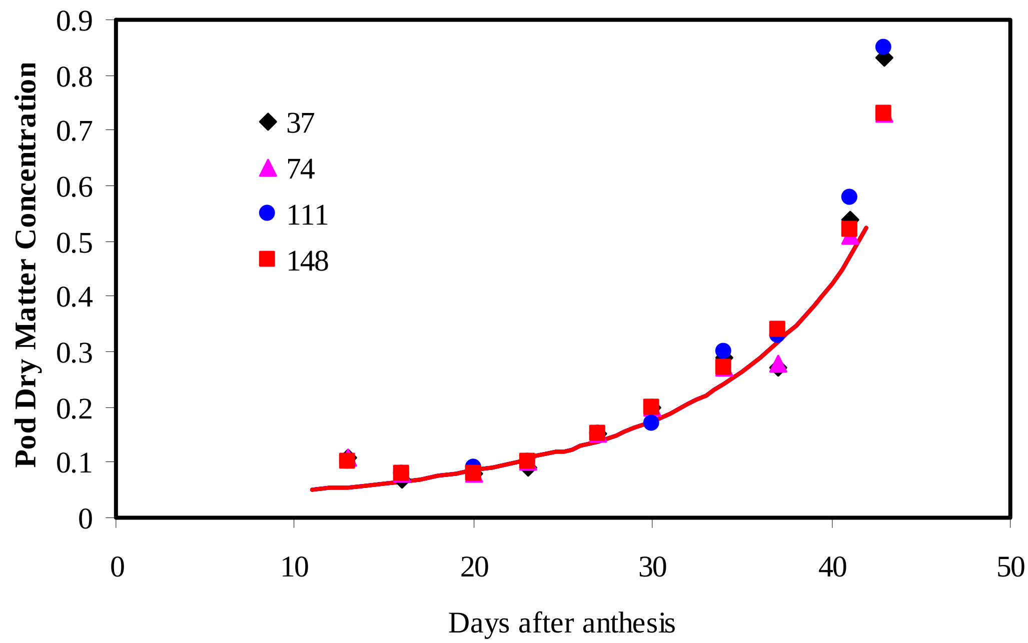

Figure 6-6. Model simulated (lines) and observed (symbols) single pod dry matter concentration as a function of days after anthesis for pods tagged 10 DAA for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

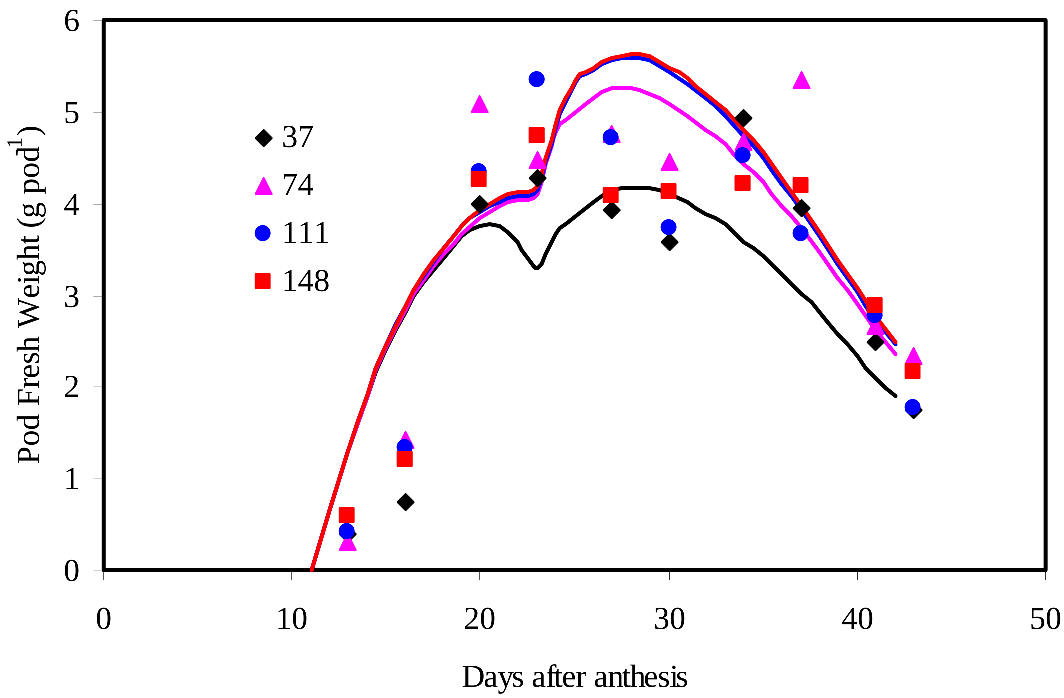

Figure 6-7. Model simulated (lines) and observed (symbols) average pod fresh weight per pod as a function of days after anthesis for pods tagged 10 DAA for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

