Calibration, Validation and Improvement of a Process-based Crop Simulation Model for Hardneck Garlic (*Allium sativum* L.)

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Abstract

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Crop models are powerful tools for assessing climate impacts on crops, assisting breeding and crop management decisions, predicting yield, and providing information for economic and policy decision making. Calibration and validation of these models are essential steps to evaluate the performance of a model in order to bridge the gap between simulation and reality, while identifying the areas that require improvements.

In this study, a process-based crop model developed for hardneck garlic (*Allium sativum* L.) was tested for the accuracy of predicting the phenological, morphological and physiological processes to simulate growth and development of a whole plant. Planting date, cultivar, and nitrogen level differences were applied in order to test the model performance under a range of storage and environmental conditions, and also to explore the phenotypic variability within the species. Leaf development phenology, leaf area accumulation, carbon partitioning, biomass, and yield, as well as leaf photosynthesis were measured and compared with model outputs to determine model performance. Modifications were made in phenology, morphology and photosynthesis modules to incorporate the effects of planting date, cultivar and nutrient levels, in an attempt to improve model simulations while obtaining a reasonable level of parsimony.

Field results showed that plant growth differed phenologically and morphologically amongst planting dates and cultivars. Differences in leaf development timing and final leaf number, along with changes in leaf length and width led to an overall inaccuracy in the simulation of leaf area accumulation, biomass gain, and final crop yield. Temperature-based phenological parameters were calibrated, and leaf area accumulation algorithms were restructured to incorporate the difference observed amongst planting date and cultivar groups. Model modifications resulted in improved model performance in predicting phenology, leaf area development and total biomass accumulation.

Further iterations of algorithm development, calibration, and testing will be needed to improve and expand its capability to include additional environmental and agricultural management factors. The calibration and validation process in relation to planting dates, cultivar, and nitrogen levels in this study was the first attempt to evaluate and improve the model performance at the whole-plant level, which provided a better understanding of the model, pinpointing the strengths and weaknesses and showing areas for improvement.

TABLE OF CONTENTS

Page

Chapter 1. Introduction

Chapter 2. Calibration, Validation and Improvement in Phenology and Morphology Predictions of a Process-based Crop Model for Hardneck Garlic (*Allium sativum* L.)

LIST OF FIGURES

Figure Number Page

LIST OF TABLES

Table Number

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Chapter 1 – Literature Review

1.1 Hardneck Garlic (Allium sativum L.)

1.1.1 Overview

Garlic is one of the oldest cultivated crops amongst the human agricultural history. It's long cultivation history in human agricultural activities, and is widely produced and consumed around the globe. This herbaceous perennial crop is harvested mainly for the specialized leaf structure, the bulb. It is incorporated into worldwide cousins, used as ornamentals, and is gaining a greater popularity due to its health benefits. Central Asia is hypothesized to be the origin for wild garlic (Engeland, 1991), and was widely dispersed throughout the region. Nowadays, garlic is widely cultivated globally, with a distribution from the equator to around 50˚ latitude. Garlic growth is ideal in regions with mild and moist winters followed by a dry summer with sufficient irradiation.

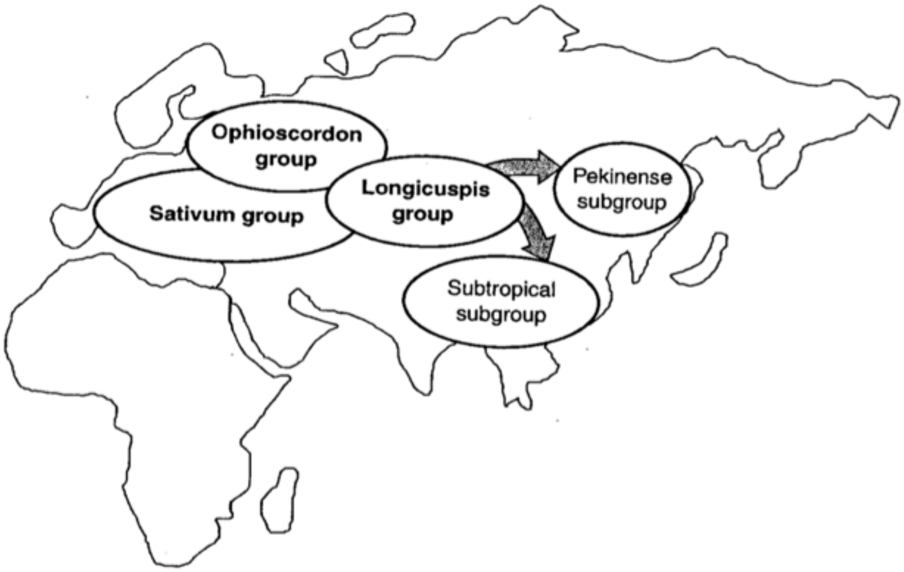


Figure 1.1. Intraspecific classification of garlic, suggesting three major groups and two subgroups (Fritsch and Friesen, 2002).

Garlic can be classified into two major groups in horticultural practices: hardneck and softneck. The major difference between the two is the production of a flowering stalk. Hardneck garlic produces a scape structure when reaching the reproductive stage, which is often termed as top setting or bolting. Flowers are produced, usually abort, and form bulbils in the inflorescence. Bulbs of hardneck garlic typically contain 1-2 whorls, producing 4-12, or up to 15 cloves depending on cultivar. Softneck garlic, on the other hand, does not produce flower stalks, with the bulbs usually containing several whorls, producing 10-50 cloves. Softneck garlic is commonly chosen for warmer climates, and generally has a much longer shelf storage time.

1.1.2 Life Cycle and Growth Habit

Due to the warm and dry summer and severe winter climate that garlic plants are adapted to, it has a relatively short aboveground growth period. As most plants in the *Allium* family, garlic is an herbaceous perennial. In temperate regions, garlic is usually planted in autumn, but in regions that experience severe winters, planting is delayed until spring. For fall planting in temperate regions, germination generally begins winter or early spring. During this low temperature period, the plants remain in their vegetative growth stage. Vernalization of the plants is caused by the exposure to low winter temperatures, and is essential for initiating future reproductive stages. Reproductive growth does not begin until early spring, with the formation of inflorescence, initiation of lateral bud primordia, and the development of storage leaves. Growth progresses into late spring or early summer, and starts to senesce as the environmental conditions start to turn warm and dry. During this period, the aboveground plant part starts to die off, partially reallocating biomass into the bulb structure. The plant enters dormancy under high temperature during the summer period, and reaches a deepest dormancy after harvest until dormancy is broken under favorable environmental conditions. This phenological pattern allows garlic plants to cope with severe cold throughout winter, and avoid extreme heat during summer. Early germination allows the plants to have a longer growth period, but also increases the risk of cold and frost damage. Even though garlic leaves have evolved to withstand heavy frost, severe winters may still cause damage to the plants. Depending on cultivar, growing region and planting date, plant growth could initiate fall and persist throughout winter.

1.1.3 Bulb Initiation and Development

The initiation of bulbing in garlic involves two processes. The first process is the formation of lateral buds in the axils of some of the youngest foliage leaves. This process is often linked with inflorescence formation, which will be described in the following section. The second process is the transition of lateral buds into storage leaves, which is when the second or third leaf of the lateral bud develops into a storage leaf, and the growing point gradually turns into dormancy as the storage leaf continues to grow (Takagi, 1990). Environmental conditions favoring these two processes are not always the same, and can be important factors that should be considered during the modeling process.

Differentiation of Storage Leaves

Storage leaf normally develops from a lateral bud primordia initiated from the second or third leaf. The lateral bud primordia then forms two to six growing points, with each turning into a lateral bud. From the lateral bud grows modified leaves, which make up the structure of the clove. The multiple cloves congregate and form the bulb (Figure 1.2). If multiple young foliage-leaves form lateral buds and develop cloves, multiple layers of cloves will then be developed in the bulb (Figure 1.2). An individual clove is a complex structure that contains the nascent elements of a mature bulb. The first leaf that develops eventually turns into a rough, papery sheath when the mother plant starts to senesce, becoming a protective structure wrapping around the clove, preventing it from disease, damage and desiccation. The second leaf formed grows into a swollen storage leaf (Figure 1.3), with a growth rate strongly affected by environmental conditions such as temperature and photoperiod. The storage leaf makes up 30-40 percent of the clove mass, and is the main carbon source during sprouting. A sprout leaf and several foliage leaf primordia are located at the very center of the clove. These additional leaves are initiated but mostly remain dormant within the center of the clove. They may further develop during the storage period depending on conditions, but remain within the clove until sprouting.

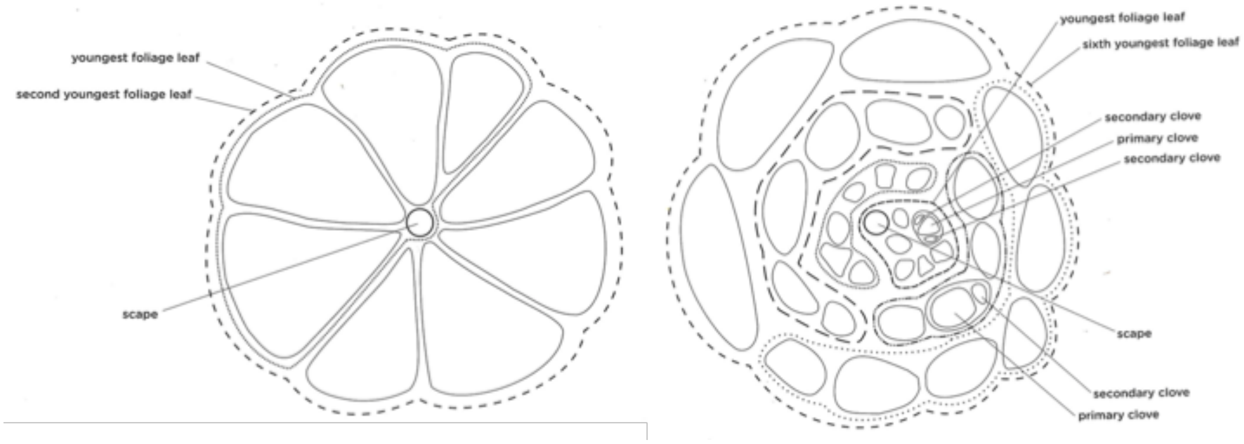


Figure 1.2. (A) Cloves formed in the axils of two youngest foliage leaves. (B) Cloves formed from the axils of the six youngest foliage leaves. Two cloves have generated axillary buds the developed into secondary cloves (Meredith, 2008).

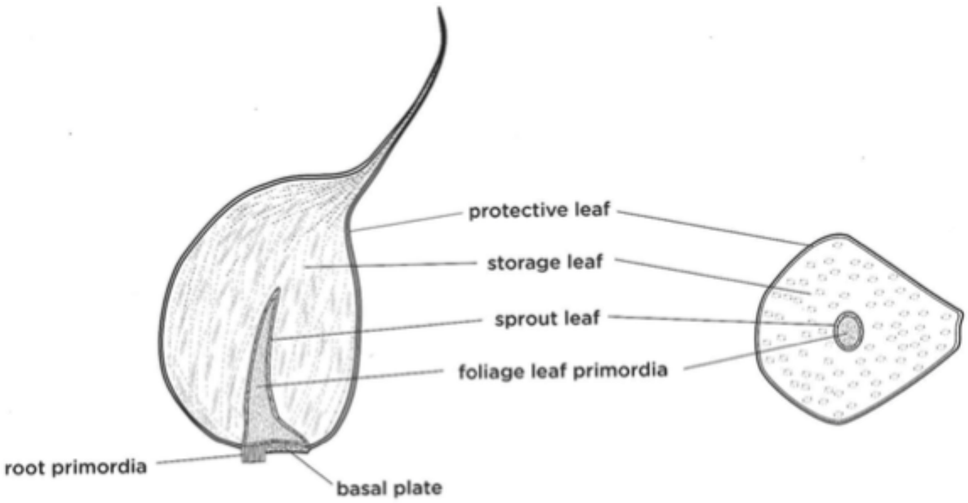


Figure 1.3. Anatomy of a clove – longitudinal and latitudinal cross sections (Meredith, 2008).

1.1.4 Storage and Dormancy

Storage Time, Storage Condition and Planting Date

As the mother plant of the garlic plant reaches full maturity, the garlic cloves within the bulb start to enter dormancy, and reaches its peak during harvest. Dormancy gradually decreases during the storage periods, and can be determined by the time it takes the plant to sprout out. This process can be affected by various factors, such as the maturity of bulb when harvested, storage conditions, and storage duration. Storage conditions also have a profound effect on growth and bulb formation after the clove is planted, and plays an important role in the plant's life cycle.

Storage Temperature and Duration and the Breaking of Dormancy

Garlic cloves are at the stage of full dormancy after harvested. This dormancy gradually decreases during the storage period, but can also be greatly affected by the conditions it's exposed to. Both high (35-40˚C) and low (5-10˚C) temperature can have an influence on breaking the dormancy within the cloves after harvest, which is also greatly interactive with storage duration. For short storage periods such as two weeks, high temperature is the most effective in breaking dormancy. However, with the increase in storage duration, the effectiveness of high temperature starts to level off, and eventually a cold storage between 5 to 10 ˚C became most efficient in breaking dormancy and promoting sprouting (Zink, 1963).

Optimal temperature for Rooting and Sprouting of Cloves

For dormant cloves, the temperature effect on root emergence and clove sprouting is critical. The optimal temperature for rooting is around 15˚C, and the optimal temperature for sprouting is approximately 22 ˚C. Both processes can be greatly delayed if temperatures fall out of certain temperature ranges. Cold treatment during storage period prior to planting is essential for storage leaf initiation, and essential for future bulb development. Between 2 and 4˚C is the most effective storage temperature to stimulate storage leaf formation for many temperate garlic cultivars prior to planting. However, other than affecting storage leaf initiation and development, the storage condition and duration can also affect leaf and inflorescence development.

Storage duration is found to affect the number of leaves formed before inflorescence (Takagi, 1990). With variation between cultivars, results showed that with a longer storage period, garlic plants tend to develop fewer leaves before emergence of inflorescence. For a crop that originally has a low leaf number, this further decrease in leaf number could have a distinct effect on plant growth and yield. Storage temperature, on the other hand, could have a combined effect on inflorescence formation. With variability between cultivars, a higher storage temperature could lead to a decrease in percentage in inflorescence formation. Optimal storage condition and storage period is therefore critical for future plant growth and development.

1.1.5 Inflorescence Initiation and Development

Inflorescence Initiation

Since temperate garlic cultivars will not form inflorescences if not exposed to cold temperature, it is believed that a qualitative vernalization is necessary for the plants to enter reproductive stage. Both storage temperature and duration can interactively affect the percentage of forming normal structured inflorescence. It is generally showed amongst cultivars that the longer the storage period, the greater the decrease in inflorescence formation. And as storage temperature deviates out of the optimal temperature range for inflorescence development, which is slightly lower than that for storage leaf development, the percentage in developing inflorescent decreases as well.

Inflorescence Formation

After the initiation of inflorescence, which is greatly influenced by storage conditions, inflorescence formation is influenced by several environmental conditions. Main factors include temperature, photoperiod, light intensity, water and nutrient supply and cultivar. Similar to inflorescence initiation, temperature and photoperiod are the two most important factors, which interact with not only each other but also the previous storage conditions.

Inflorescence Growth and Development

Growth of inflorescence and lateral cloves are concurrent, therefore serve as an important indicator of bulb formation. However, since the formation of these two structures happen during similar times in plant development, competition over photosynthates may occur. Based on environmental conditions that favor each structure, the increase of growth in one could lead to the decrease in the other, and vice versa. Typically, long photoperiods accompanied by warm temperatures favor clove growth, hence bulb formation, while negatively affecting inflorescence development. Short photoperiods and low temperatures, on the other hand, have a negative effect on bulb formation while favoring inflorescence growth.

1.1.6 Plant Structure and Carbon Allocation

The garlic plant structure can be separated into two parts, vegetative structures and reproductive structures. Vegetative structures include the roots, stem, pseudostem, leaf blades and bulb. Reproductive structures include the scape, spathe, umbel capsule, umbel, flowers, bulbils and seeds. Carbon allocation to different plant parts change throughout the growth cycle, which is tightly related with phenology and plant development, and is essential for determining the physical yield.

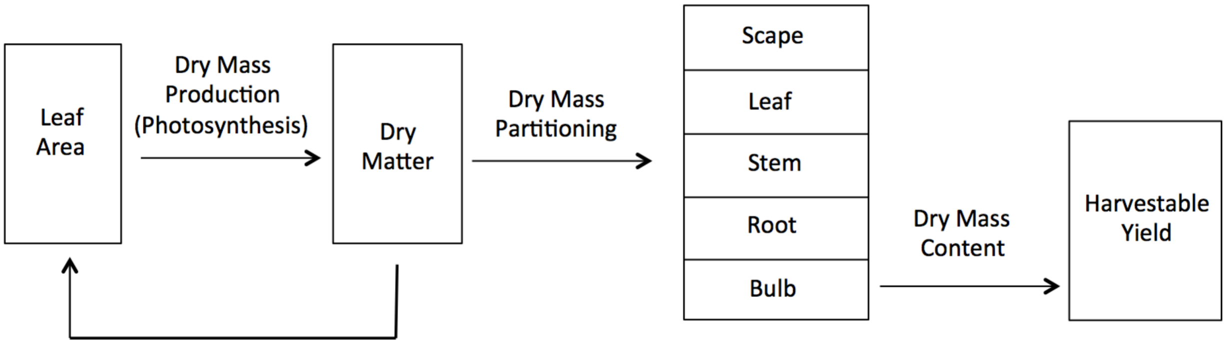


Figure. 1.4. Dry matter production and partition in garlic, and the relationship with yield.

1.1.7 Cultivar Choice

The long cultivation history in the *Allium* family has led to a great variety of agricultural plants, which were served as food source, ornamentals, and also incorporated into therapeutic products. The diversified cultivation in garlic created a wide range of characteristics, differing in size, shape, flavor, cold hardiness, storage properties, phenology, ecological adaptation and so on.

Two cultivar groups were chosen for the purpose of this study, due to the difference in plant morphology and phenology.

Asiatic – cv. Korean Mountain

Asiatic cultivars are easily identified by their distinctive umbel capsule, which has an exceptionally long beak when fully developed. Bulbils are also prominent in this cultivar group, which ranges from large to huge in size, and dark reddish or purple in color. When planted, some bulbils can produce harvestable sized bulbs when planted. The scape, on the other hand, is typically shorter rather than elongated and coiling. Unlike many other bolting garlic cultivars, scape removal is not required to produce large bulbs. Asiatic leaves are yellow-green, and relatively broad. Maturity can come fast under warmer growing conditions, and bulb wrappers might split if not harvest on time, which is in contrast to other cultivar groups where plants should be left longer for maturation.

Turban – cv. Shantung Purple

The turban group is named for the turban shape of the umbel capsule. Turban cultivars generally germinate earlier, which makes them one of the earliest harvest groups. However, this phenology also results in a shorter storage period. Scape typically bends over after forming the umbel capsule, but does not curl. The umbel capsule has a relatively short beak, and produces many small to medium sized bulbils. Similar to Asiatic cultivar, the bulb size is not greatly affected if scape is left on the plant.