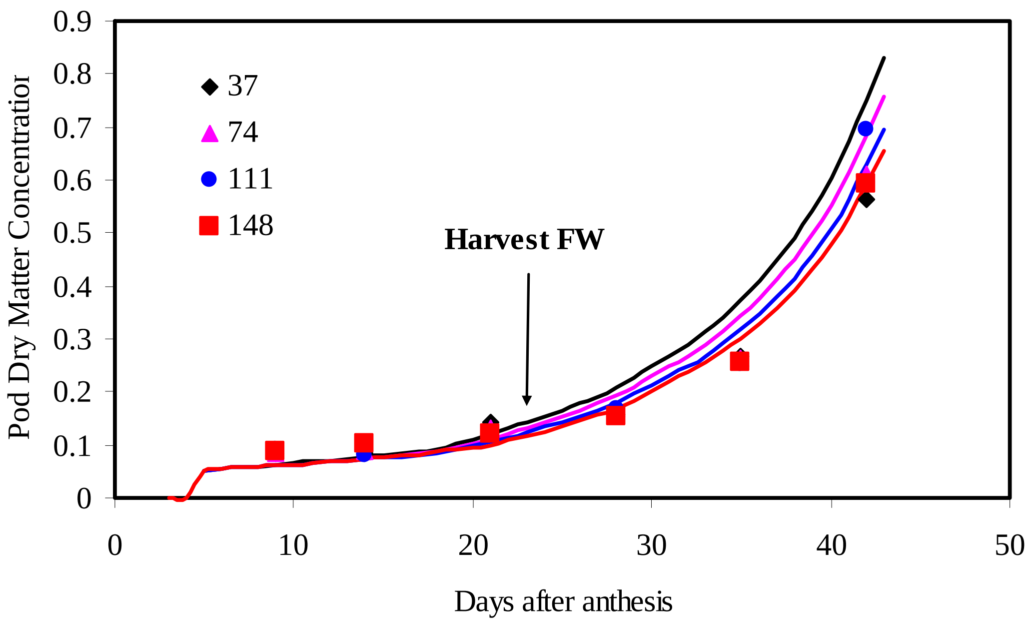

Figure 6-8. Model simulated (lines) and observed (symbols) total pod dry matter concentration as a function of days after anthesis for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

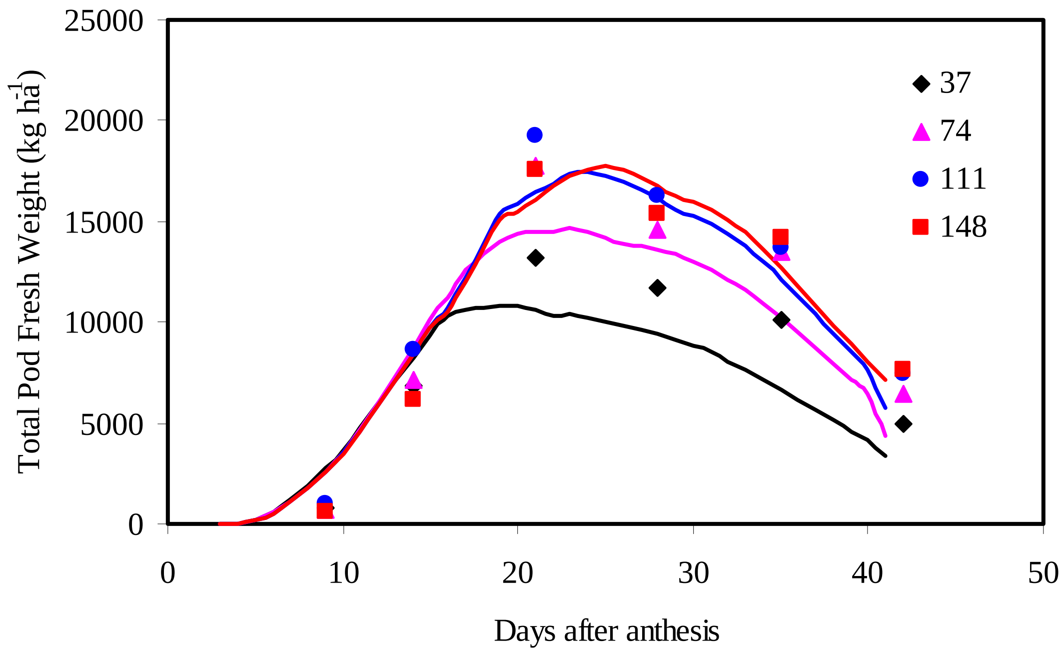

Figure 6-9. Model simulated (lines) and observed (symbols) total fresh market pod yield as a function of days after anthesis for snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

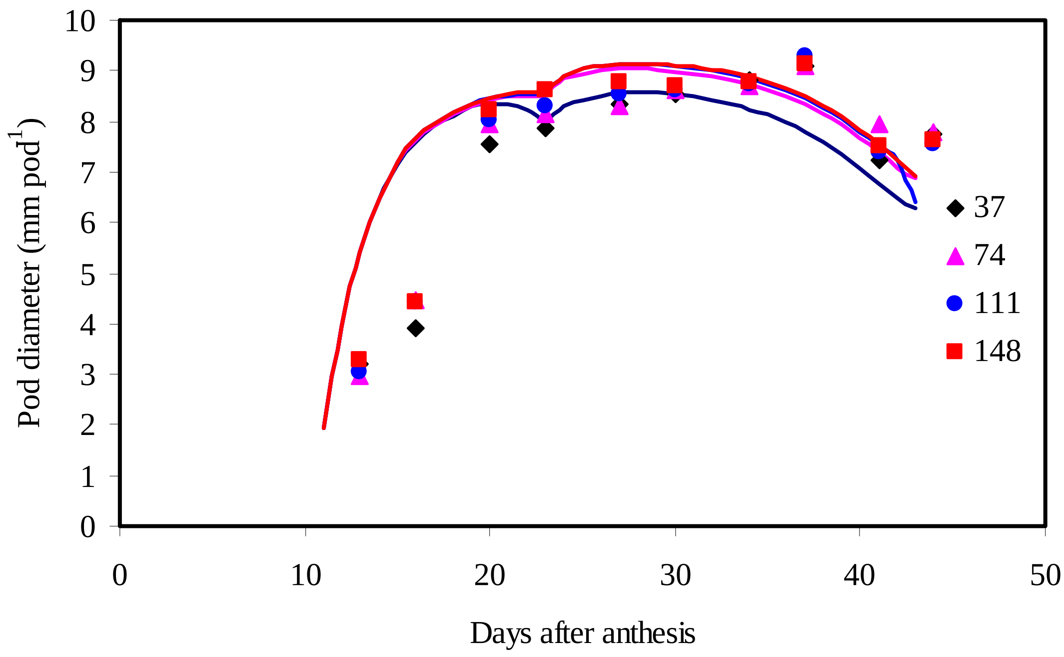

Figure 6-10. Model simulated (lines) and observed (symbols) single pod diameter as a function of days after anthesis for pods tagged 10 DAA on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