1.1.8 Environmental Factors

Factors Inducing Storage Leaf Differentiation

Several factors affect, and induce storage leaf differentiation. Photoperiod and temperature are the two main factors. Exposure to cold temperature during winter, followed by a long photoperiod in spring is essential for bulbing in temperate-region garlic cultivars. Lack of either one of the conditions could easily cause delay in bulb formation, or affect bulb size (Ledesma *et al*., 1980; Rudge, 1984). These conditions generally apply to the formation of storage leaves, with a few exceptions under extreme conditions such as really long photoperiods or extremely low temperature (Takagi, 1990). In general, a critical photoperiod has to be satisfied in order to induce storage leaf development, with the combined effect of temperature.

Storage Conditions that Affect Storage Leaf Formation

After bulbs are harvested, cloves enter dormancy. Certain storage conditions can affect the degree of dormancy, and can further affect initiation and development of storage leaf once the cloves are planted. The optimal storage temperature in order to stimulate the formation of storage leaves after planting may vary with cultivar, but has a general range between 2-4 ˚C. The limit of an effective storage temperature for storage leaf induction, however, may range much wider, while interacting with photoperiod. A longer photoperiod is associated with a higher temperature limit, and vice versa.

Effects of Temperature and Photoperiod on Storage Leaf Growth

Other than storage conditions, environmental conditions the plants are exposed to during the stage of storage leaf development also influences the growth and development of storage leaf. The optimal temperature for storage leaf growth ranges from 17-26 ˚C. Growth is reduced under a lower temperature, and inhibited under higher. Photoperiod also factors in to this aspect, with a faster growth achieved under a longer photoperiod.

Planting Date

As a hardy plant, garlic can tolerate moderate cold conditions to below zero centigrade. Due to this characteristic, in temperate regions where winters are generally mild, garlic plants can be planted from autumn through early winter and harvested between late spring and early summer. With this planting date, plants generally sprout out early winter through early spring, and are able to tolerate the low temperature during this period while maintaining a slow growth rate at the same time. As for cooler regions that have extremely cold winters, cloves are planted between January and March, and harvested between September and November.

1.2 Crop Simulation Models and Their Applications

1.2.1 A Brief History

The very first thought of linking a single environmental factor with the biological systems came along with the German chemist, Justus von Liebig, back in 1840 when he formulated the ‘law of minimum’, stating that in an ecosystem, plant growth would be controlled and limited by the most deficient component in that system. Blackman in the early 20th century further applied this thought process to photosynthesis, with environmental factors such as irradiance and CO_2 being the limiting factor (Blackman, 1905;). Even though this principle often oversimplifies natural biological processes, it stimulated further research in order to describe a dynamic system that is influenced by multi environmental factors such as photosynthesis and plant growth.

Research in canopy light interception and transmission, canopy aerodynamics, biochemical processes in plant photosynthesis, stomatal conductance and gas diffusion, plant respiration, plant phenology all set the foundation of crop modeling. As the computing capacity increased over time, the ability to synthesize this knowledge became possible. Computer modeling of leaf canopy architecture, light distribution profile within canopy, CO_2 flux, leaf photosynthesis and several pioneer crop modelers did canopy photosynthesis in the mid 60s such as de Wit (1965) and Monteith (1964). These first attempts to use computer programs to synthesize and simulate plant growth systems led to numerous further researches looking into details and knowledge gaps in both plant physiology and computer programming.

Nowadays, many sophisticated crop models exist, either in a form of a specific crop, or in the form representing a general cropping system. Different environmental factors are incorporated into these models based on the complexity of the model. Factors usually include light, temperature, CO_2 concentrations, water and nutrient status, plant pathology and entomology. With the high performance computing capacity that can be achieved nowadays, models have the capability to be complex and sophisticated, with information intertwined and interrelated. However, simulation models are still a simplified representation of the actual world. No model is a perfect representation of the system, with associated uncertainties and limitations. Nevertheless, these simulation models are powerful tools that allow us to synthesize knowledge of plant growth and physiology, to test hypotheses, and to describe complex systems such as growing patterns and growth dynamics under different scenarios. The ability to capture the dynamic growing pattern of a crop gives these models the capability to predict phenology, carbon gain and allocation, yield, and growth patterns under future climate conditions. This leads to a wide range of applications such as pest management, risk evaluation and yield prediction, which can be helpful tools for crop production and management. Crop models also serve as valuable tools in climate impact research, either for predicting plant growth and yield under novel environmental conditions, or serving as tools to aid breeding directions best suited under future climate scenarios.

1.2.2 Descriptive and Explanatory Models

Crop models can be distinguished into descriptive and explanatory models. The different modeling approaches give the models strengths and limitations in terms of simulation and prediction.

Descriptive models, also known as statistical models, are generated using the relationships based on a few state variables. This type of modeling approach considers the underlying processes as a whole, which makes model parameters easy to estimate, and efficient to run. However, lack of true understanding of the underlying processes that build and governs the system makes it difficult to add new input factors, and simulations are often unreliable when applied at new locations or conditions. Explanatory models, also known as mechanistic, or process-based models, on the other hand, are more complex in structure since it synthesizes the underlying processes that formulate the whole system. The strength of explanatory models is that due to incorporation of underlying processes, it has the flexibility to be applied to different or novel conditions. The photosynthesis-based model is a common structure used in explanatory crop models, which can be broadly applied to a variety of crops. This processed based model is structured on the basis of photosynthesis, carbon flow, and carbon partition (Fig. 1.5). The detailed understanding of the relationship between environmental conditions and photosynthesis gives the model a strong linkage with the climatic data, making it valuable for real-time, on-site simulations, and are also useful for climate-related research.

1.2.3 Process-based Crop Models

Since the crop model used in this research is structured as a process-based model, this type of modeling approach will be discussed in further detail. The model is generally divided into two parts, the carbon flow, and the plant development timeline. The carbon flow is the key part of the model, which is based on the understanding of the biochemical processes of photosynthesis, and the linkage of it with different environmental factors. Simulation of photosynthesis is based on leaf area development and light interception, which can be linked to the canopy structure and phenology. The crop phenology, which can be referred to as the plant developmental timeline, serves as a regulator that determines the developmental and growth stages of the plant. This particular piece within the model is what makes a process-based model capable for real-time dynamic simulations.

Leaf Development and Leaf Area Accumulation

Leaves are the major organs for photosynthesis, and calculation of PAR is largely based on their surface area. Leaf development can be determined through four processes: the rate of leaf emergence, the rate and duration of expansion, and the rate of senescence. However, the actual controls that regulate leaf area development are not well understood. Nevertheless, methods still exist to approach this matter.

Light Interception

Simulation of a single leaf can be very different from simulating the whole canopy. The properties of a single leaf don't necessarily add up linearly during the process of scaling up. Both leaf area and the shading and clumping of leaves within the canopy determine light interception of the plants, which leads to the important concept of leaf area index (LAI). Leaf area index is a dimensionless quantity that characterizes plant canopies, and is defined as leaf area per unit ground surface area (leaf area / ground area, m^2/m^2). The higher the value, the more leaf area exists over a certain ground area, indicating a dense and over-shading canopy and vice versa.

An understanding of the relation between leaf area and light interception is important for canopy photosynthesis simulation. A greater leaf area generally leads to a greater light absorption, and a greater platform and resource for the photosynthesis machinery leading to a higher biomass production. However, with the increase of leaf area comes the mutual shading that decreases light interception. An exponential equation is ideal for describing such characteristics of the light environment within the canopy. The law of Lambert-Beer (Monsi and Saeki, 1953) is a common approach:

$$I / I_o = e^{-k * L} \quad \text{Eqn. 1.1}$$

With I_o representing the radiation on top of the canopy, and I the light intensity at depth L of the canopy, L represented as leaf area index, and *k* stands for the extinction coefficient within the canopy environment, which depends both on the geometry of radiation and the geometry of the leaf position an orientation.

Sun/shade Modeling Approach – An Alternative for Modeling Light Interception

The tight relationship between light intensity and photosynthesis is the reason why an accurate modeling approach for light interception is important in crop modeling. Linking leaf area and light interception of the leaves leads to the basics in modeling photosynthesis. A sun/shade modeling approach is used to capture the property of canopy light interception and photosynthetic activity. The model divides the leaves within the canopy into two categories: sun-lit leaves, and shaded leaves. The proportion of sun-lit and shaded leaves is dynamic and changes with sunlight angle throughout the day. This modeling approach also allows the model to capture canopy features such as the penetration of irradiance through the canopy and the range of leaf angles that exist within the canopy (De Pury & Farquhar 1997).

Photosynthesis

A detailed understanding of the function and mechanism of the biochemistry behind photosynthesis made it possible for a mechanistic modeling approach. The biochemical model for C3 photosynthesis is a well-established photosynthesis built by Farquhar et al. (Farquhar et al. 1980), and is widely used in ecophysiological models. The biochemical model for C3 plant photosynthesis can be seen as one of the most important component for a carbon-based mechanistic model. It is important because the process of photosynthesis is the first step to determine the gain of carbon for plants through the atmosphere, which is eventually transformed into plant structure in the form of biomass. This portion of the model is probably also the most well-studied and established portion within the whole crop model. A detailed description of the biochemical process of the Rubisco enzyme is given in the photosynthesis module, which incorporates environmental factors: ambient CO_2 concentration, air temperature, and light intensity, giving the model the flexibility to adjust according to the given environmental condition.

Respiration

Respiration is often divided into two components in most crop models, growth respiration and maintenance respiration. Growth respiration is the respiration required to sustain growth. Maintenance respiration, on the other hand, is respiration required to maintain the basic functionality of living of the plant, such as protein turnover and ion fluxes (Bouma, 1994).

Maintenance respiration is usually calculated as the product of dry weight and a maintenance coefficient. The maintenance coefficient is often determined as a function of both temperature and organ type. Age or relative growth rate are additional factors that may affect maintenance coefficient, since maintenance respiration may decrease with the aging of the crop and is often accompanied by decrease in growth rate (Amthor, 1989). Growth respiration, on the other hand, is calculated as the product of dry weight growth rate and a growth coefficient. The growth coefficient mainly depends on the composition of the biomass formed, and the substrate from which it is derived (Amthor, 1989). Growth coefficient is a function of species and organ type, but is independent of environmental factors including temperature (Penning de Vries et al., 1974). For the simplicity of model building, maintenance respiration usually has priority over growth respiration, which is based on an underlying assumption that carbon would be allocated to sustain functionality before being allocated to increase growth.

Carbon Gain, and Dry Matter Partitioning

After accounting for carbon gain through photosynthesis, and carbon loss through respiration, total carbon gain can be calculated, which is the total carbon available for plants to accumulate dry matter (DM). Carbon partitioning to different plant structures vary at different growth stages therefore is tightly linked to the phenological timeline embedded into the model. A partition ratio is predetermined based on the morphological changes throughout the growth cycle, and can also be modeled as a function of environmental conditions such as stress factors or nutrient availability. This method captures the overall pattern of carbon distribution throughout the growth cycle of a plant, but is also highly empirical. Uncertainties are high in this part of the whole model due to the complexity and lack of understanding of the carbon partitioning process.

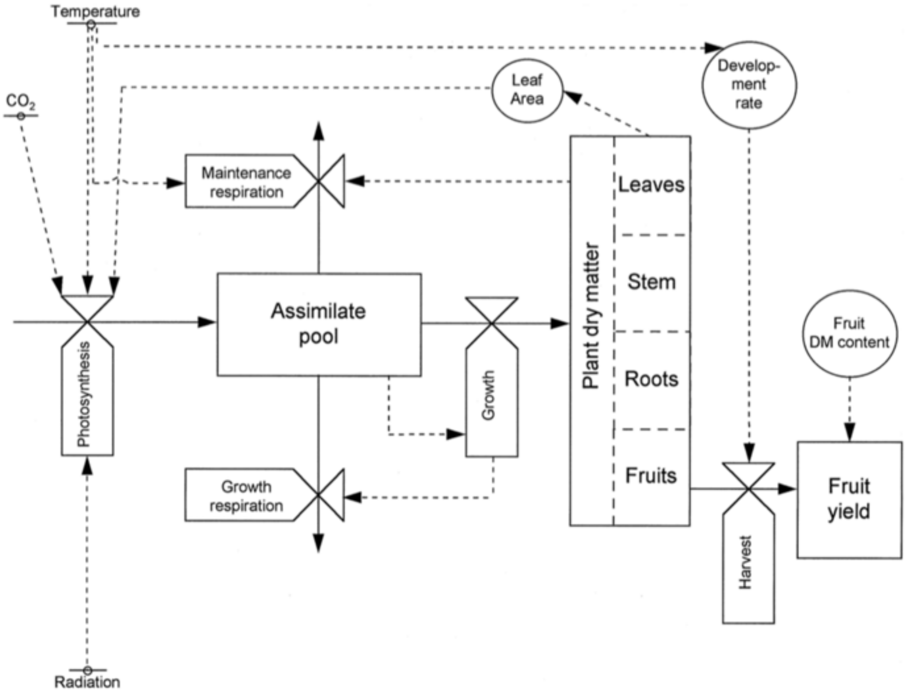


Figure 1.5. General structure of a photosynthesis process-based crop model (Marcelis et al. 1998).

1.3 Process-based Crop Modeling for Hardneck Garlic

The physiological, morphological, and ecological components that form the growth and development of hardneck garlic, and the interactions and feedbacks between the processes make crop modeling a complicated task. Methods of the current model structure are only a simplified version of reality, describing only on significant and major processes while leaving out many others. However, trying to capture the complete reality is not what models are designed for and built for, but rather, they are used as tools to represent reality within an acceptable range of uncertainty. It is a tool to help us estimate and predict, but as with all estimations and predictions, along comes inevitable errors. Comparison between model outputs and field observations of leaf development phenology, leaf morphology and leaf area accumulation, biomass gain and biomass partitioning can lead to a better understanding of model performance and the associated error. Even though errors are often inevitable, model performance can still be improved if actual data is available for detailed calibration.

The two main purposes of this study is therefore to evaluate the performance of a process-based crop model developed specifically for hardneck garlic, and attempt to structure and calibrate the model in a way that minimal observed data are required for calibration in order to produce reasonable and meaningful data under, while also having the flexibility to adjust and adapt under a range of environmental conditions that the crops may be exposed to with the choice of different farming practices.

Chapter 2. Calibration, Validation and Improvement in Phenology and Morphology Predictions of a Process-based Crop Model for Hardneck Garlic (*Allium sativum* L.)

2.1 Introduction

Garlic is one of the oldest cultivated crops amongst the human agricultural history. Its long cultivation history in human agricultural activities and its widespread production and consumption worldwide make it one of the important crops within the Allium family. This herbaceous perennial crop is harvested mainly for its specialized leaf structure, the bulb. The garlic bulb is incorporated into worldwide cuisines, also used as ornamentals, and is also gaining a greater popularity due to its health benefits. Central Asia is hypothesized to be the origin for wild garlic (Engeland, 1991), and is widely dispersed throughout the region. Nowadays, garlic is widely cultivated globally with a distribution from the equator to around 50˚ latitude, in regions with mild and moist winters followed by a dry summer with sufficient irradiation. Production is up to 1.3 million hectares with yields reaching up to 22 million mega grams in total as of year 2010 (Food and Agriculture Organization of the United Nations, 2010).

Crop models are essential tools for evaluating climate impacts on crop production, predicting yield, assisting breeding and management decision making, providing risk assessments for economic decision and policy making, and has also became an important tool for assessing and predicting impacts future changing climates may have on cropping systems. Detailed greenhouse and field experiments are usually required in order to obtain the phenological, morphological, and physiological information of the crop required to structure a whole-plant based model. The long cultivation history and the importance of the crop have created a rich literature describing detailed garlic botany, physiology, nutrient conditions, and water inputs. This valuable information has made it possible to construct a mechanistic model that is able to describe the morphology, growth and development of garlic based on our current knowledge, with simulation results that can be implemented specifically for production and management.

Processes that determine crop growth and development are described through individual modules, which are intertwined into a complex structure to represent the dynamic growing process of the whole plant. Phenology, morphology, photosynthesis, biomass gain and biomass partitioning are the five major sections within a process-based crop model, each fundamentally important and tightly linked. Phenology determines the timeline of development, and morphology determines the structure of the plant, and most importantly, the gain and loss of total leaf area throughout the life cycle of the plant. Leaf area determines the amount of photosynthesis, leading to biomass gain that is then partitioned to different plant parts. Phenology and morphology can be seen as the backbone structure of the whole model while photosynthesis and carbon gain fills in the flesh. Yield prediction is one of the most important pieces of information people are interested in gaining from crop simulation models, and the final step of carbon partitioning builds on top of all the previous processes, which emphasizes once more the importance of each individual module, and the tight linkage in between. The performance of the model, however, may vary largely depending on environmental conditions, agricultural practices and cultivar choices, therefore calibration and validation of the model for different conditions is an essential step for model development.

The objective of this study is to calibrate and evaluate the performance of a crop simulation model developed for hardneck garlic under the growing scenarios of two cultivars choices and a range of planting dates. Three areas of interest were chosen within the model structure for evaluation: 1) phenology, which is defined as the timing of emergence for individual leaves; 2) morphology, which is defined as the total leaf area gain of the plant; 3) biomass gain and allocation. Before the model is used for real-world applications, calibrating and testing the three fundamental structures within the garlic crop model under a range of environmental conditions and cropping scenarios is necessary to provide a better understanding of the strengths and weaknesses of the current model while pinpointing areas that require modifications and improvements.

2.2 Material and Methods

The experiment took place in the Douglas Research Conservatory, a facility of the University of Washington Botanic Gardens (47˚ 39’ 27”N, -122˚ 17’ 21”, 10 m elevation), Seattle, WA. The experiments were repeated twice over three consecutive calendar years, starting from September 2013 through July 2015.

Plant Material

Garlic bulbs of two hardneck garlic cultivars, Shantung Purple (SP) and Korean Mountain (KM), were purchased at September 2013 and 2014 from Hood River Garlic (Hood River, OR). The bulbs were harvested July 1st at the farm for the hardneck cultivars, and hung up to cure for two weeks, and shipped mid August. Cloves were received early September, and were placed under 4˚C cold storage conditions until planting. An early and late planting was chosen for both years of experiments, and plants were planted at a density of 55 plants/m^2 in 3 raised beds (1.8m long × 1.2m wide × 0.4m height) at the Center for Urban Horticulture, University of Washington.

Planting Date and Experimental Design

Garlic cloves were planted in raised beds 1.8m in length, 1.2 in width, and 0.4m in height located at the Center for Urban Horticulture, University of Washington. Commercially available topsoil (1:1:1 of sandy soil, composted sawdust and manure; Sky Nursery, Shoreline, WA) was used to fill up the raised beds. Two planting dates were chosen for both year 2013 and 2014, with the early planting date at October 30th and the later planting date on December 17th for year 2013, and October 1st and November 20th for year 2014. Plots were divided into four sections, and cultivar-planting date combinations were randomly chosen for each section, and the setting was replicated for all three raised beds as indicated in Figure 2.1.