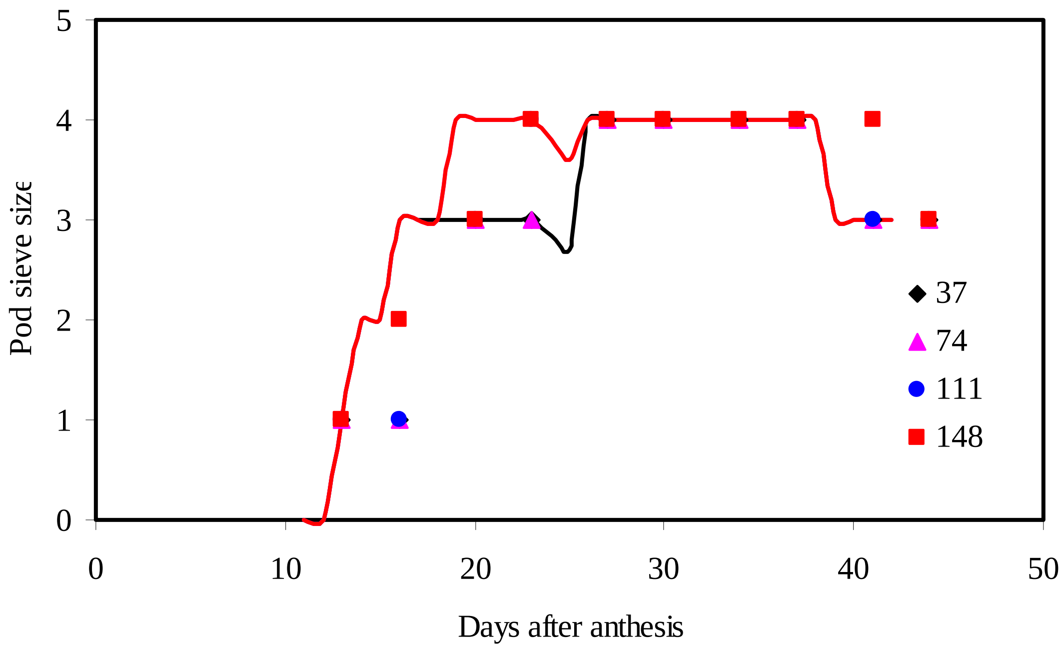

Figure 6-11. Model simulated (lines) and observed (symbols) single pod sieve size as a function of days after anthesis for pods tagged 10 DAA on snap bean cultivar Ambra grown under four N rates in Gainesville FL during spring 2007

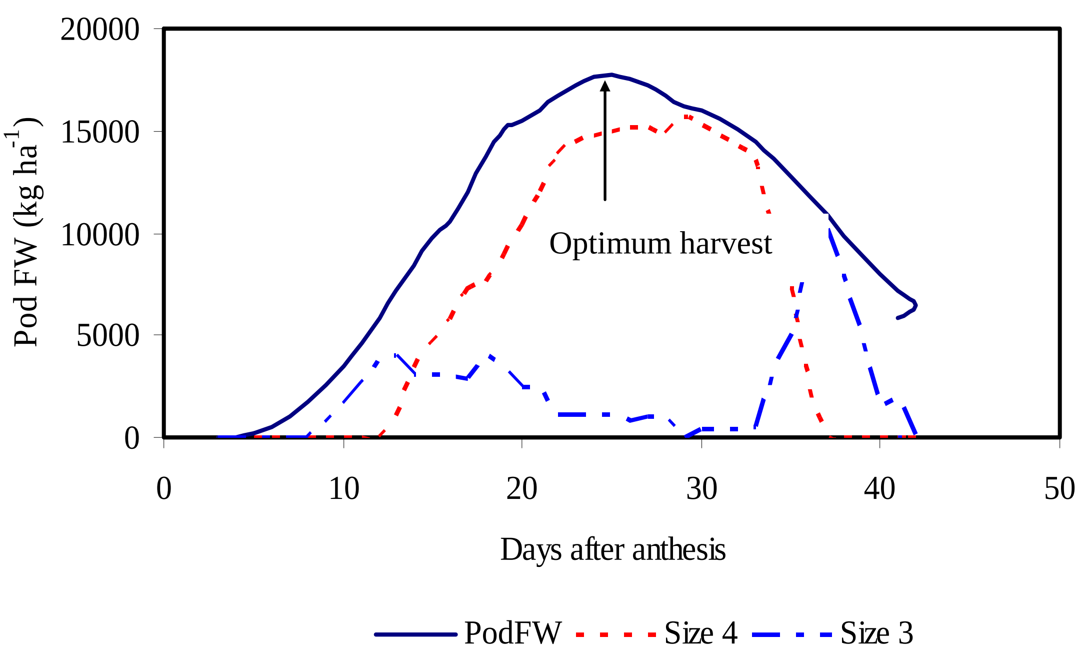

Figure 6-12. Cumulative progression of total pod fresh weight and fresh pod weight in pod sieve sizes 3 and 4 as a function of days after anthesis for snap bean cultivar Ambra grown under N rate of 148 kg ha^{-1} in Gainesville FL during spring 2007