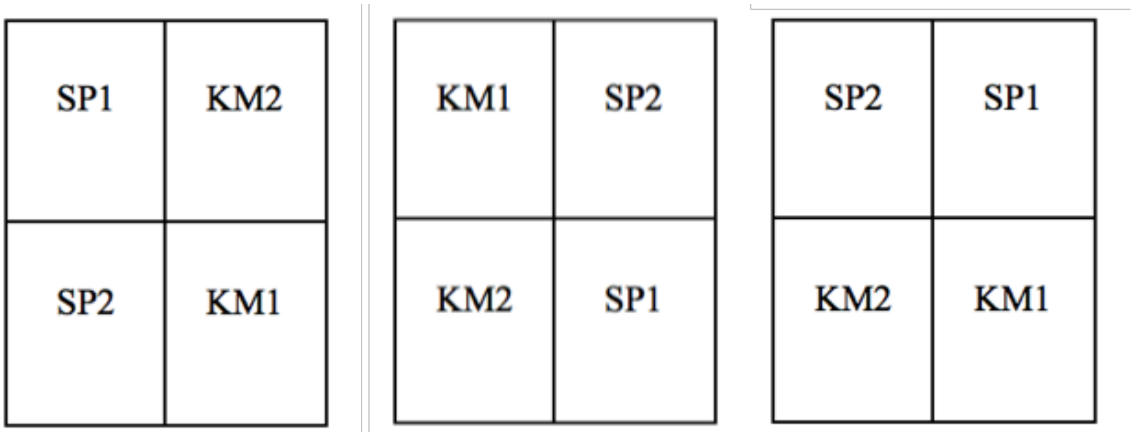


Figure 2.1. Schematic of experimental layout. Two cultivars of hardneck garlic plants, c.v. Shantung Purple (SP) and c.v. Korean Mountain (KM) were planted in 1.8m × 1.2m raised beds with an early planting date (1) and a late planting date (2), and were replicated over three plots.

Husbandry

All plots were fertilized with a commercialized control-release fertilizer [CRF (14N-14P-14K, Osmocote Smart-Release Plant Food; Scotts, Marysville, OH)] prior to planting, with actual dates differing depending on the planting date, and was fertilized through top dress at the middle of March [CRF (17N-3P-6K), Scotts Topdress with Micronutrients; Scotts, Marysville, OH]. Total N supply during the experiment was 240 kg-ha^{-1}, with 60% supplied as base fertilization and 40% as top-dress. Base fertilization was well mixed into the soil prior to planting, while the top-dress fertilizer was split in half and applied once in early February and once in early March. Plots were hand-weeded throughout the planting season to ensure that plants were under optimal conditions and not competing with other plants for nutrient and water. Plants were hand-watered twice a week through dry seasons beginning April.

Leaf Development Phenology Documentation

Leaf development phenology was recorded weekly for each cultivar and planting date. Leaf emergence date is defined as the timing when leaf tips become visible to the eyes, while leaf maturation date is when the collar structure is developed at the base of the leaf blade, and leaf senescence date when over 80% of the plant leaves have withered and yellowed. Scape appearance date is determined as the date when the tip of the scape structure appears after the emergence and development of the final leaf. Dates of leaf emergence, maturation, senescence, and scape appearance were documented for each individual plant and values were averaged to represent the population.

Morphology and Biomass Measurements

Five harvesting points were chosen throughout the course of the growth cycle of the plant. Specific dates varied for each variety planting date combination due to the difference in phenological development rates. For each harvest, leaf length and width were measured individually using a ruler for each existing leaf. Leaf length was measured starting from the base of the leaf blade where the collar structure is formed all the way to the leaf tip, while leaf width was measured at the widest point of the leaf. Leaf area was then measured using a leaf area measurement machine (LI-3100, LICOR, Lincoln, NE, USA). Chlorophyll meter readings were taken with a chlorophyll meter to estimate the chlorophyll content within each leaf (SPAD 502 Plus Chlorophyll Meter, Minolta, Japan), and also to serve as an indicator for leaf age. Measurements were taken with 5 cm intervals for each leaf and values were averaged to represent the whole leaf. Plants were further separated into root, bulb, pseudostem and leaves with a razor blade and placed in a 70˚C-drying oven for at least 2 week before the biomass of each organ part was measured.

Environmental Data Collection

Weather data was collected from AgWeatherNet (http://weather.wsu.edu/index.php?p=88650), a weather station network from Washington State University. Current and historical weather data can be freely accessed throughout weather stations located throughout Washington State, with a higher density of weather stations in the irrigated regions of eastern Washington. Data were collected from the Seattle weather station located at the UW Center for Urban Horticulture (47˚ 66’ N, -122˚ 29’, 30 m elevation). Standard variables included air temperature, relative humidity, dew point temperature, soil temperature at 8 inches, rainfall, wind speed, wind direction, solar radiation and leaf wetness. Data is collected every 5 seconds and summarized every 15 minutes by a data logger while hourly data were used for running the model.

2.3 Model Description

2.3.1 Model Structure

Several interconnected modules compose the overall structure of the process-based model for hardneck garlic in order to capture the dynamic pattern of carbon gain and carbon flow throughout the life cycle of the whole plant.

The process-based crop model can be roughly divided into two main sections in terms of the model structure: carbon flow and phenological timeline. Carbon flow determines the total carbon gain and distribution throughout the whole plant, while the phenological timeline provides the model with a dimension of time, which links biomass gain together with phenological development. Total carbon gain is calculated through simulating photosynthesis and respiration, and then partitioned to different plant organs. The phenological timeline, on the other hand, is associated with determining leaf development, leaf area accumulation, and the change in sink strength for organs as the plants go through different developmental stages. Leaf development and leaf area accumulation is the major linkage between the carbon flow and phenological timeline portions of the model, since the amount of photosynthesis and carbon gain is directly correlated with the leaf area present. Partitioning of carbon to different plant parts is largely determined by the age and developmental stage of a plant. Therefore, the phenological timeline also plays an important role in order to determine how much carbon should be partitioned to each organ at different stages within the life cycle of the plant. A dynamic showing the basic structure of such mechanistic crop models is shown in Figure 1.5 (Marcelis et al., 1998).

2.3.2 Phenological Development

Temperature is one of the most important factors that affect plant growth and development. Yin and colleagues adopted a standard density function, the beta function, for a nonlinear modeling approach that describes crop development as a function of temperature (Yin et al., 1995). This function is originally used as a skewed density probability function in statistics (Bock and Krischner, 1998), but is applicable in describing phenological development due to the flexibility in the bell-shaped curve to account for complex temperature responses within plants (Fig. 2.2). The original equation used for this approach is shown in equation 2.1,

$$r = R_{max}\left[\left(\frac{T-T_{min}}{T_{opt}-T_{min}}\right)\left(\frac{T_{max}-T}{T_{max}-T_{opt}}\right)^{\frac{T_{max}-T_{opt}}{T_{opt}-T_{min}}}\right]^{c} \text{...Eqn. 2.1}$$

where r describes the rate of temperature related growth processes, while R_{max} indicates the maximal leaf tip appearance rate (LTAR, leaves/day), which occur under the optimal temperature (T_{opt}). The c value within this equation is the only value that has no physiological meaning, which simply modifies the shape of the curve. This model was further modified and simplified by Yan and Hunt in order to model the temperature response of plants by only using cardinal temperatures (Eqn. 2.2) (Yan and Hunt, 1999), which is also the equation formula used in this current study. By eliminating c and setting T_{min} to zero, the equation is simplified from Eqn. 2.1 to Eqn. 2.2.

$$r = R_{max}\left(\frac{T_{max}-T}{T_{max}-T_{opt}}\right)\left(\frac{T}{T_{opt}}\right)^{\frac{T_{opt}}{T_{max}-T_{opt}}} \text{.. Eqn. 2.2}$$

Three parameters are required for this phenology simulation: the optimal temperature (T_{opt}, ˚C), the maximal growth rate (R_{max}), which represents the maximal development rate for leaf emergence (LDR, leaves/day), and the final leaf number, while the maximal temperature (T_{max}) for the function is preset to 43˚C.

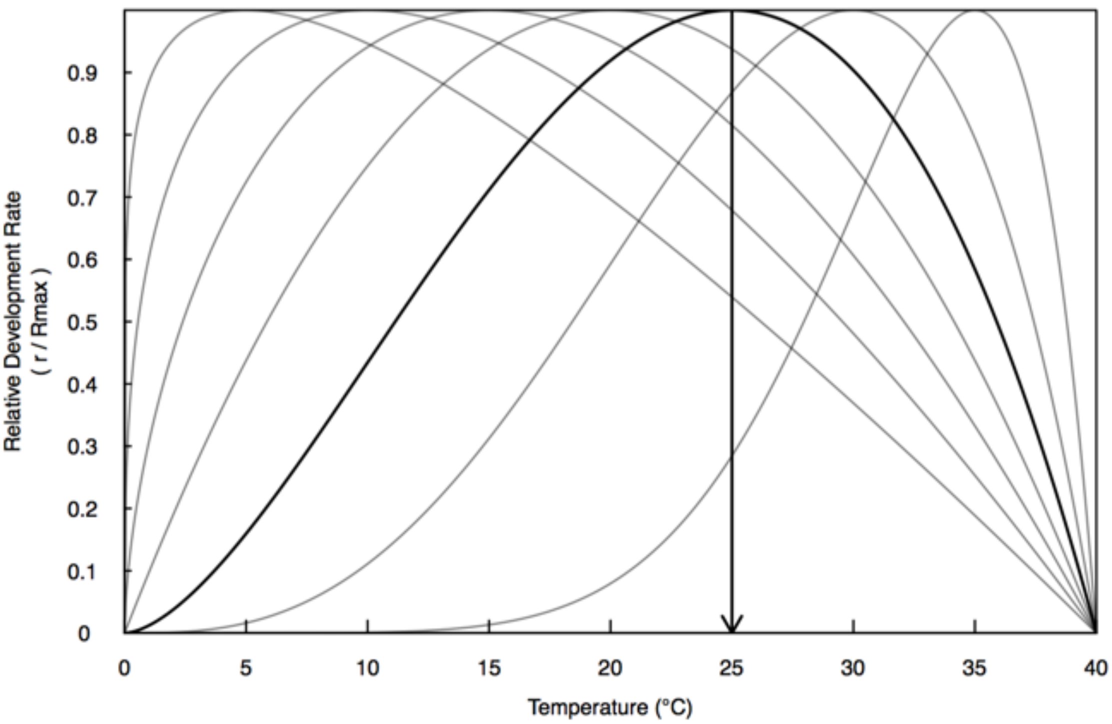


Figure 2.2. Beta distribution of the temperature response of relative leaf developmental rate. The minimum and maximum temperatures are fixed at 0 and 40˚C, respectively, but the optimal temperature (Topt) varies between 5 and 35˚C. The curves shows that even with fixed minimal and maximal temperatures, the temperature response still varies greatly under different optimal temperatures (Modified from Yan and Hunt, 1999, Figure 1).

2.3.3 Morphological Simulation

Morphological simulations within the model are defined as the simulation of total leaf area, which is predicted, based on an allometric relationship developed between leaf length and leaf area. Therefore, predicting final leaf length for individual leaf numbers, and understanding the relation leaf elongation has with temperature are the two key components for leaf area simulation. Due to this model structure, the prediction of total leaf area is tightly linked with the development of individual leaves, making phenology an important underlying component when considering morphology simulations.

Final leaf length for individual leaf numbers (Length) is simulated also by using a beta distribution function, but by substituting the temperature related parameters into leaf number and leaf length (Eqn. 2.3). Length indicating the simulated matured leaf length for specified leaf number and LNum the leaf number that length is being simulated. Three parameters are also needed for this simulation: $LNum_{max}$, the maximal leaf number that the plant can genetically achieve, $LNum_{opt}$, the optimal leaf number, and Len_{max}, the maximal leaf length, which is achieved at the optimal leaf number ($LNum_{opt}$).

$$Length = Len_{max}\left(\frac{LNum_{max}-LNum}{LNum_{max}-LNum_{opt}}\right)\left(\frac{LNum}{LNum_{opt}}\right)^{\frac{LNum_{opt}}{LNum_{max}-LNum_{opt}}} \text{..........................Eqn. 2.3}$$

Visualization of the leaf-length beta function is shown in Figure 2.4. The equation itself used in this condition does not give a very strong biological or physiological meaning to the parameters, but the shape of the function still explains the nature of garlic leaf morphology pretty well. The basic concept was to describe the younger leaves to be shorter, while length increases along with leaf number until a certain optimal leaf number then starts to decline. The high flexibility within the beta function also gives it the ability to be parameterized to different cultivars or environmental conditions that may affect leaf morphology.

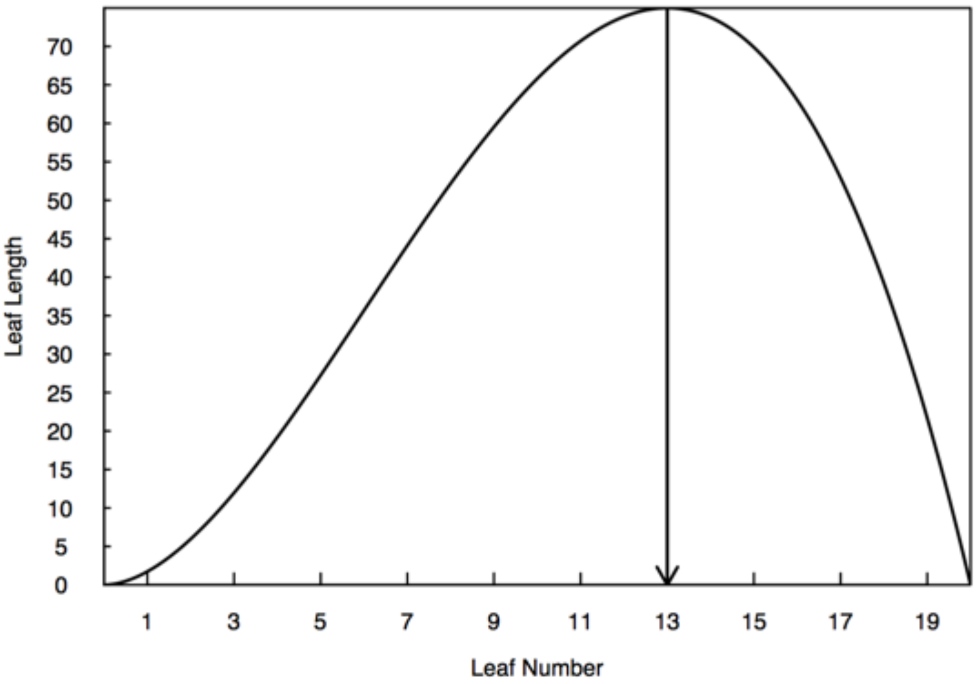


Figure 2.3. The beta distribution used to simulate final leaf length for individual leaf numbers.

Once the final leaf length for individual leaf numbers is simulated, the timing it takes each individual leaf to reach the final leaf length is then determined through leaf elongation rate (LER, cm/day). This temperature dependence function of leaf elongation rate adopts the same beta distribution function used to describe leaf development phenology, but by modifying the R_{max} from describing leaf tip appearance rate (LTAR, leaves/day) into describing leaf elongation rate (LER, cm/day) (Figure 2.3). The growth of the leaf, here only described through the elongation of the leaf, is based on the temperature conditions, elongating faster when temperature falls closer to T_{opt}, and vice versa. Once the leaf elongation reaches the final leaf length for the specific leaf number in development then the process is aborted, and the leaf matures.

The process of leaf area accumulation is tightly linked with leaf development phenology. The leaf needs to be initiated and emerge based on the phenological timeline before it can start to elongate and accumulation leaf area, therefore phenology is essentially the first key step to a successful crop model simulation. Once the leaf emerges, elongation begins with the two processes functioning independently. When final leaf length and maximal leaf area is achieved for individual leaves, the leaf stays matured for a certain amount of time before it starts to senesce and eventually dies off.

2.3.4 Photosynthesis

Phenology and morphology of the plants were discussed in the past two sections exclusively based on leaves. The model focuses greatly on leaf development phenology, leaf morphology and leaf area accumulation all because leaves are the main source for photosynthesis and carbon production within the plant. Carbon is the main source for plant growth and biomass gain, therefore is emphasized greatly in crop models. Once the amount of leaf area present is predicted, the process of photosynthesis simulation is started.

The biochemical model for C3 plant photosynthesis developed by Farquhar et al. in 1980, which will be noted as the biochemical photosynthesis model in the following text, can be seen as one of the most important component for a carbon-based mechanistic model (Farquhar et al., 1980). It is important because the process of photosynthesis is the first step to determine the gain of carbon for plants through the atmosphere, which is eventually transformed into plant structure in the form of biomass. This portion of the model is probably also the most well-studied and established portion within the whole crop model. A detailed description of the biochemical process of the Rubisco enzyme is given in the photosynthesis module (see Kim *et al.*, 2013), which incorporates environmental factors: ambient CO_2 concentration, air temperature, and light intensity, giving the model the flexibility to adjust according to the given environmental condition.

Despite the sophisticated structure of this model, parameterization can be a difficult task. Several parameters for the model are relatively constant, either within species or within cultivars. These values can be estimated and applied through existing experimental data, and are commonly obtained through detailed gas-exchange measurements. However, other parameters may be dynamic, having a high sensitivity to the surrounding environment, which includes the two major parameters in the biochemical photosynthesis model: intercellular CO_2 levels (C_i), and leaf temperature (T_L). In order to dynamically solve for these values, a coupled modeling approach was applied where the biochemical photosynthesis model was coupled with the stomatal conductance developed by Ball, Woodrow and Berry (Ball et al., 1987), and an energy balance equation. This coupling approach allowed the calculation of photosynthesis to be solved by taking into account of the biochemical limitation of CO_2 occurring within the plant tissues, as well as the stomatal limitation of CO_2 which occurs due to the opening and closing of stomata (Kim *et al*., 2013).

2.3.5 Respiration

Respiration is a complex metabolic process in higher plants. A large portion of the carbohydrates that a plant assimilates each day are expended in respiration in the same period, which makes it an important process to consider after simulating photosynthesis in order to predict how much carbon is eventually available for plant growth.

Respiration is divided into two categories, maintenance respiration and growth respiration. Maintenance respiration is defined as respiration during processes that maintain cellular structures and intracellular gradients of ions and metabolites, along with cellular acclimation to environmental changes (Amthor, 2000). Growth respiration, on the other hand, is respiration during the process of growth, which can be defined as conversion of reserve materials into new structures. Carbon gained through photosynthesis is subtracted by carbon loss through these two forms of respiration, and the final product would be the carbon available for plant growth.

2.3.6 From Leaf to Canopy

A single layer sun/shade model was used to estimate canopy photosynthesis (de Pury and Farquhar, 1997). This modeling approach provides a method to aggregate leaf-level photosynthesis that corresponds to simulated total leaf area, and modify it into a more realistic canopy-level photosynthesis by considering the self-shading properties a whole-plant level canopy possesses (Figure 2.5).

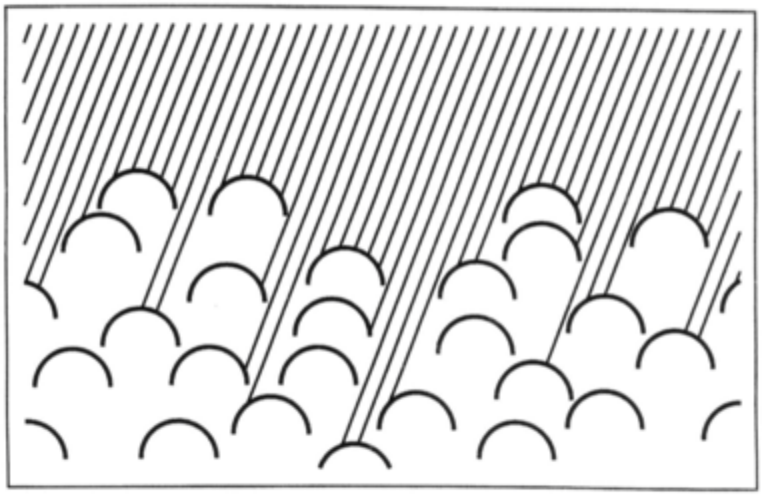


Figure 2.4. Radiation penetration through a canopy of uniform leaf angle distribution, which is represented by a random arrangement of hemispherical arrays of leaves (de Pury and Farquhar, 1997).

A single-layer is used to represent canopy photosynthesis by fractionating the leaves into two categories, sun-lit and shaded leaves. Even though this modeling approach treats the whole canopy as a big leaf, a higher accuracy can be achieved when compared to traditional big-leaf modeling approaches, and a higher efficiency can be reached when compared to multi-layer modeling approaches (de Pury and Farquhar, 1997). The proportion of sun-lit and shaded leaves within the canopy changes throughout the day due to solar angle and elevation, while the photosynthetic properties are treated differently for the two leaf categories, with irradiance absorptions and photosynthetic capacity acting as the two variables distinguishing the two. Total canopy-level photosynthesis is calculated as the summation of both sun-lit and shaded leaves, as listed in Eqn. 2.4. A_c indicates the canopy-level photosynthesis, while A_{cSun} and A_{cSh} stand for the photosynthetic rate for sun-lit leaves and shaded leaves respectively, and R_c as the canopy-level respiration.

$$A_c = A_{cSun} + A_{cSh} - R_c \quad \text{Eqn. 2.4}$$

2.3.7 Carbon Partitioning

After total carbon gain is calculated by subtracting the carbon loss through respiration from the carbon gained through photosynthesis, the next step is to partition it to different plant parts in the form of biomass. This process is achieved through assigning partitioning coefficients to individual plant parts, such as root, shoot, leaves, and bulb in the case of garlic. These partitioning coefficients change throughout the whole plant life cycle according to phenology outputs, a simple visualization is shown in Figure 2.6.

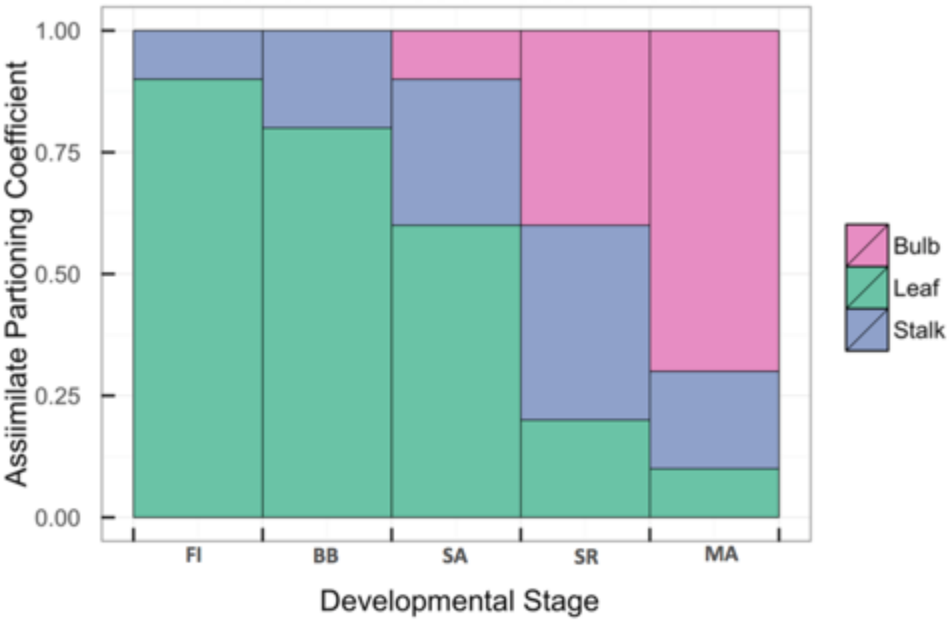


Figure 2.5. Concept of carbon partitioning coefficients based on developmental stages. FI indicating floral initiation, BB as bud burst, SA as scape appearance, SR as scape removal, and MA as maturation. The pink color shows biomass partitioned to the bulb, the green to the leaves, and purple to the stalk (pseudostem).

2.3.8 Environmental Input

Temperature, light intensity, relative humidity and atmospheric CO_2 concentrations are four major environmental inputs required to run the model simulations. These factors directly link to the photosynthesis module, which is what makes the photosynthetic process responsive to real-time environmental conditions.

2.4 Model Calibration and Validation

The phenology and morphology aspects of the whole-plant model were focused for the scope of this study. Both parts of the model is structured based on a beta distribution function. Independent datasets from consecutive experimental years were used for model calibration and validation respectively. Field observations from experimental year 2014-2015 were used for phenology and morphology calibration while observations from year 2013-2014 were used for validation.

Phenology Module

The beta distribution function used to simulate leaf development phenology was described earlier in model descriptions for phenological development. Parameters T_{opt} and R_{max} were parameterized for values that best fit field phenology observations of timing for individual leaf emergence based on RMSE values between model simulations and field observations. Parameter values were determined using data from the experimental year 2014-2015, and leaf development phenology results were compared with phenology results of year 2013-2014 in order to test the model performance of calibration results on an independent dataset.

Morphology Module

Since morphology outputs are tightly linked with phenology results, calibrated phenology parameters T_{opt} and R_{max} obtained from year 2014-2015 were adopted while simulating total leaf area outputs. An additional parameter required for morphology simulations, leaf elongation rate (LER, cm/day) was calibrated through year 2014-2015 field observations of relations between leaf elongation rate and the environmental temperature. Model simulations of total leaf area was generated with calibrated parameters from year 2014-2015, and tested against field observations of year 2013-2014. Model performance of the morphology module was determined by RMSE values calculated amongst field observations and model simulations.

Total Biomass Gain and Partition

Total biomass gain and partitioning was not the main focus of this study, therefore specific calibrations were not performed on the biomass gain and partitioning module within the model. However, since the accuracy of biomass gain and partitioning is closely linked with the accuracy of phenology and morphology predictions, I performed an additional analysis of comparing model outputs of biomass gain and partitioning before and after calibration and adjustments in the phenology and morphology modules. Field observations of total biomass and biomass partitioning to roots, stem, bulb and leaves were documented for experimental year 2013-2014 and 2014-2015, and both were compared with model simulations in order to understand the influence improvements in these two modules had on biomass related outputs. RMSE values were calculated in order to determine model performance prior and post calibration.

2.5 Results

2.5.1 Phenology Module

Phenology determines the timing of the individual processes within the model, which structures leaf area accumulation, photosynthesis, carbon gain and partitioning, therefore an accurate phenological prediction is one of the essentials first steps for a successful crop model.

2.5.1.1 Field Observations

Phenological events of leaf emergence, maturation and senescence for both cultivars were recorded frequently throughout the whole plant life cycle (Figure 2.7 and 2.8). Detailed timing of leaf emergence, and the duration to reach maturation and senescence for individual leaf numbers can be seen in Figure 2.10 and 2.11 for the cultivar SP and KM respectively. The emergence date, leaf development rate and final leaf number differed amongst cultivar, and also amongst planting dates within the same cultivar. The cultivar SP had an overall earlier phenological development and a greater final leaf number compared to KM. The later planting date resulted in a decrease in final leaf number in both cultivars, and the time period for leaves to reach maturation and eventually senesce was shorter for individual leaves for both cultivars compared to the earlier planting date.

The phenological difference in leaf development rate could be associated with the different temperature plants are exposed to within same development stages. The relation between leaf appearance rate and daily mean temperature can be seen in Figure 2.9. The relation is causal, but a pattern of higher temperature leading to a greater leaf appearance rate can still be seen. The time lag between the early and late planting dates exposed earlier planted plants to a warmer environment during the initial growth stage, facilitating initial growth and eventually leads a further mismatch in timing. This difference between phenological developments of the two planting dates is more distinctly seen in the cultivar SP (Figure 2.10).

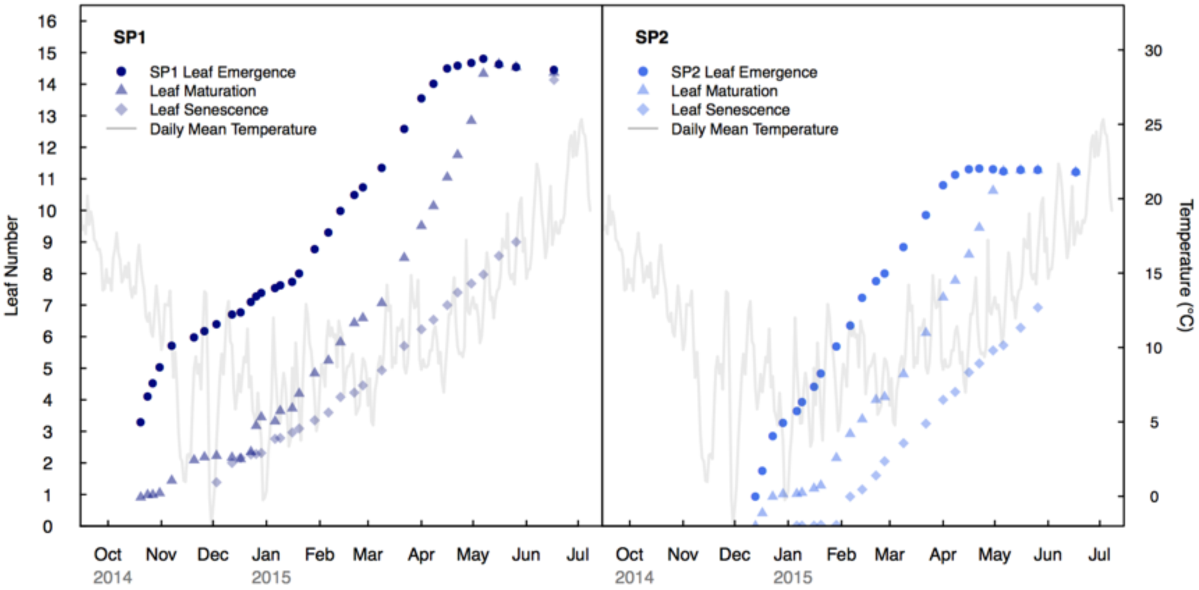


Figure 2.6. Leaf development phenology for cultivar SP. Dark blue represents the earlier planting date and light blue the latter. Solid circles indicate the timing for leaf appearance, the triangles the timing of leaf maturation, and the diamond the timing of senescence. n = 30 for each data point.

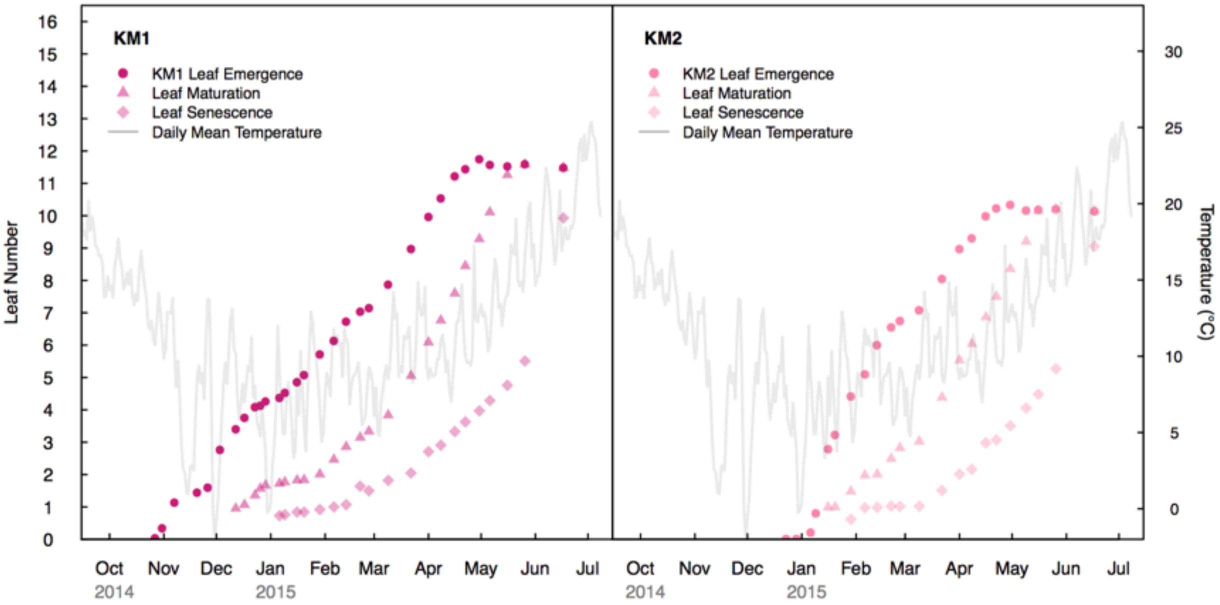


Figure 2.7. Leaf development phenology for cultivar SP. Dark blue represents the earlier planting date and light blue the latter. Solid circles indicate the timing for leaf appearance, the triangles the timing of leaf maturation, and the diamond the timing of senescence, n = 30 for each data point.

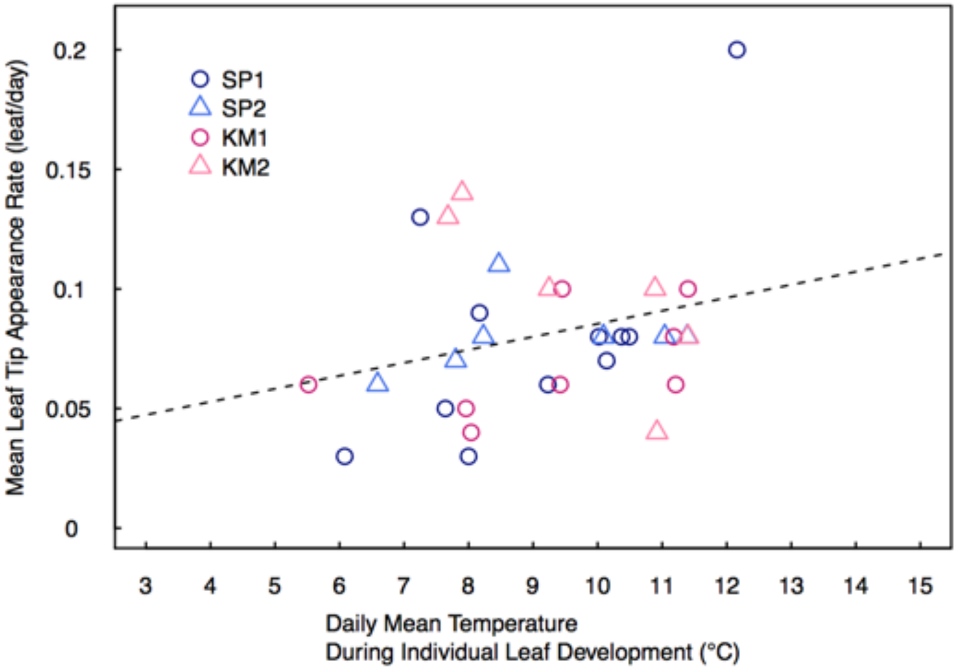


Figure 2.8. Relation between daily mean temperature during individual leaf development (˚C) and mean leaf tip appearance rate (leaf/day).

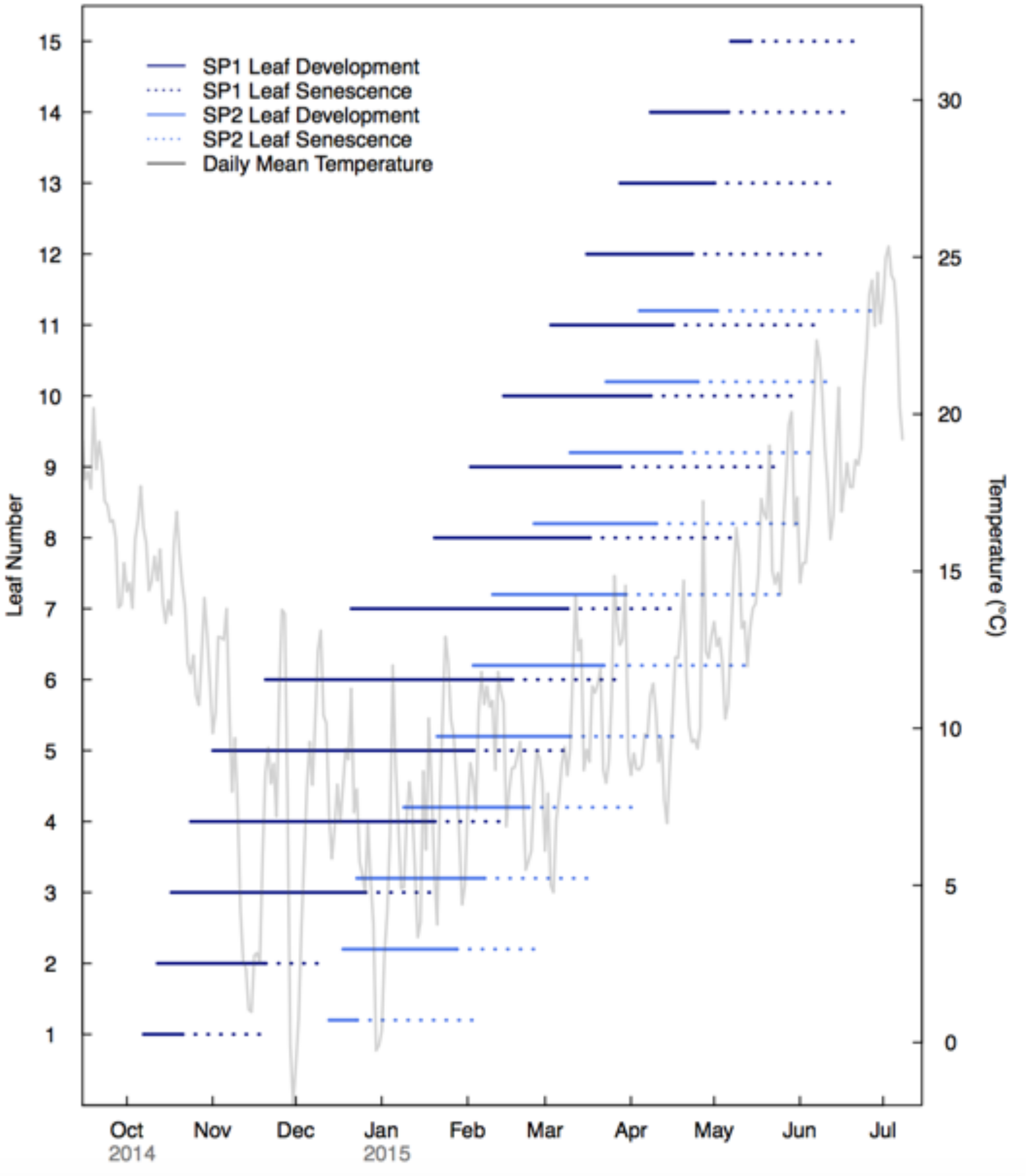


Figure 2.9. Leaf development and senescence time of individual leaf numbers for the two planting dates of cultivar SP. The dark blue color represents the earlier planting date (2014.10.03), and the light blue color represents the later planting date (2014.11.20). Solid lines indicate the time period from leaf emergence to leaf maturation, and dashed lines indicate the time period from leaf maturation to complete senescence. The gray line shows the daily mean temperature over the growth period.