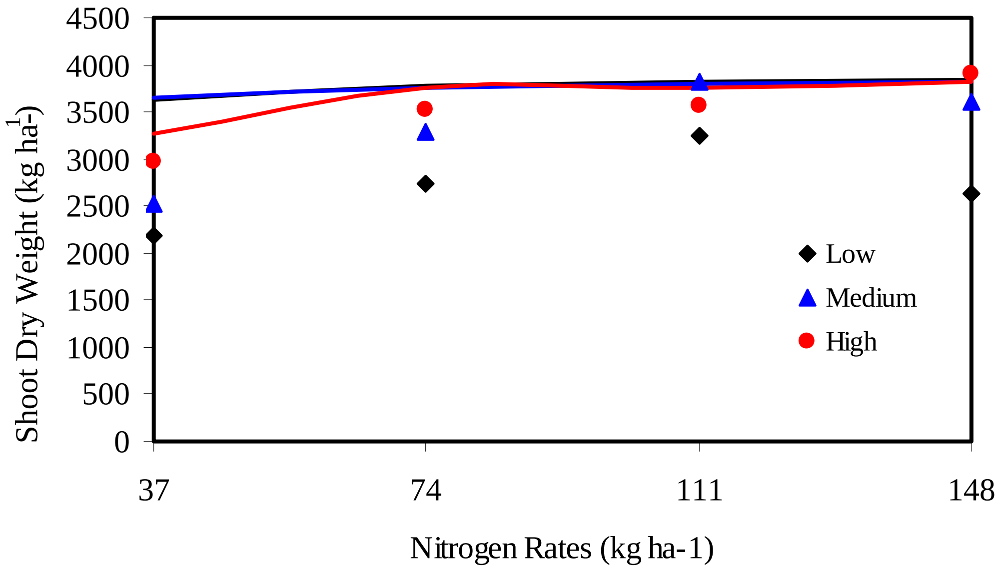

Figure 6-13. Mode simulated (lines) and observed (symbols) shoot dry weight of snap bean cultivar Ambra at fresh harvest date (64 DAS) as affected by N rates under low, medium, or high irrigation regimes in Gainesville FL during spring 2007

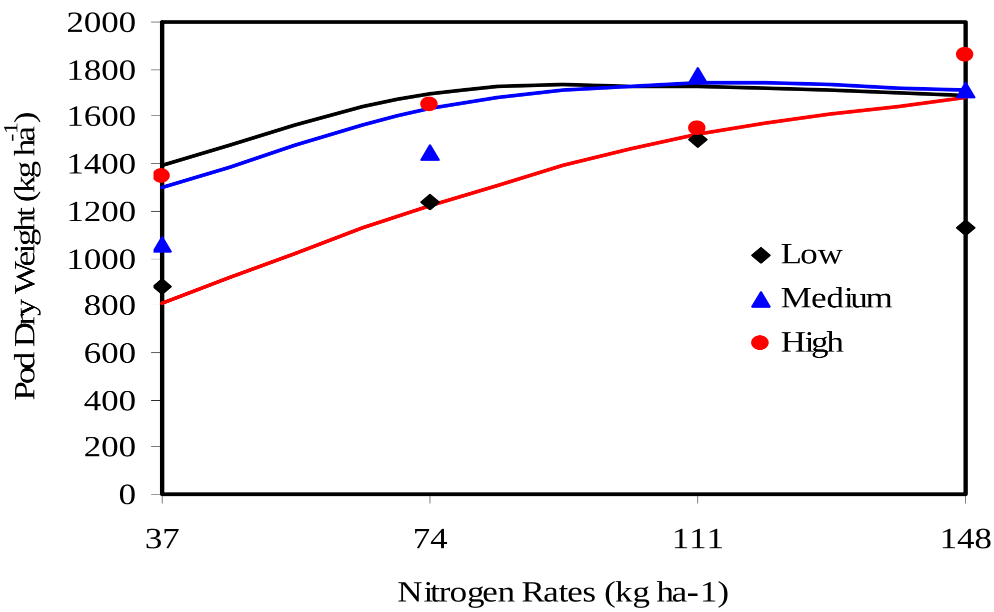

Figure 6-14. Model simulated (lines) and observed (symbols) pod dry weight of snap bean cultivar Ambra at fresh harvest date (64 DAS) as affected by N rates under low, medium, or high irrigation regimes in Gainesville FL during spring 2007

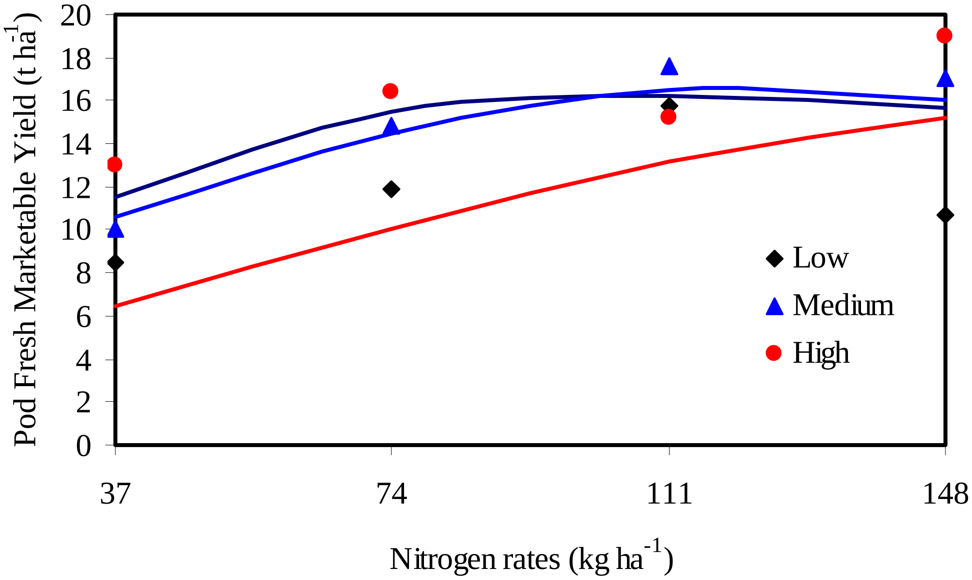

Figure 6-15. Model simulated (lines) and observed (symbols) pod fresh weight of snap bean cultivar Ambra at fresh harvest date (64 DAS) as affected by N rates under low, medium, or high irrigation regimes in Gainesville FL during spring 2007