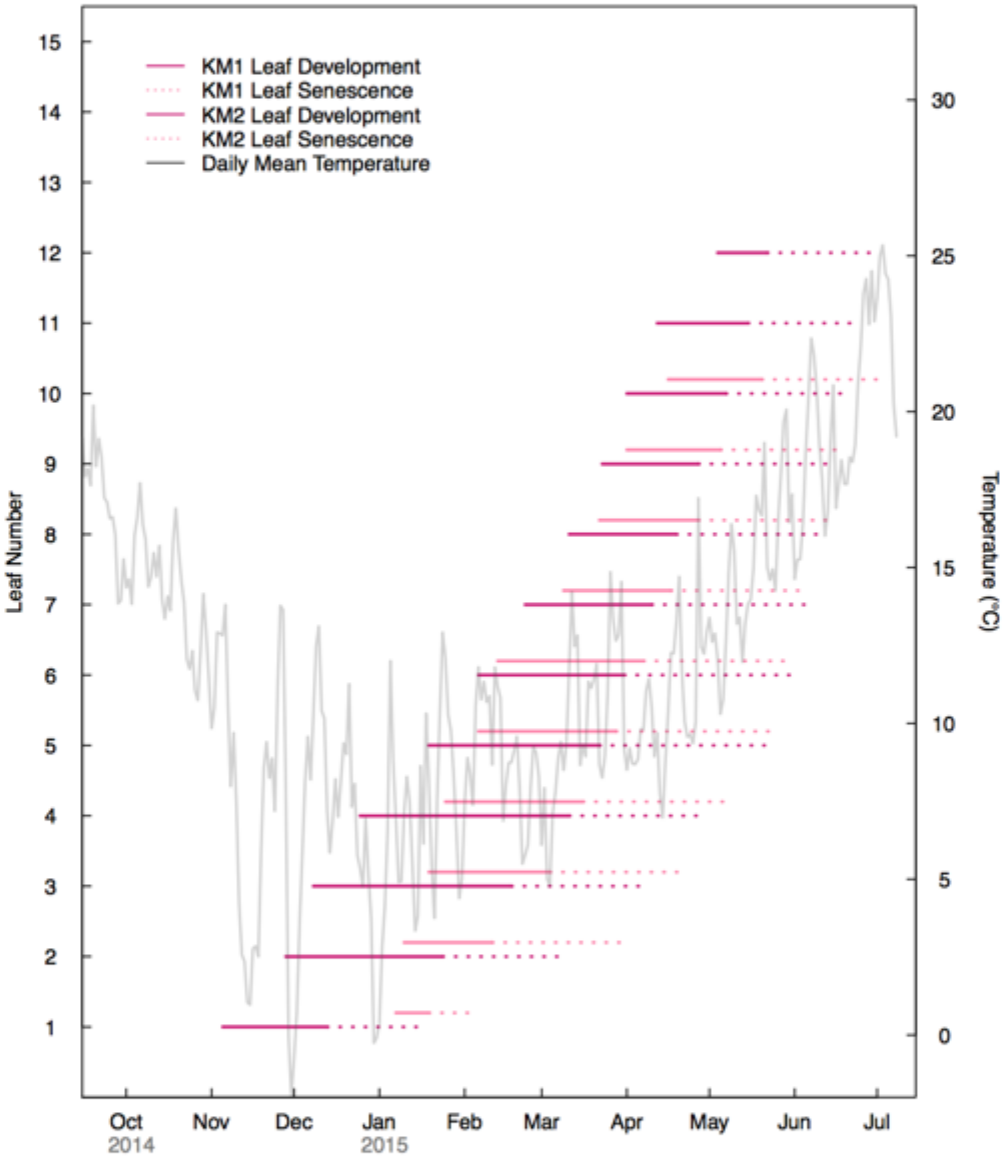


Figure 2.10. Leaf development and senescence time of individual leaf numbers for the two planting dates of cultivar KM. The dark pink color represents the earlier planting date (2014.10.03), and the light pink color represents the later planting date (2014.11.20). Solid lines indicate the time period from leaf emergence to leaf maturation, and dashed lines indicate the time period from leaf maturation to complete senescence. The gray line shows the daily mean temperature over the growth period.

2.5.1.2 Model Simulation

A temperature-based beta distribution function was used in the phenology module to simulate leaf development (Figure 2.3). The three parameters required for the function are: the optimal temperature (T_{opt}, ˚C), the maximal growth rate (R_{max}, leaves/day), and the final leaf number. The final leaf number for each cultivar and planting date combination were manually input into the model as known parameters, while T_{opt} and R_{max} values of 25˚C and 0.23 (leaves/day) were adopted from previous greenhouse and field experiments when the model was in development.

Results from the first attempt of model simulation are shown in Figure 2.12. The model simulations for both cultivars were able to capture the overall pattern of leaf development, but showed less than ideal simulations for the earlier planting dates, especially for the cultivar KM. RMSE values calculated between model predictions and actual observations were 1.27, 0.63 for the first and second planting date for cultivar SP respectively, and 3.80 and 1.28 for cultivar KM. Results indicate that the current parameters used for the phenology module requires calibration, and also the possibility that different sets of parameter values may be necessary for separate species.

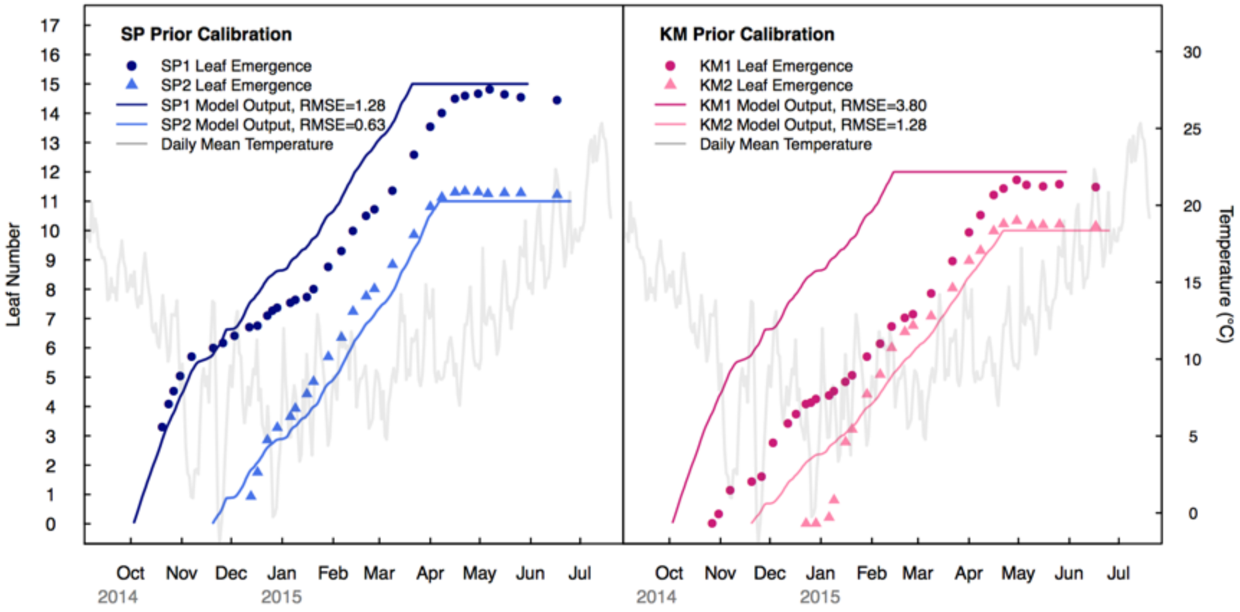


Figure 2.11. Observed and simulated leaf development phenology for both cultivars (SP: Shantung Purple, represented in the color blue; KM: Korean Mountain, represented in the color pink) and planting dates (1: early planting, 2014.10.03; 2: late planting, 2014.11.20). Points represent field observations and lines model simulations. The solid circles represent phenological observations from the earlier planting date, and solid triangles represent observations from the later planting date.

2.5.1.3 Model Calibration

Temperature Relations of Leaf Development and Parameter Search

Results from the initial validation indicated that calibration with updated parameters of T_{opt} and R_{max} is necessary in order to improve the model performance for phenology prediction. These beta function parameters were estimated through the conversion between beta function and the conventional growing degree days (GDD) model. The growing degree calculated here are defined as the heat units required for the emergence of individual leaves, which can also be seen as the interval between similar growth stages of successive leaves. A special terminology, phyllochron, is used to define this physiological characteristic. It represents a period of time between the emergence of one phytomer (a set of tiller, leaf and root which emerges from the base of the plant) and the emergence of the next (Veeramani et al., 2012), and is often used to determine the rate of leaf appearance in grass species (Eqn. 2.5).

$\Phi = \sum_{i=1}^{n}(\min(T_{opt}, T) - T_b)$ …… Eqn. 2.5

$r = 1/n = (T - T_b) / \Phi$ …… Eqn. 2.6

$R_{max} = 1/n_{min} = (T_{opt} - T_b) / \Phi$ …… Eqn. 2.7

In order to calculate phyllochron (Φ), three pieces of information is needed as represented in Eqn. 2.5: the time period between emergence of an individual leaf to the next (n), the daily mean temperatures throughout that period (T), and the base temperature (T_b). The time period between individual leaf developments were calculated from field observations of leaf appearance for both cultivar and planting dates (Figure 2.10, Figure 2.11). The corresponding temperature during the period is also available through the on-site weather station, and the base temperature was empirically determined as 0˚C based on field observations of plant growth under various temperature conditions.

Phyllochron was determined for each cultivar by averaging the values calculated through Eqn. 2.5 for each planting date. Actual phyllochron values for individual phytomers for each cultivar and planting date combination is also shown in Figure 2.13. Phyllochron values were then used in Eqn. 2.6 and 2.7 to generate leaf development rate (r), and leading to R_{max}. However, since T_{opt} is still unknown in this case, a range of physiologically reasonable T_{opt} values from 20˚C to 40 ˚C with the interval of 1˚C were chosen generate R_{max} values. These parameter combinations were then used for the phenology module to generate phenology simulations, and the simulation results were then compared with actual field observations. Model performance for each parameter combination was determined through RMSE values, and the parameters that led to the lowest RMSE values were chosen (Table 2.1). Final T_{opt} and R_{max} values chosen for cultivar SP and KM were 27, 0.22, 31, and 0.24 respectively.

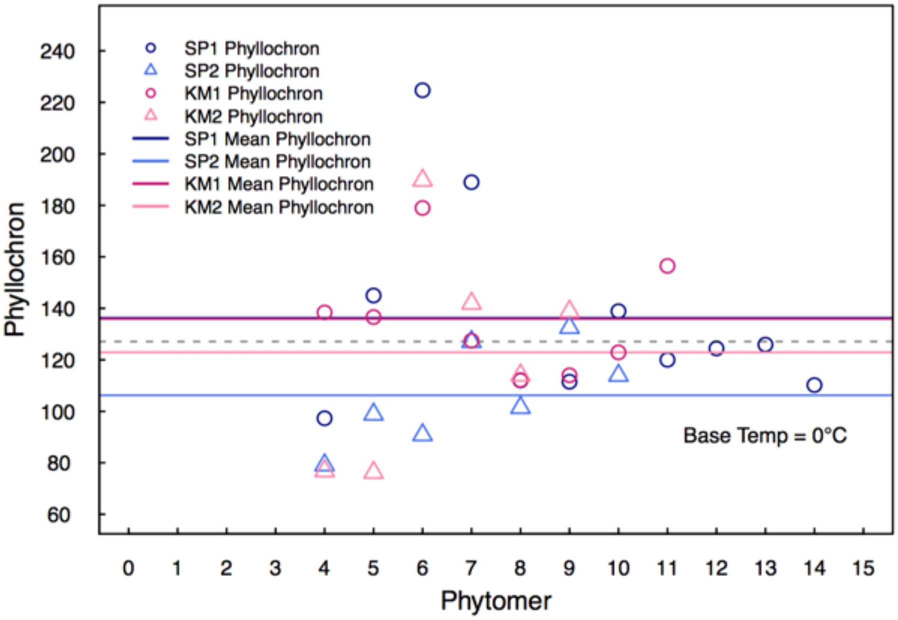


Figure 2.12. Phyllochron calculations of individual phytomer for the earlier (open circles) and later (open triangles) planting dates for cultivars SP (blue) and KM (pink). Colored lines show the average phyllochron value for each cultivar and planting date combination.

Table 2.1. Parameter list for phenology module prior and post calibration, and the corresponding model performance for all cultivar and planting date combinations.

	Prior-Calibration			Post-Calibration		
	Topt	Rmax	RMSE	Topt	Rmax	RMSE
SP1	25	0.23	1.27	27	0.22	0.53
SP2			0.63			0.71
KM1	25	0.23	3.80	31	0.23	1.51
KM2			1.28			1.78

2.5.1.4 Model Performance Post Calibration

Leaf development phenology simulations were updated with the new parameter sets obtained after calibration, and the outputs of field observation and model predictions comparisons are shown in Figure 2.14. RMSE values decreased for the first planting date in both cultivar SP and KM, with values lowering from 1.27 to 0.53 for cultivar SP, and 3.80 to 1.51 for cultivar KM. Results indicated an improvement in model performance for earlier planting dates in both cultivars, but a slight decrease in performance for later planting dates. However, overall model performance for phenology simulation improved in both cultivars when considering cultivars as a whole. Parameter and RMSE values prior and post calibration are shown in Table 2.1.

2.5.1.5 Model Validation

Model validation was performed under an individual dataset from year 2013-2014 with the same cultivars but different planting dates. Calibrated parameter sets obtained from year 2014-2015 were applied, and model outputs were compared with field observations to determine model performance. Validation results for leaf development phenology prior and post parameter calibration are shown in Figure 2.15. Model outputs with original parameter sets were less ideal for earlier planting dates in both cultivars, but showed greater accuracy for later planting dates. Model performance for earlier planting dates improved with calibrated parameter sets. RMSE values improved from 1.58 to 0.53 for cultivar SP, and 5.5 to 2.24 for KM. However, model performance decreased for later planting dates. RMSE values increased from 0.49 to 1.81 for cultivar SP, and increased from 1.9 to 2.74 for KM. The overall model performance for each cultivar can be represented by adding up the RMSE values of both planting dates. Results showed that calibrated parameter sets improved overall performance for cultivar KM, with total RMSE values decreasing from 7.4 to 4.98. However, calibration in parameter values did not contribute to a better accuracy for cultivar SP, but rather resulted in a slightly increased total RMSE value from 2.11 to 2.3.

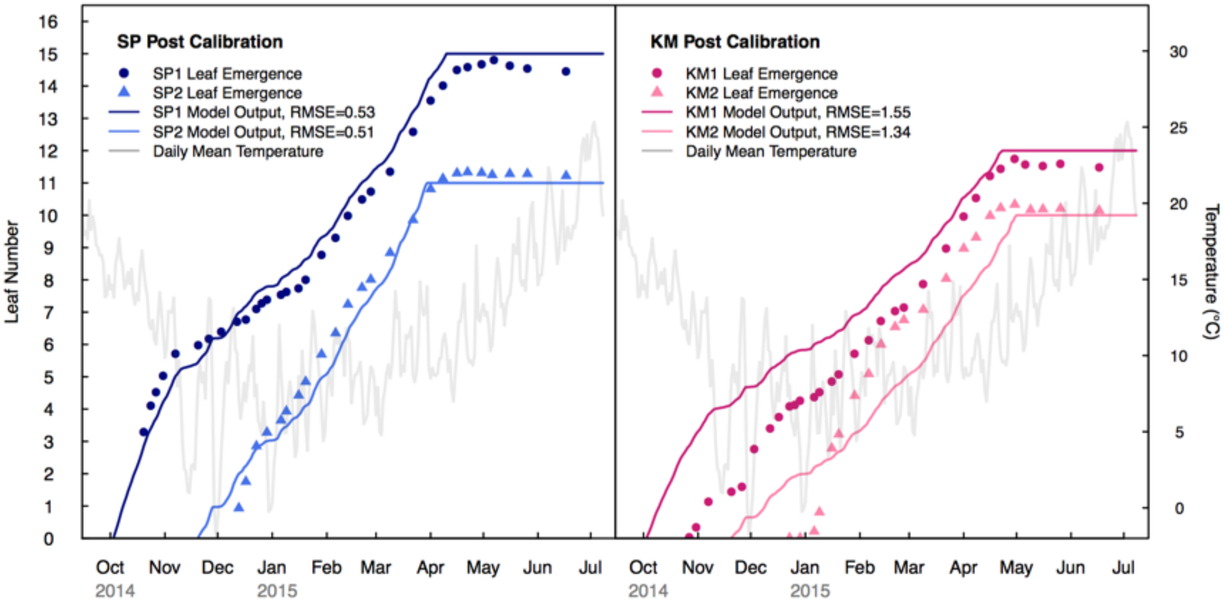


Figure 2.13. Observed leaf development phenology for both cultivars (SP: Shantung Purple, KM: Korean Mountain) and planting dates (1: early planting, 2: late planting) along with model simulation outputs after modifications were applied for the phenology module. Points represent field observations and lines model simulations. Circles represent phenological observations from the earlier planting date (2014.10.03), and triangles represent observations from the later planting date (2014.11.20).

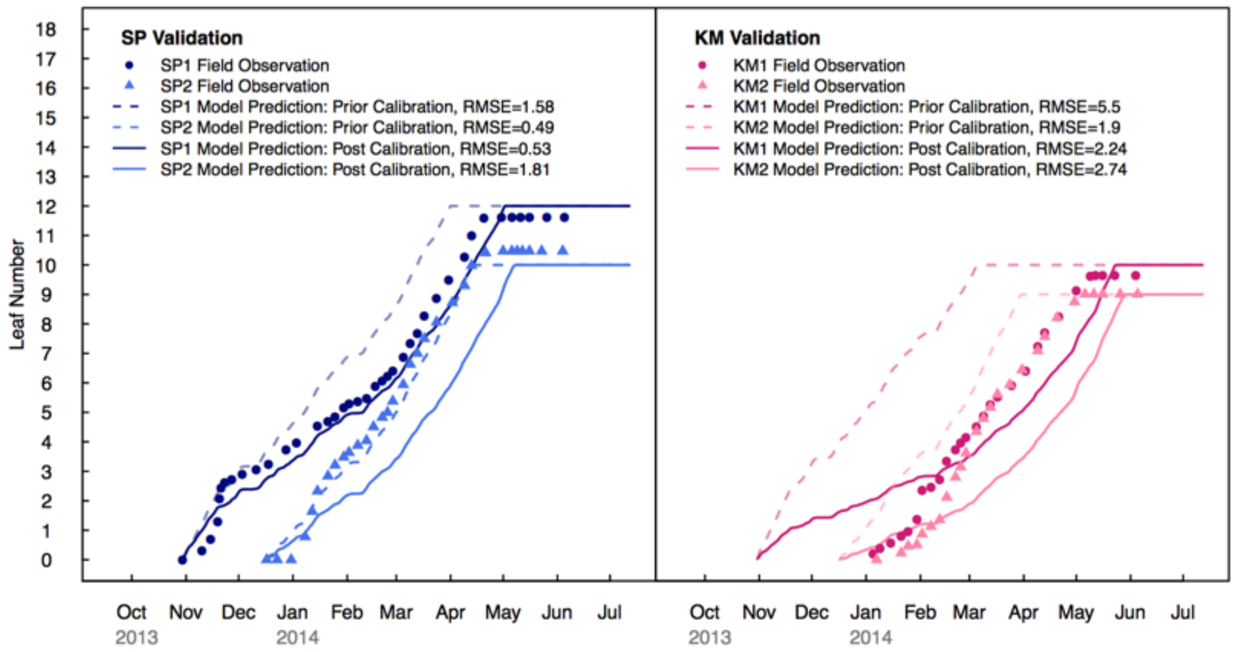


Figure 2.14. Validation results of phenology module for both cultivars and planting dates. Solid circle represent field observations from the early planting date of experimental year 2013-2014, while solid triangles represent observations from the later planting date. Dashed lines show model outputs prior to calibration and solid lines show results post calibration. Model performance is evaluated through RMSE values.

2.5.2 Morphology Module

The morphology module was chosen as the next step to evaluate the model performance after examining leaf development phenology due to the tight linkage it has with phenology, and the importance it holds in terms for photosynthesis and biomass gain. The terminology morphology here specifically refers to leaf length, width, area, and leaf area accumulation. Phenology and morphology, which can also been seen as leaf development and leaf area accumulation in the scope of the model structure, are tightly linked; inaccuracy in either part could both lead to discrepancy between field observations and model simulations.

2.5.2.1 Field Observations

Field measurements of the leaf area of individual leaves for all cultivar and planting date combinations are shown in Figure 2.16. Cultivar differences along with planting date differences can all be seen. Regardless of cultivar, the earlier the planting date, the greater the total number of leaves generated (Figure 2.17 and 2.18), leading to an overall greater leaf area for earlier planting dates (Figure 2.20). Differences between planting dates are more distinct within cultivar SP. When comparing amongst the same planting dates between cultivars, Shantung Purple shows a greater total leaf number, and a greater total leaf area compared to Korean Mountain (Figure 2.19).

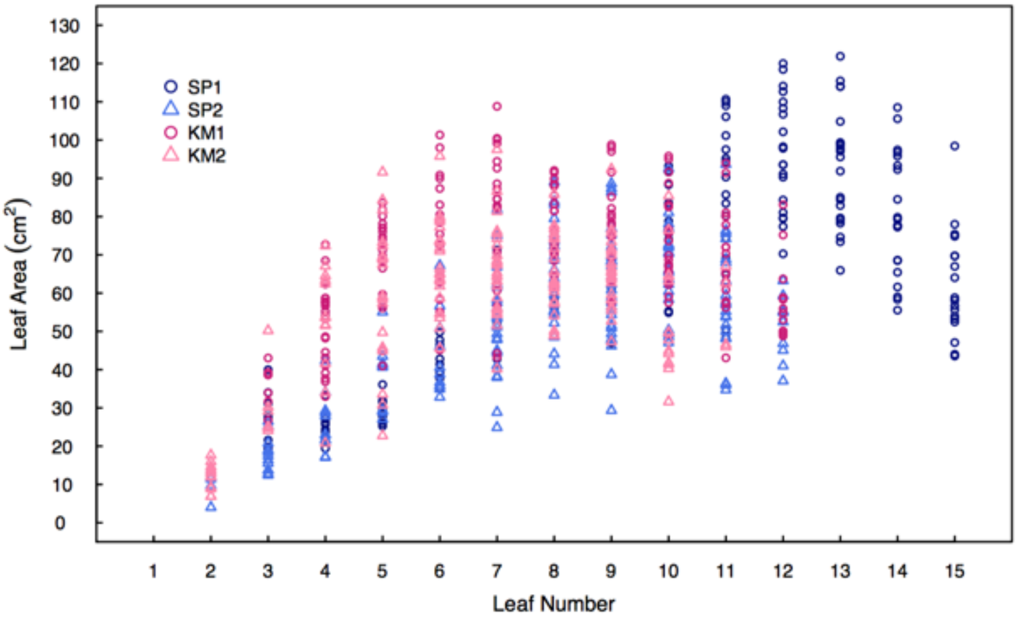


Figure 2.15. Leaf area observations for individual leaf numbers for cultivar SP (blue) and KM (pink). Circles indicate observations from the earlier planting date (2014.10.03), and the triangles indicate observations from the latter planting date (2014.11.20).

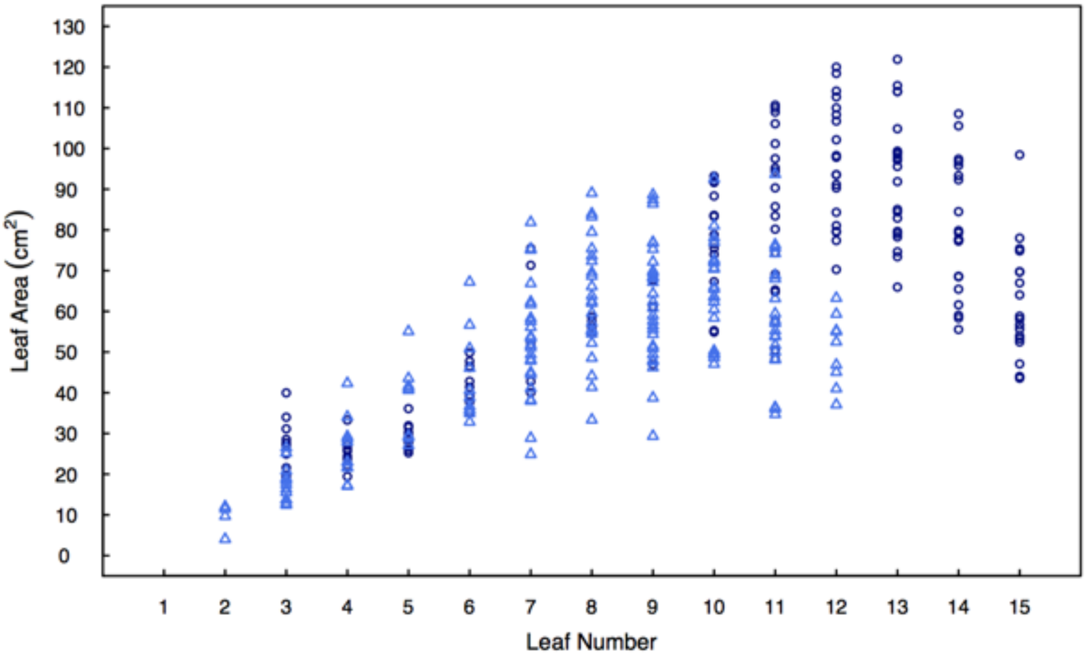


Figure 2.16. Leaf area for individual leaf numbers for the cultivar SP. Circles indicate observations from the earlier planting date (2014.10.03), and the triangles indicate observations from the latter planting date (2014.11.20).

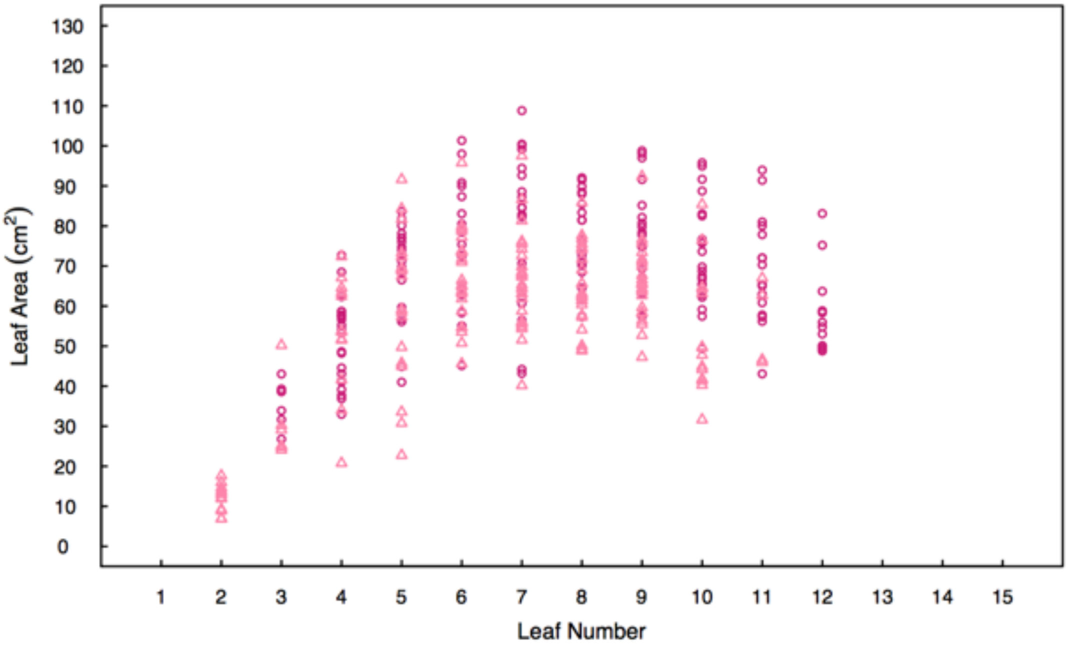


Figure 2.17. Leaf area for individual leaf numbers for the cultivar KM. Circles indicate observations from the earlier planting date (2014.10.03), and the triangles indicate observations from the latter planting date (2014.11.20).

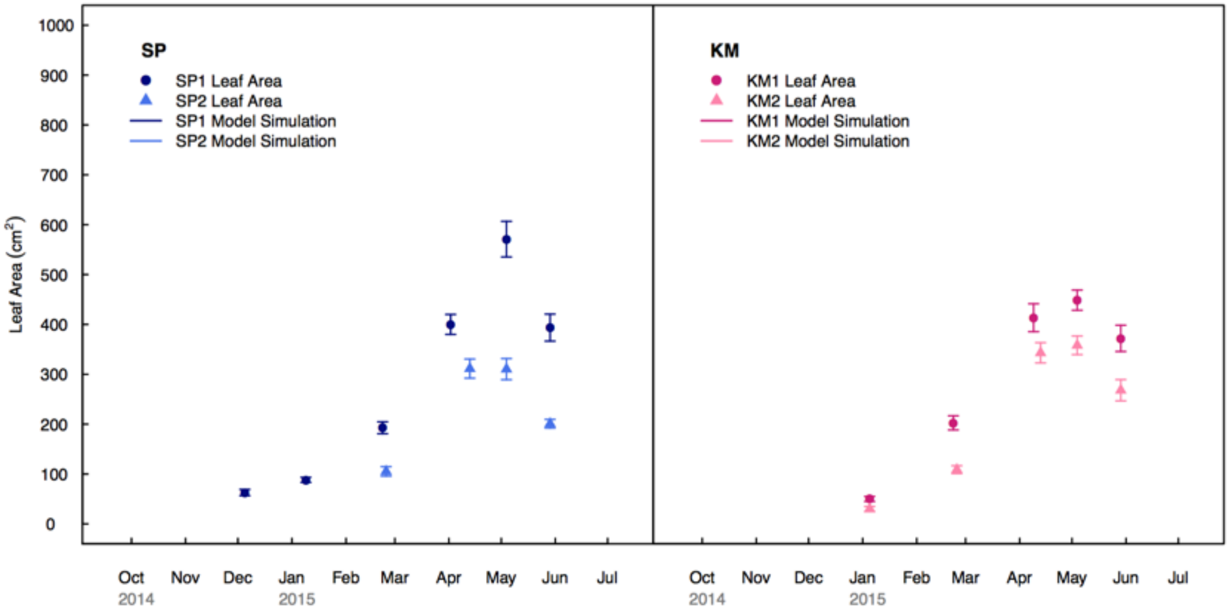


Figure 2.18. Total leaf area accumulation throughout development for cultivar SP (blue) and KM (pink). Circles indicate measurements from the earlier planting date (2014.10.03), and triangles from the latter planting date (2014.11.20).

2.5.2.2 Model Simulations

Since leaf area prediction is tightly linked with phenology, parameter choice for the phenology module would also influence model outputs for leaf area simulations. Comparison between field observations and model simulation of leaf area accumulation over time are shown in Figure 2.20. Default parameter values of T_{opt} = 25˚C, R_{max} = 0.23 (leaves/day) and LER_{max} = 1.25 (cm/day) were used to generate initial leaf area simulation outputs. Initial results showed a tendency of overestimation in total leaf area for both cultivar and planting dates, which is most obvious near the peak of total leaf area. The timing of leaf area accumulation is also mismatched for both cultivars and planting dates. Leaf area accumulation timing is overall delayed, with greater inaccuracy seen in the later planting date.

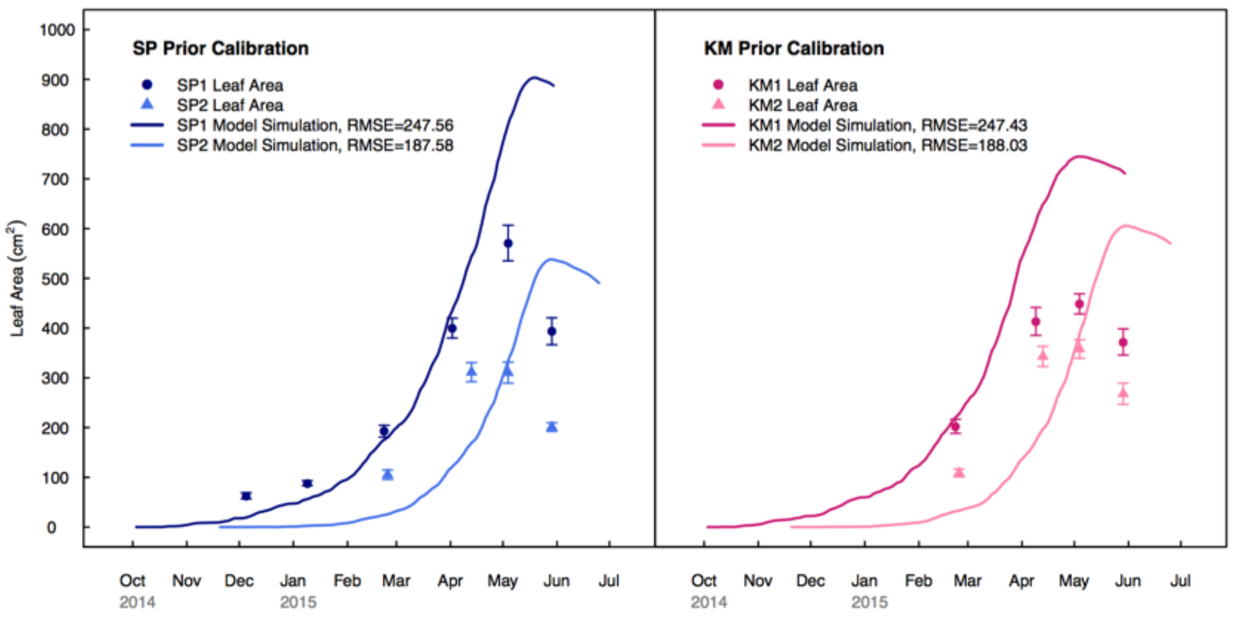


Figure 2.19. Leaf area accumulation observation (cm^2) and model simulation over time with model preset parameters of $T_{opt} = 25^\circ C$, $R_{max} = 0.23$, $LER_{max} = 1.25$.

2.5.2.3 Model Calibration - Phenology Module Inputs and LER

Overall overestimation in leaf area predictions by using default model parameters indicated a requirement for calibration for the morphology module as well. However, when calibrating the morphology module, the phenology module needs to be taken into account as well since the two are tightly linked. Leaf area simulations were regenerated with calibrated cultivar-based phenology parameters: T_{opt} and R_{max} (Table 2.1) and updated LER values of 6 (cm/day) calculated through field observations of leaf growth rate. Comparison between field observation and model simulations with updated phenology parameters is shown in Figure 2.20. It can be seen that the model simulations with updated phenology parameters showed an improvement in model performance. Adjustments in phenology module parameters along with a modified LER value solved for the mismatch in the timing and overestimation of leaf area accumulation.

However, despite the great improvement after calibration, slight overestimation is still seen in both cultivars, and the accuracy in leaf area simulation is the poorest during the peak timing of leaf development, which when the leaf area accumulated is the greatest. This time range ranges from mid March to Mid May, which is the most productive stage for garlic plants, and also is the point when most leaf area is present to photosynthesize. Having an accurate leaf area simulation, especially during important developmental stages when the plant is most productive has great importance, therefore the morphological aspects of the garlic leaves along with the current leaf area simulation algorithm was re-evaluated, calibrated and modified in aim for a further improvement in leaf area simulation.

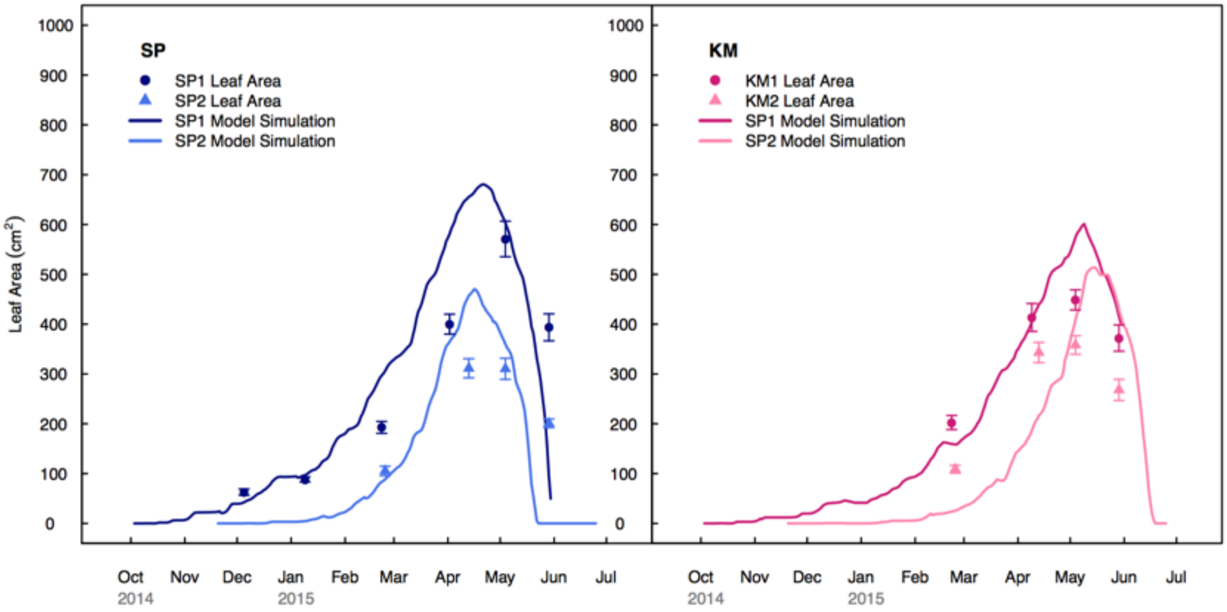


Figure 2.20. Leaf area accumulation observation and model simulation over time with calibrated parameters.

2.5.2.4 Current Morphology Module Algorithm for Leaf Area Simulation

The current algorithm for leaf area simulation was briefly discussed in the model description section, but will be discussed more in depth here. The original structure used to simulate leaf area starts by simulating leaf length through the length-based beta function described earlier.

Once length is simulated, leaf width is generated as a function of leaf length through a linear relation described in Eqn. 2.8, and leaf area further simulated as a function of both leaf length and width (Eqn. 2.9.). This kind of allometric relationship is often used in simulations for leaf area, and is convenient since maximal leaf length is the only required parameter input. However, a further evaluation of the relationships between the leaf length, width and area for garlic leaves showed that this method might not be the best way for leaf area simulation. The second goal for model improvement after re-calibrating parameters for the phenology module was to come up with a modified method for leaf area simulation to lower error.