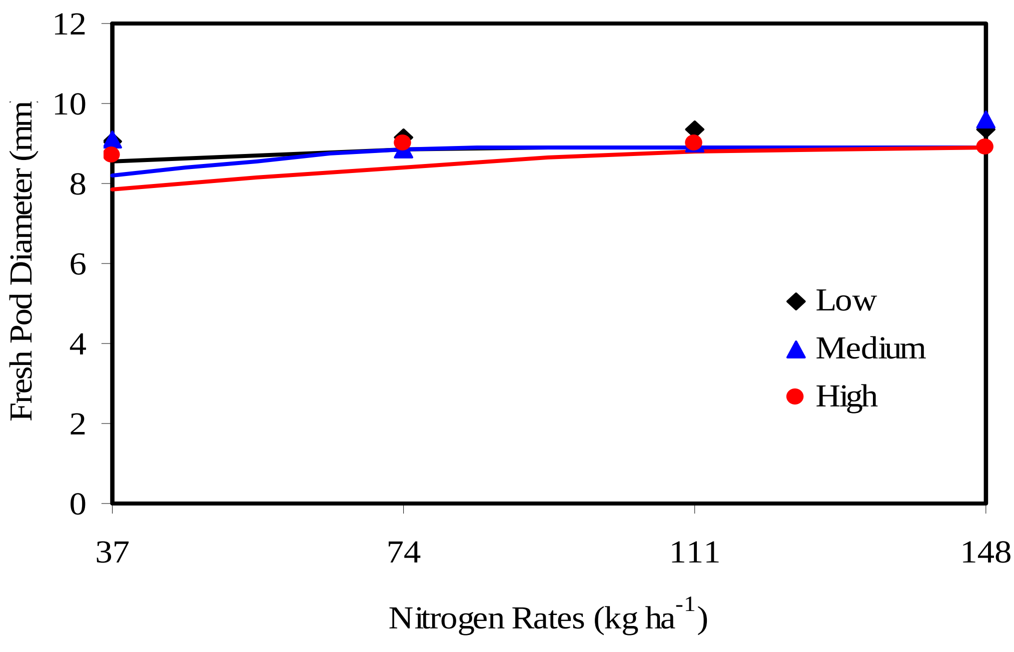

Figure 6-16. Model simulated (lines) and observed (symbols) fresh pod diameter of snap bean cultivar Ambra at fresh harvest date (64 DAS) as affected by N rates under low, medium, or high irrigation regimes in Gainesville FL during spring 2007

CHAPTER 7
SUMMARY AND CONCLUSIONS

Snap bean (*Phaseolus vulgaris*) is an economically important vegetable grown in Florida which accounts for 35% of the total harvested U.S. fresh market of snap bean and 55% of the overall U.S. crop value. Computer simulation models have become valuable management tools for assessing crop growth, yield and nutrient movement in plant and soil in relation to the weather, soil and management practices. Existing simulation models have limited capability in assisting production of crops such as snap bean which are primarily grown for fresh market because most models only predict yield on dry matter basis. The purpose of this study was therefore to develop a snap bean simulation model to predict the fresh market yield and quality of pods as affected by irrigation and nitrogen levels. In this effort, a field experiment was conducted at the Irrigation Research and Education Park located on the University of Florida in Gainesville, Florida, during March-June 2007 to study the growth and N uptake response of snap bean (*Phaseolus vulgaris* L.) to N fertilization (Chapter 3) and to evaluate the yield response of snap bean to the interactive effect of irrigation regimes and N fertilization (Chapter 4). Data collected in this experiment were used to adapt the CSM version of the CROPGRO Dry bean model to simulate the growth and development of snap bean (Chapter 5) and finally to develop a fresh weight and pod-size module in order to simulate fresh market yield and quality using the calibrated CROPGRO model as starting point (Chapter 6). Four N fertilization rates (37, 74, 111 and 148 kg N ha^{-1}) were applied to snap bean cultivar Ambra grown under three irrigation regimes (Low (66% crop Et, Medium (100% Et) and High (133% crop Et)) as main plots distributed in a split plot design, with four replications.

Snap Bean Growth Study

The first objective of this study was to provide insight into the pattern of crop physiological variables over the full growth period to maturity for field-grown snap bean under different N rates at medium irrigation regime. Measurements of canopy growth, leaf area index, dry matter and N distribution in plant parts were performed weekly, starting at 14 days after sowing. Results indicated that snap bean growth parameters analyzed in this study responded consistently to N fertilization. Leaf area index, aboveground biomass and distribution, plant N accumulation and allocation among plant tissues all showed consistent patterns with increasing N rates. More specifically, the leaf area index (LAI) increased rapidly, with minor effect of N rates. Maximum values of LAI for treatments of 37 and 111 kg N ha^{-1} were 2.0 and 2.6, respectively, at 55 days after planting. Thereafter, a decline in LAI was observed which was relatively more rapid at the lowest N rate. The dry matter accumulation of snap bean did not differ meaningfully across N rates until about 55 days after planting but thereafter the lowest N rate showed lower dry matter accumulation rate as opposed to the three higher N rates which did not show any apparent differences from each other. Average crop growth rates computed from the slopes of near-linear periods of total biomass increase (34-76 DAP) were 81, 108, 109 and 109 kg ha^{-1} d^{-1} for 37, 74, 111 and 148 kg N ha^{-1}, respectively. With differences between N rates typically becoming more evident over time, towards the end of the growing season, final DM accumulation was 26% higher for the three higher N-fertilizer rates than the lowest N rate. Fractional distribution of total dry matter among above-ground plant parts indicated that across all the N treatments, snap bean allocated maximum dry matter to the seeds, followed by pods, stems and leaves towards the end of growing season.