Leaf Width = f (Leaf Length) …………………………………………………….... Eqn. 2.8

Leaf Area = f (Leaf Length, Leaf Width) …………………….……………………..……Eqn. 2. 9

In order to have a better understanding of the morphological aspects of garlic leaves in attempt to formulate a better allometric relationship to simulate leaf area, the relations between leaf number and leaf length, as well as leaf number and leaf width was analyzed first for both cultivars (Figure 2.23 and Figure 2.24). From the relationship between leaf length and leaf number, it can be seen that in both cultivar, leaf length increases with leaf number, peaks at a relatively high leaf number, usually the second or third to last leaf developed, and then slightly decreases until the final leaf number is developed.

Leaf number and leaf width has a similar pattern as leaf length in both cultivars, showing an increase in width while leaf number increases, but the value peaks at earlier at a lower leaf number, and starts to decrease towards the final leaf (Figure 2.22 and 2.243. This pattern shows that the algorithm currently used to simulate leaf width as a function of leaf length, assuming that the longer the leaf length the wider the width, may not always hold true. Since peak leaf width is reached at a lower leaf number than peak length, when length may still be increasing for certain leaf numbers, the width may already have started to decrease. The relation between leaf length and width is shown in Figure 2.24. It can be seen that the relation is relatively loose, especially towards higher leaf numbers.

Effects of planting date on leaf morphology can also be seen in final leaf number, leaf length and leaf width. In both cultivars, the final leaf number decreased when planting date was pushed back, while also causing the final leaf length and width to be smaller than the earlier planted plants, leading to an overall decrease in total leaf area. These differences were more distinct in cultivar SP. This morphological difference led to a need for different beta function parameter values for separate planting dates. However, the current model structure does not take into account the morphological differences caused by the effect of changing planting dates. This issue will further be discussed.

Leaf area of a matured leaf is affected by leaf length and width, therefore the difference seen in length and width amongst cultivars and planting dates did not lead to a surprise for the relationship seen between leaf number and leaf area (Figure 2.17 and 2.18).

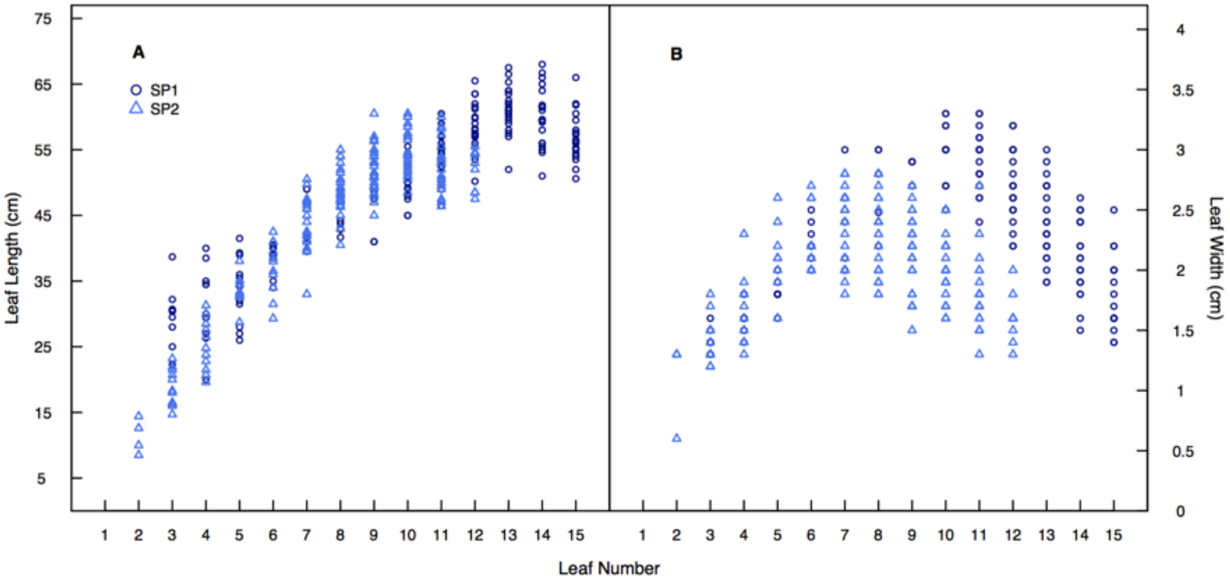


Figure 2.21. Leaf length and width for individual leaf numbers for the cultivar SP. Circles indicate observations from the earlier planting date (2014.10.03), and the triangles indicate observations from the latter planting date (2014.11.20).

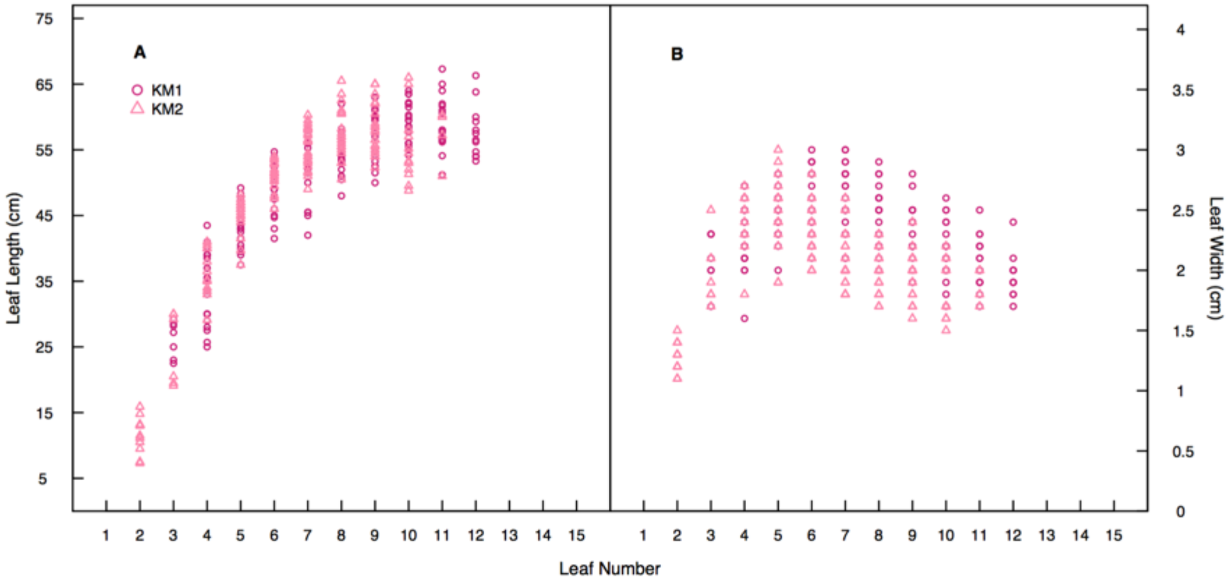


Figure 2.22. Leaf length and width for individual leaf numbers for the cultivar KM. Circles indicate observations from the earlier planting date (2014.10.03), and the triangles indicate observations from the latter planting date (2014.11.20).

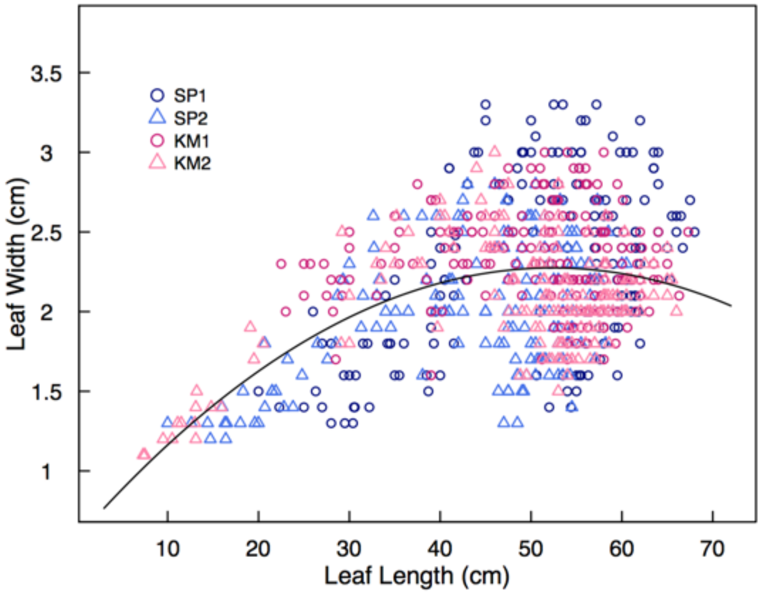


Figure 2.23. Leaf length and width relation for all cultivar and planting date combinations. The points show field observations, and the line shows the modeled regression between length and with.

Based on the understanding of the relationships between leaf number, leaf length, leaf width, and leaf area, two main issues with the current morphology module structure can be pointed out. First of all, a single set of parameters for the beta distribution to simulate leaf length for different cultivars and planting dates may not be realistic since morphological difference in all of these aspects are seen through field experiments. Second of all, the allometric relation used to simulate leaf width from length may not be the best relation for width simulation since, and errors in leaf width estimation may further lead to an overall error in area estimation.

2.5.2.5 Modification in Current Leaf Area Simulation Algorithm

The first issue with the current morphology module is the need for individual parameters for different cultivars and planting dates. Results of fitting the leaf number and leaf length relationship with the current beta function parameters for the two planting dates of cultivar SP and KM is shown in Figure 2.25 and 2.26. Required inputs of maximal leaf length, optimal leaf number and the maximal leaf number were obtained through field observations and measurements. Results were not as ideal for both planting dates, showing an overall underestimation for lower leaf numbers. These results indicate that a single set of parameters, when only allowing adjustments for the maximal leaf length, may not be a realistic modeling approach.

Recalibrating the beta distribution parameters individually for each cultivar and planting date combination may be the most straightforward and accurate method to account for the morphological differences observed. However, this seemingly easy process would most likely results in increased complexity and difficulty in order to calibrate the model. Individual parameters may lead to a most accurate simulation for this current scenario, but is also difficult to apply to other conditions, whether it’s a difference in cultivar, planting date, or other factors that may potentially cause changes in final leaf number, leaf length, and the leaf number where maximal leaf length is achieved. Therefore, a different approach trying to address this issue was practiced.

Leaf length and width data along with leaf number were all normalized into a scale within zero and one. Therefore, regardless of the difference in the final leaf number or maximal leaf length, the relationship between leaf number and length would all be normalized into a comparable scale. Results for the leaf length and leaf number relation after normalization is shown in Figure 2.27. Results show that the difference in leaf length observed between cultivars and amongst planting dates were minimized after normalization, and a common beta function was able to describe the relationship.

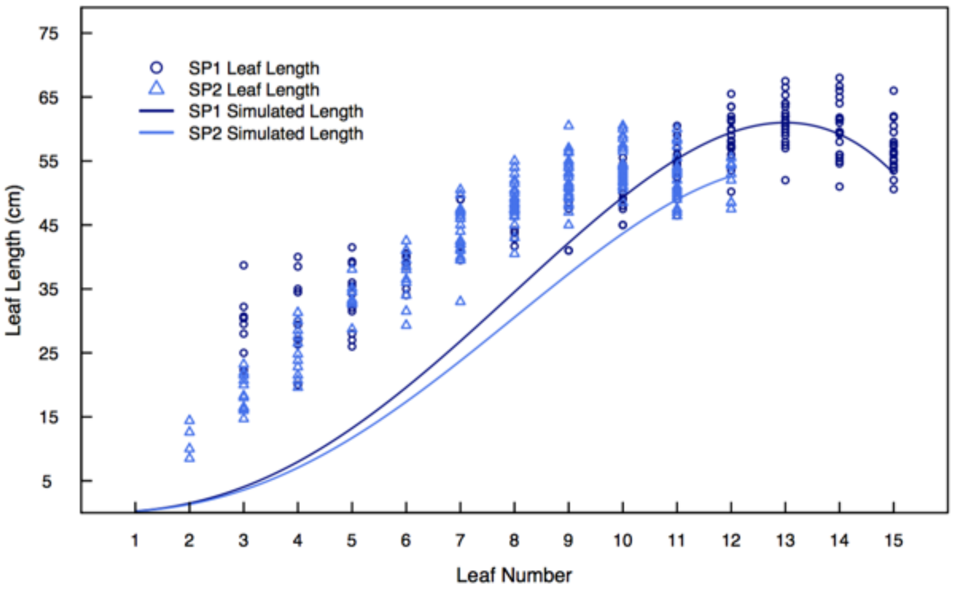


Figure 2.24. The beta distribution function used to simulate the final leaf length for individual leaf numbers for cultivar SP. Open circles indicate field measurements from the earlier planting date (SP1), and open triangles for the latter planting date (SP2). The lines represent the model simulation, with the dark blue line indicating simulations for SP1, and light blue for SP2.

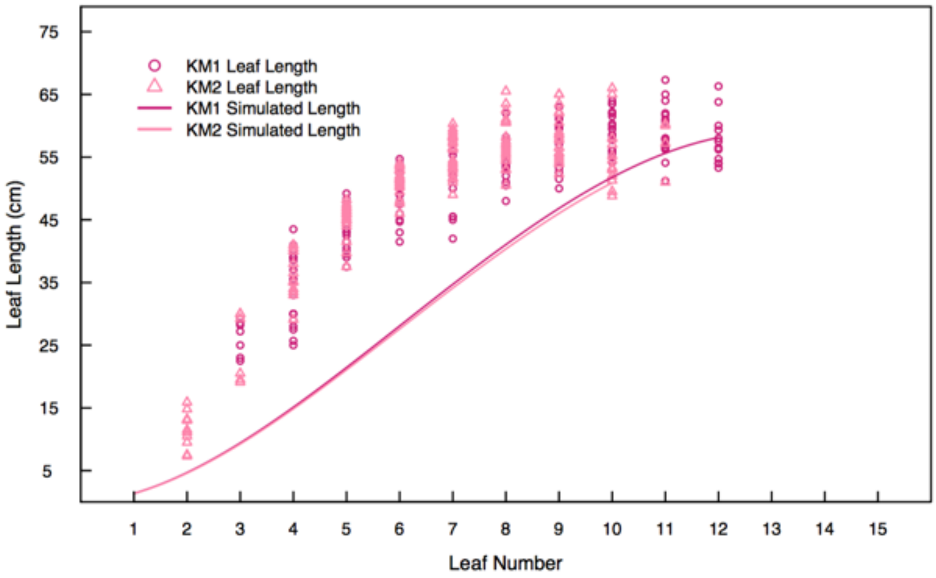


Figure 2.25. The beta distribution function used to simulate the final leaf length for individual leaf numbers for cultivar KM. Open circles indicate field measurements from the earlier planting date (KM1), and open triangles for the latter planting date (KM2). The lines represent the model simulation, with the dark blue line indicating simulations for KM1, and light blue for KM2.

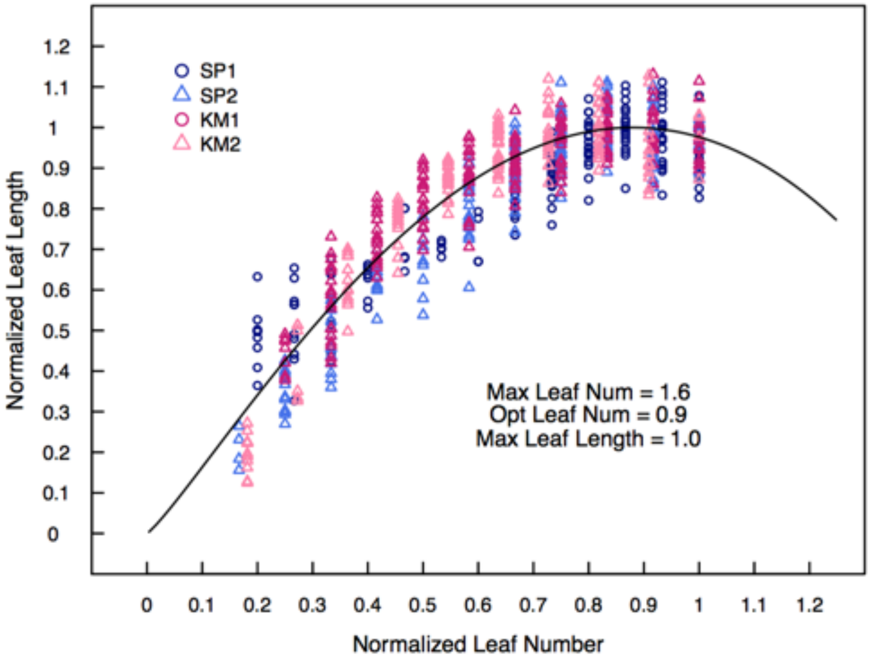


Figure 2.26. The beta distribution function used to simulate the final leaf length for all cultivars for individual leaf numbers, under a normalized scale between zero and one.

The second issue with the current model is the leaf area simulation method. The current leaf area simulation method starts by simulating leaf length first through the beta distribution, and simulating leaf width on top of that through a linear relation between the two. Finally, leaf area is predicted as the function of both length and width. However, the loose relationship between length and width may lead to potential errors in the final leaf area prediction, as mentioned earlier.

Since leaf length and leaf area showed a stronger relationship (Figure 2.28), an alternative method to simulate leaf area, which bypasses the process of simulating leaf width was tested. Within this method, leaf length is first simulated through the normalized leaf length beta function, and then converted back to normal scale. Leaf area is then directly simulated through a polynomial model as a function of leaf length.

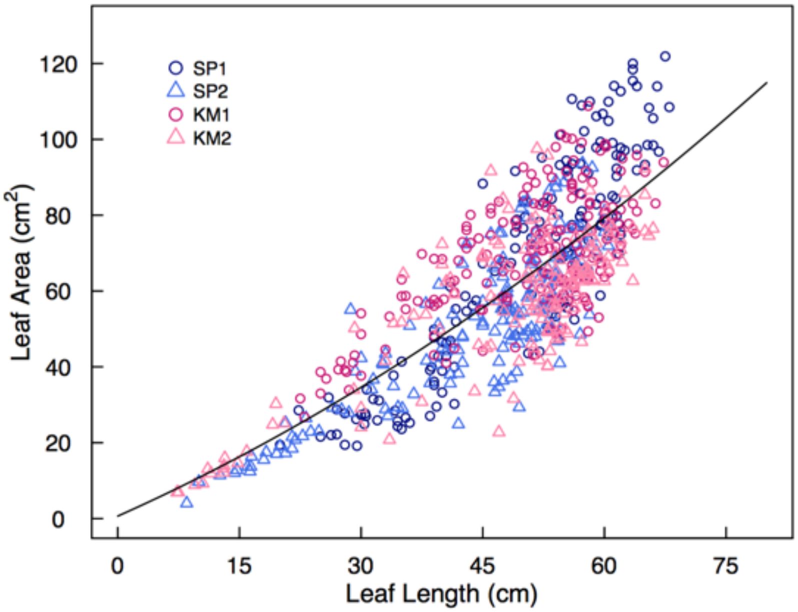


Figure 2.27. Leaf length and area relations for all cultivar and planting date combinations. The points represent field observations, and the line represents the linear model: Area = 0.64 + 0.95 * Length + 0.006 * (Length)^2.

2.5.2.6 Model Performance After Modification

Model performance after modifications in the morphology module is shown in Figure 2.29. The simulation performance improved for both cultivars, especially for the time period when the plants had the greatest total leaf area. However, leaf area simulation for the latter planting date for cultivar KM still showed discrepancy between field observations, which corresponds to the inaccuracy also seen in the phenology outputs.