Nitrogen distribution in plant components was largely affected by N fertilization. Leaf N concentration in all treatments was relatively high at very early stages of plant development, and started declining consistently due to remobilization of N to other plant parts, notably to seed. N uptake was considerably increased by N fertilization. The crop absorbed almost of its N prior to 57 DAS.

Snap Bean Yield and Pod Quality Study

Proper management of water and fertilizers are vital to the high productivity of snap bean in the commercial production system while concurrently reducing the environmental consequences of intensive management practices. This study evaluated the effects of interaction of water irrigation and inorganic N-fertilizer on fresh market production and quality of snap bean. Harvest for fresh market yield and pod quality aspects occurred at 64 days after sowing. Results indicated that individual effects of irrigation and N fertilizer levels showed significant influence on the fresh market yield of snap bean and the interaction of irrigation and N rates was also significant. More specifically, at the low irrigation regime (66% ET), fresh market yields were 8.5, 11.8, 15.7, and 10.6 Mg ha^{-1} for the 37, 74, 111, and 148 kg N ha^{-1} treatments, respectively. At the medium irrigation treatment (100% Et), yields were in the order of 10.1, 14.8, 17.5, and 17.1 Mg ha^{-1} and finally, at the high irrigation level (133% ET), they were 12.9, 16.3, 15.2 and 18.9 Mg ha^{-1}, respectively. Therefore, irrigation amplified the N effect except at the low irrigation at which the difference between the lowest N rate (N37) and the highest rate (N148) was very small. Furthermore, at low irrigation regime, increasing N rates did not increase linearly the fresh market yield. There was no yield benefit with N-rates over 111 kg ha^{-1} (IFAS recommended N rates for snap bean) at low or medium irrigation. However, at high irrigation regime, increasing N fertilizer from 37 to 148 kg N ha^{-1} substantially increased fresh marketable yield, confirming that the soil water content (irrigation regime) is a very important limiting factor to fresh market yield, followed by N effect. Additionally, results illustrated that pod quality parameter for fresh marketable yield such as pod diameter responded linearly to both irrigation and N rates while pod length and number of seed per pods were linearly responsive to the irrigation regimes and quadratically to the N rates. Overall, there was no interaction of irrigation and N rates on these pod quality parameters. Despite these small significant differences, it appeared from these results that pod quality parameters overall were not affected in a major way by irrigation and N effects. Finally, analyzing the temporal and spatial distribution of both nitrate and ammonium contents in the soil profile showed that nitrate and ammonium were higher in the deepest layers (90-120 cm) at the end of the season irrespective of irrigation regimes, implying accumulation of these nutrients leading to possible leaching into ground water.

CROPGRO Snap Bean Model Development Study

Crop modeling is a mathematical method developed for predicting the growth, development, and yield of a crop, given a set of genetic coefficients and relevant environmental variables. In this study, the CROPGRO Dry Bean simulation model embedded in DSSAT 4.5 was adapted to accurately simulate the shoot dry matter accumulation and pod dry matter, and a new module was added to the calibrated model to simulate the fresh market yield and pod quality of snap bean. The approach of model adaptation involved iterative calibration of the species, cultivar, and ecotype files of dry bean to parameterize CROPGRO for snap bean. The measured data from the field experiments described in previous sections were used during this procedure. Calibration was conducted by minimizing the error between observed and simulated variables. As a result, CROPGRO Dry Bean captured most of the patterns of crop growth and development in snap bean and has adequate capabilities to predict the life cycle, biomass accumulation and yield components of snap bean over time, suggesting thus that the physiology of snap bean is relatively similar to other legumes simulated by the model, such as dry bean. Simulated changes in dry matter accumulation globally matched well with observed measurements. The Root Mean Square Error (RMSE) values of calibration data was 390, 129, 164 and 196 kg ha^{-1} and the d-statistic was 0.98, 0.99, 0.99 and 0.99, respectively for the N rates of 37, 74, and 111 and 148 kg ha^{-1} indicating good prediction of this variable. The model predicted well the distribution of total dry matter within plant. Across all N rates, simulation of the time courses of dry matter partitioning was in general in accordance with the pattern of distribution of measured dry matter partitioning. With adjustments of parameters defining N uptake and mobilization in the species files, the simulated yield and yield components were generally in good agreement with the data obtained under different N rates. More specifically, RMSE and d-statistic of pod weight for the calibration were 150, 191, 224 and 315 kg ha^{-1} and 0.99, 0.99, 0.99 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}.

The main goal of this study was to develop a snap bean simulation model to predict fresh market yield and quality of pods. In this effort, pods of 2-cm length and near uniform size were tagged at 10 days after anthesis and time-sequence measurements were made to evaluate pod growth and quality aspects. With data collected on the tagged pods, a Dry Matter Concentration algorithm (DMC) was developed as a function of thermal time and enabled computing the pod fresh weight. Also, a functional relationship between measured pod diameter (which defines pod quality) and measured pod fresh weight was developed, subsequently allowing prediction of the U.S. standard grades of fresh market of snap bean which depend on pod diameter. A new module to simulate the aggregated time-courses of fresh market yield (kg ha^{-1}) and pod quality was thus developed through introduction of the different algorithms and code added to the calibrated CROPGRO simulation model structure. As a result, the CROPGRO Snap Bean model exhibited good performance in simulating the seasonal pod dry matter concentration irrespective of the N rates. This result indicates that dry matter concentration of snap bean pods appears to be relatively unaffected by N stress. Additionally, simulation of the time course of total aggregated pod fresh weight of snap bean grown under four N rates indicated that at high N rate, the model predicted well the accumulation of pod fresh weight, but slightly under-predicted pod fresh weight as the N supply was reduced. More specifically, during the early pod growth phase, the model showed good prediction ability for the progression of pod fresh mass for the three highest N treatments, but for the low N treatment, it began to under-predict the pod fresh weight from 20 days after anthesis until the end of growing season, although this may not be important to fresh weight prediction after that time. The Root Mean Square Error (RMSE) values of pod fresh weight prediction were 1.67, 1.81, 1.95 and 1.36 Mg ha^{-1} and the d-statistic values were 0.95, 0.97, 0.97 and 0.98, respectively, for the N rates of 37, 74, 111 and 148 kg ha^{-1}.

Simulation of pod diameter and pod sieve sizes which define snap bean pod quality was also acceptable. Single pod diameter and sieve size progression over time appeared to relatively follow the general trend of the measured values under different N treatments, except that the model was initially too rapid in predicting the pattern of fresh pod diameter but this later consistently matched the dynamics of measured pod diameter. The RMSE values of pod diameter simulation were 1.55, 1.41, 1.39 and 1.32 and the d-statistic values were 0.73, 0.79, 0.80 and 0.82 for N treatments 37, 74, 111 and 148 kg ha^{-1}. Analyzing concurrently the simulated progression of snap bean total fresh market yield and fresh yield in pod sieve sizes 3 and 4 over time for this variety of snap bean under the agroclimatic conditions prevailing in Gainesville, indicates that the period of harvest for higher yield and higher bean quality should have occurred around 21 days after anthesis. Our harvest was 23 days after anthesis, *i.e.* 2 days later. Finally, simulating the seasonal changes in crop production variables under different irrigation regimes and N rates helped to evaluate the model stability and performance. An analysis of the influence of interactive effect of irrigation regimes and N rates on fresh weight pod indicated that the model predicted too high under low irrigation regime and predicted too low under high irrigation regime in simulating pod fresh weight at fresh harvest date. This finding was attributed to relatively higher prediction of N leaching in high irrigation regime and consequently lower available N for uptake as opposed to low irrigation. This may indicate that the model is not properly accounting for water uptake and transpiration or possibly not correctly accounting for N mineralization aspects under the differential soil water regimes.

Implications of the Research and Future Work

A crop simulation model capable of predicting growth and fresh market production and quality of snap bean as affected by irrigation and N fertilization was developed based on the existing CROPGRO Dry Bean model in DSSAT 4.5. Although the proposed model for snap bean fresh market production and quality is still in its initial development stage, preliminary modeling results appear to be encouraging. As the first working version, the model could provide potential users with relatively accurate prediction of yield and period of harvest for pod quality for crops grown under high N fertility, and therefore could be used as an application tool or in decision-support process. However, the current level of accuracy and prediction capability in the model must be enhanced through further testing and validation studies based on field experiments conducted in different agroclimatic zones (South Florida for instance) and also different snap bean cultivars. Besides a dry matter concentration approach for simulating fresh weight, further viable mechanisms that influence accumulation of fresh weights in snap bean should be also investigated with the ultimate goal of improving the fresh weight module and the robustness of the model for general use in the future. The discrepancy results obtained from the effect of irrigation levels on simulated pod yields, especially at lower N rates, need to be tested to improve the robustness of the model under high and low irrigation conditions.

APPENDIX
EFFECT OF N TREATMENTS ON SNAP BEAN CROP DRY MATTER ACCUMULATION, N CONCENTRATION AND N ACCUMULATION

Table A-1. Pair wise comparison of the effects of sampling days (DAS) and N treatments on total shoot dry weight of snap bean, grown in Gainesville during spring 2007

DAS	Pair wise Comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	0.27	0.21	0.21	0.87	0.87	0.99
20	0.54	0.54	0.44	0.94	0.86	0.92
27	0.87	0.81	0.99	0.94	0.86	0.80
34	0.22	0.14	0.30	0.79	0.85	0.65
41	0.01	0.002	0.02	0.61	0.86	0.50
50	< 0.0001	< 0.0001	< 0.0001	0.42	0.88	0.34
55	< 0.0001	< 0.0001	< 0.0001	0.36	0.90	0.30
62	< 0.0001	< 0.0001	< 0.0001	0.32	0.93	0.26
69	< 0.0001	< 0.0001	< 0.0001	0.31	0.96	0.29
76	< 0.0001	< 0.0001	< 0.0001	0.32	0.98	0.31
83	< 0.0001	< 0.0001	< 0.0001	0.33	0.99	0.33

Table A-2. Pair wise comparison of the effects of sampling days (DAS) and N treatments on pod dry weight of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise Comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	-	-	-	-	-	-
20	-	-	-	-	-	-
27	-	-	-	-	-	-
34	-	-	-	-	-	-
41	-	-	-	-	-	-
50	0.69	0.36	0.36	0.75	0.80	0.92
55	0.10	0.001	0.002	0.40	0.53	0.77
62	0.0001	< 0.0001	< 0.0001	0.05	0.18	0.50
69	< 0.0001	< 0.0001	< 0.0001	0.0005	0.05	0.32
76	< 0.0001	< 0.0001	< 0.0001	0.005	0.04	0.29
83	< 0.0001	< 0.0001	< 0.0001	0.008	0.04	0.31

Table A-3. Pair wise comparison of the effects of sampling days (DAS) and N treatments on seed dry weight of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	-	-	-	-	-	-
20	-	-	-	-	-	-
27	-	-	-	-	-	-
34	-	-	-	-	-	-
41	-	-	-	-	-	-
50	-	-	-	-	-	-
55	0.91	0.39	0.12	0.58	0.19	0.36
62	0.04	0.01	0.39	0.84	0.21	0.23
69	< 0.0001	< 0.0001	< 0.0001	0.67	0.39	0.17
76	< 0.0001	< 0.0001	< 0.0001	0.36	0.85	0.24
83	< 0.0001	< 0.0001	< 0.0001	0.28	0.29	0.36

Table A-4. Pair wise comparison of the effects of sampling days (DAS) and N treatments on leaf N concentration of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	0.43	0.06	0.11	0.002	0.02	0.53
20	0.69	0.005	0.03	0.001	0.01	0.60
27	0.84	0.0006	0.005	0.001	0.009	0.71
34	0.31	< 0.0001	0.0002	0.002	0.006	0.87
41	0.04	< 0.0001	< 0.0001	0.005	0.006	0.88
50	0.001	< 0.0001	< 0.0001	0.04	0.01	0.56
55	0.0002	< 0.0001	< 0.0001	0.14	0.03	0.42
62	< 0.0001	< 0.0001	< 0.0001	0.47	0.12	0.32
69	< 0.0001	< 0.0001	< 0.0001	0.92	0.28	0.27
76	< 0.0001	< 0.0001	< 0.0001	0.71	0.48	0.25
83	< 0.0001	0.0002	< 0.0001	0.48	0.68	0.24

Table A-5. Pair wise comparison of the effects of sampling days (DAS) and N treatments on pod N concentration of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	-	-	-	-	-	-
20	-	-	-	-	-	-
27	-	-	-	-	-	-
34	-	-	-	-	-	-
41	-	-	-	-	-	-
50	< 0.0001	< 0.0001	< 0.0001	0.55	0.15	0.39
55	< 0.0001	< 0.0001	< 0.0001	0.46	0.05	0.23
62	0.0001	< 0.0001	< 0.0001	0.33	0.005	0.007
69	0.04	0.003	< 0.0001	0.30	0.001	0.04
76	0.98	0.38	0.008	0.40	0.007	0.07
83	0.20	0.66	0.19	0.51	0.02	0.13

Table A-6. Pair wise comparison of the effects of sampling days (DAS) and N treatments on shoot N mass of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	0.06	0.06	0.05	0.86	0.90	0.75
20	0.29	0.58	0.34	0.61	0.87	0.71
27	0.88	0.14	0.37	0.31	0.56	0.07
34	0.08	< 0.0001	0.001	0.09	0.25	0.62
41	0.0003	< 0.0001	< 0.0001	0.01	0.07	0.57
50	< 0.0001	< 0.0001	< 0.0001	0.001	0.009	0.55
55	< 0.0001	< 0.0001	< 0.0001	0.0005	0.004	0.57
62	< 0.0001	< 0.0001	< 0.0001	0.0003	0.002	0.61
69	< 0.0001	< 0.0001	< 0.0001	0.0005	0.002	0.66
76	< 0.0001	< 0.0001	< 0.0001	0.0008	0.003	0.71
83	< 0.0001	< 0.0001	< 0.0001	0.001	0.005	0.74

Table A-7. Pair wise comparison of the effects of sampling days (DAS) and N treatments on pod N mass of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	-	-	-	-	-	-
20	-	-	-	-	-	-
27	-	-	-	-	-	-
34	-	-	-	-	-	-
41	-	-	-	-	-	-
50	0.98	0.004	0.07	0.009	0.10	0.72
55	0.42	< 0.0001	0.002	0.002	0.01	0.95
62	0.02	< 0.0001	< 0.0001	0.0004	0.0002	0.34
69	0.0005	< 0.0001	< 0.0001	0.0006	< 0.0001	0.06
76	< 0.0001	< 0.0001	< 0.0001	0.007	< 0.0001	0.03
83	< 0.0001	< 0.0001	< 0.0001	0.04	0.0002	0.03

Table A-8. Pair wise comparison of the effects of sampling days (DAS) and N treatments on seed N concentration of snap bean, grown in Gainesville during the spring 2007

DAS	Pair wise comparison of N treatments					
	37 vs 74	37 vs 111	37 vs 148	74 vs 111	74 vs 148	111 vs 148
14	-	-	-	-	-	-
20	-	-	-	-	-	-
27	-	-	-	-	-	-
34	-	-	-	-	-	-
41	-	-	-	-	-	-
50	-	-	-	-	-	-
55	0.95	0.57	0.62	0.66	0.70	0.95
62	0.08	0.05	0.12	0.83	0.88	0.98
69	0.0009	0.0001	0.0008	0.022	0.33	0.95
76	0.0002	< 0.0001	0.0001	0.08	0.15	0.91
83	< 0.0001	< 0.0001	0.0002	0.07	0.14	0.90

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BIOGRAPHICAL SKETCH

Desire Djidonou is a native of Benin, a republic in western Africa. He earned an "Agronomist Engineer Degree" (Major: Crop Production) from the College of Agronomic Sciences of the National University of Benin. He then worked 2 years on a cowpea research project to promote an Integrated Pest Management approach for controlling the pests and diseases that inflict this legume.

Upon completion of these project activities, Desire enrolled in graduate studies in the Management of Animal and Vegetable Resources in the Tropics at the University College of Agronomic Sciences of Gembloux (Belgium). This year-long program enabled him to deal with various topics such as intensification and sustainability of farming systems through the analysis of mixed crop and livestock production. One year later, he began an agricultural internship with Glades Crop Care, Inc., based in Jupiter, Florida. This company offers to Florida vegetable growers, an agricultural consultancy through integrated pest management programs. As a member of the consulting team, Desire carried out scouting responsibilities on vegetables such as tomatoes, peppers, potatoes and cucurbits. He also had the opportunity to be involved in contract research activities where he participated in the evaluation of pesticide efficacy in different cropping systems.

In August of 2006, Desire began a Master of Science program in the Agronomy Department of the University of Florida under the direction of K.J. Boote. His major field of study was ecology and physiology with an emphasis on crop modeling.