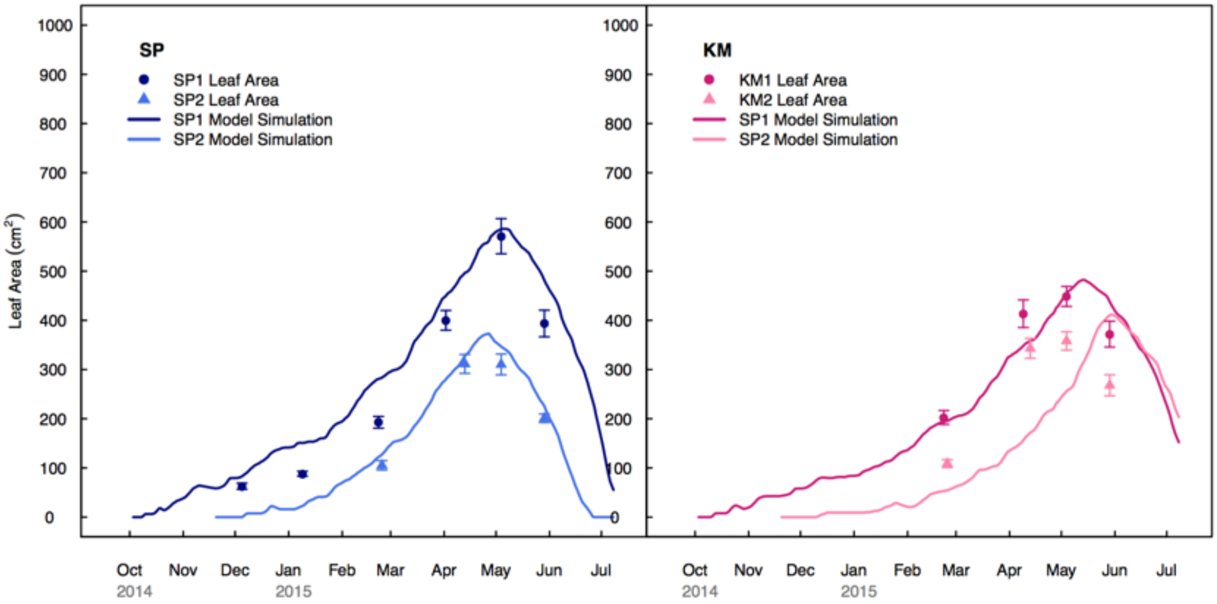


Figure 2.28. Leaf area observation and simulations after modifications in the morphology module for both planting dates of cultivar SP (blue) and KM (pink). Solid points indicate field observations while lines indicate model simulations.

2.5.2.7 Model Validation

The calibrated morphology module was validated with an independent morphology dataset from year 2013-2014 experiments. Validation results are shown in Figure 2.30. Model performance determined through validation differed amongst cultivars. The overall timing for leaf area accumulation was improved, and the original overestimation in total leaf area was adjusted to produce more realistic outputs with cultivar SP. Model performance is determined through RMSE values, and values decreased from 193.58 to 62.98 for the early planting date, and decreased from 179.15 to 76.76 for the later planting date. However, model performance in predicting leaf area accumulation was not ideal for cultivar KM, showing a delay in timing estimation for leaf area accumulation, along with overestimation in total leaf area. Total model performance decreased after applying calibrated parameter sets, with RMSE values increasing from 224.00 to 237.51 for the earlier planting date, and increasing fro 186.67 to 194.88 for the later planting date. Inaccuracy in cultivar KM may be traced back to the low model performance in phenology predictions, leading to greater overall model performances for cultivar SP.

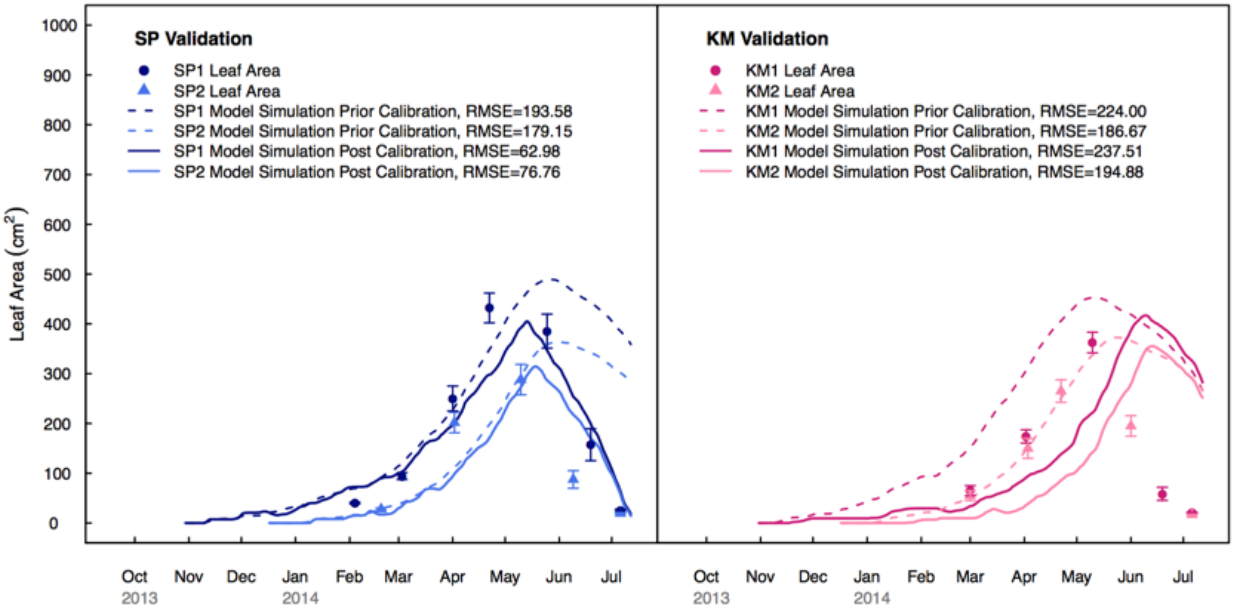


Figure 2.29. Leaf area accumulation validation for both planting dates of cultivar SP (blue) and KM (pink). Solid points indicate field observations from the earlier planting date and solid triangles show observations from the later planting date. Dashed lines show model simulations with un-calibrated parameter sets, and solid lines indicate outputs from calibrated parameter sets along with a modified leaf area simulation algorithm.

2.5.3 Biomass Accumulation and Partitioning

Biomass simulation and final yield prediction may be the two most important outputs people wish to obtain from crop models. However, the biomass output is towards the end point in the whole model simulation process, and the results largely depend on the accuracy of previous processes such as phenology and morphology. Calibration and improvement in the biomass gain and partitioning part of the model was not the main focus of this study, but was rather used as an indicator to analyze the calibrations and modifications made in phenology and morphology modules.

2.5.3.1 Field Observation and Model Simulation

Total biomass accumulation simulation results can be seen in Figure 2.31. Overestimation is seen in both cultivars and planting dates, with greater error seen in Shantung Purple. This corresponds to the previous overestimation seen in leaf area prior to phenology module calibration and modifications in the morphology module. Results of further carbon partitioning to individual plant parts such as stem, leaves, roots, and bulb for both cultivar and planting dates are shown in Figure 2.32 and Figure 2.33. Biomass partitioning results are less than ideal, with an overestimation in stem, leaves, and roots in Shantung Purple, and a great overestimation in leaf biomass in Korean Mountain.

Carbon partition coefficients were also calculated for all cultivar and planting date combinations shown in Figure 2.34 to 2.37. Partitioning patterns differed amongst treatments, but overall followed similar patterns. During early to mid vegetative developmental stages, greater carbon is located in the original seed clove as well as newly developed leaves. As growth progresses through the vegetative development stage, carbon within the original seed cloves gradually decreases and is eventually used up for growth of other plant parts, particularly for the pseudostem and leaves. As the plant transitions from vegetative development into the reproductive stage, increased amount of carbon is utilized for bulb and scape development while partitioning to leaves and pseudostem gradually decreases. Prior to final harvest, plants have reached complete maturity, with the greatest bulb size and biomass, and beginning to show the sign of aging through senescence of foliage leaves, leading to the decrease in carbon partitioning towards leaves. Root biomass is relatively stable throughout development, but shows a decrease in the partitioning coefficient due to an overall increase in total biomass.

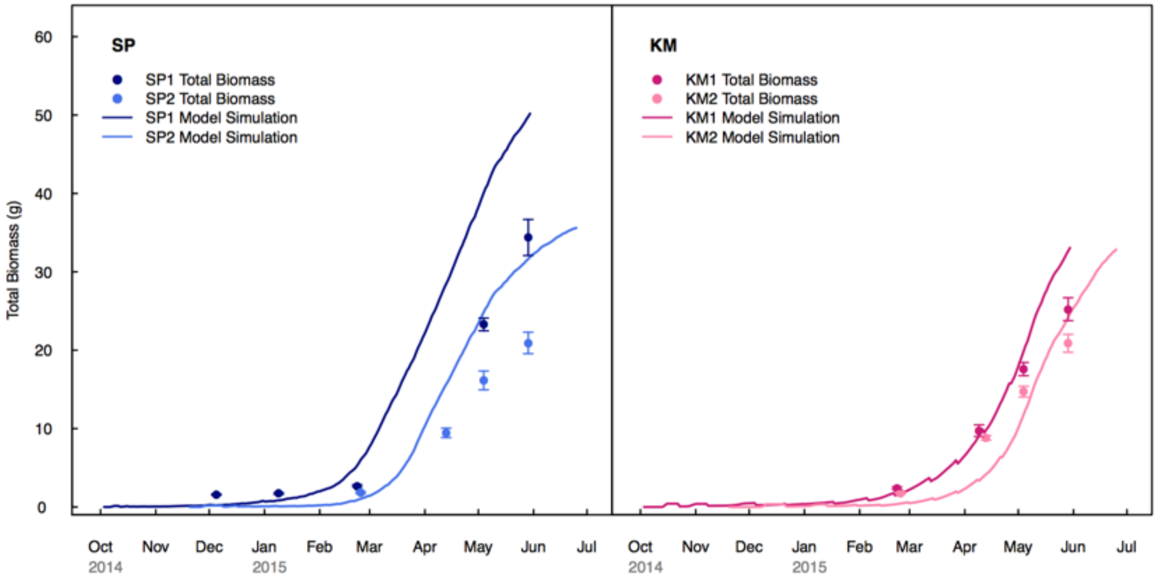


Figure 2.30. Total biomass accumulation for two planting dates and cultivar SP (blue) and KM (pink) prior to model calibration and modification. Solid points indicate field observations while lines indicate model simulations.

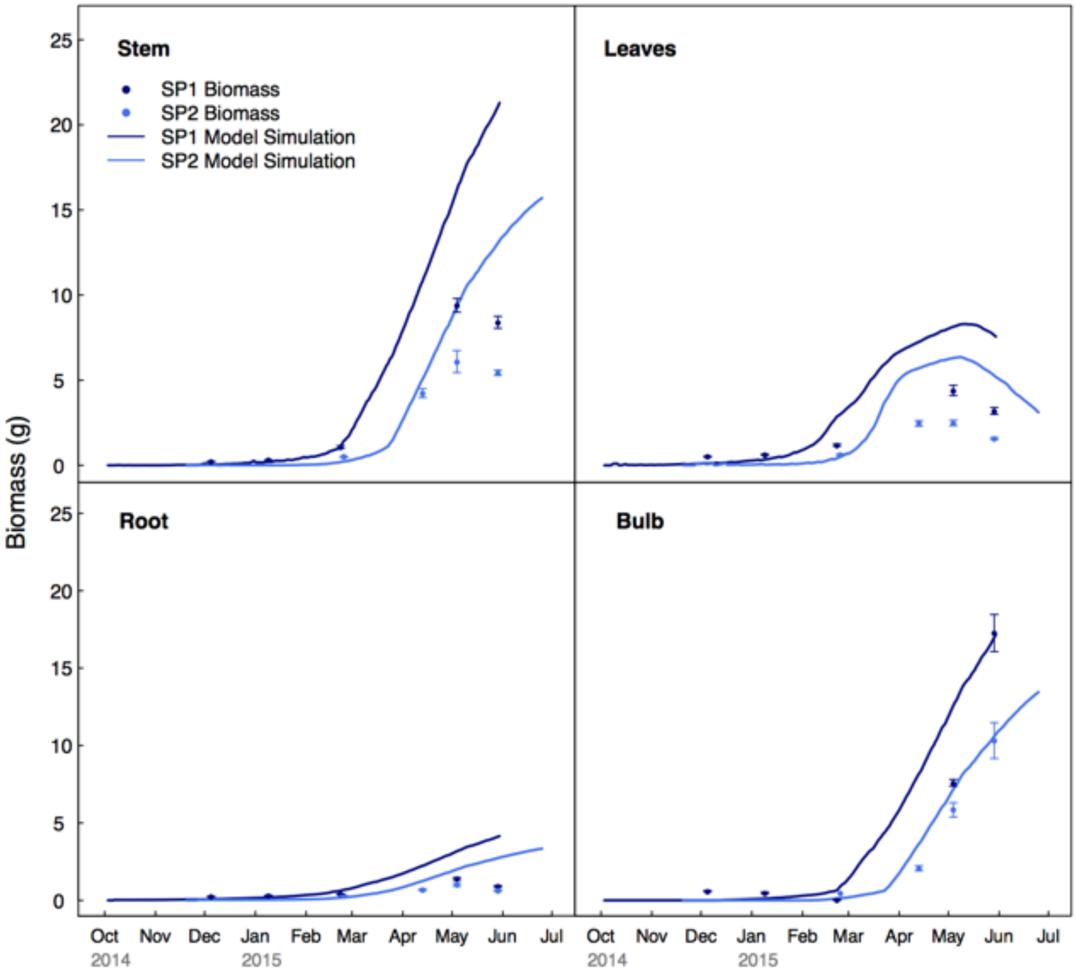


Figure 2.31. Biomass partitioning to stem, leaves, roots and bulb for cultivar SP prior to model calibration and modification. Solid points indicate field observations while lines indicate model simulations.

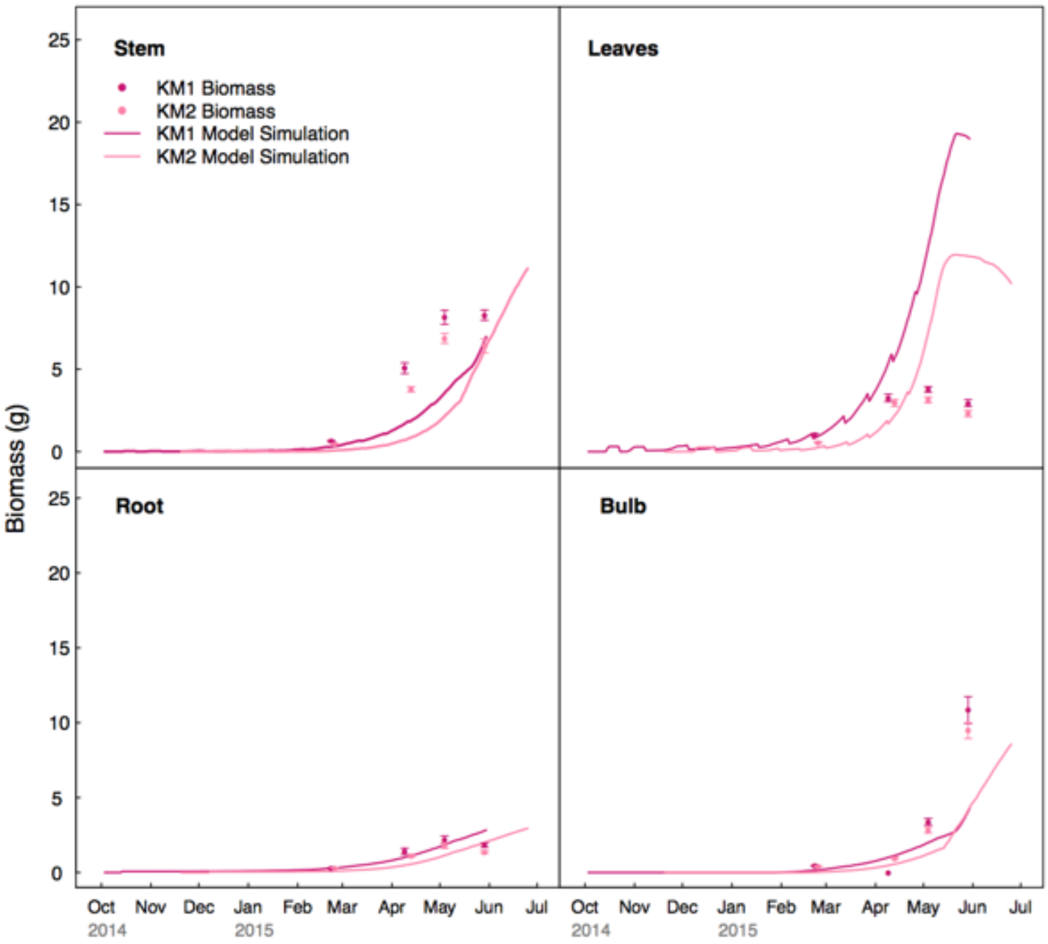


Figure 2.32. Biomass partitioning to stem, leaves, roots and bulb for cultivar KM prior to model calibration and modification. Solid points indicate field observations while lines indicate model simulations.

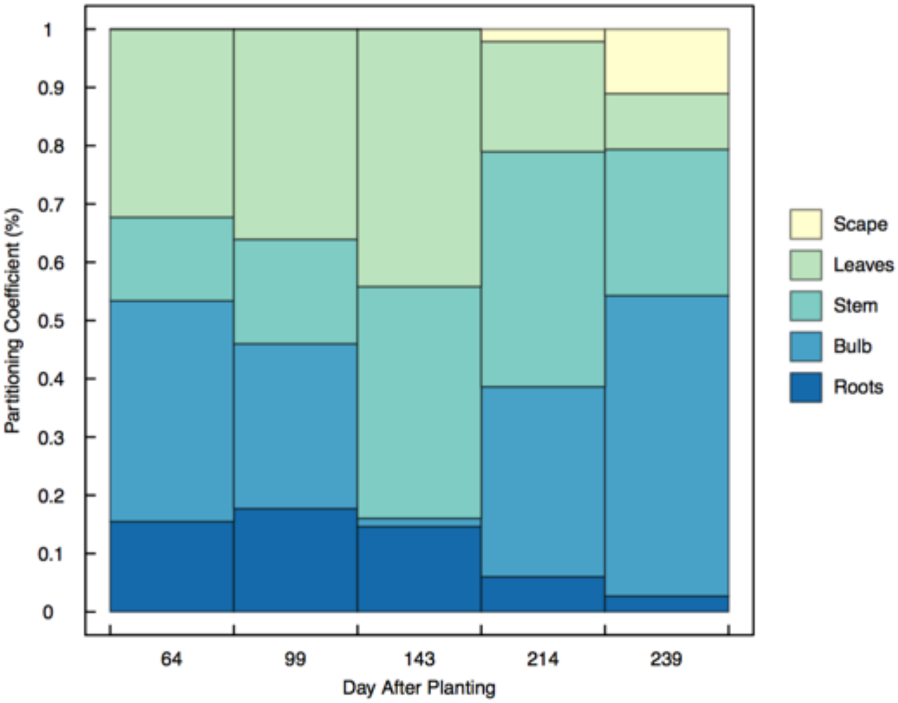


Figure 2.33. Carbon partitioning coefficients for root, bulb, stem, leaves, and scape for SP1 throughout plant development.

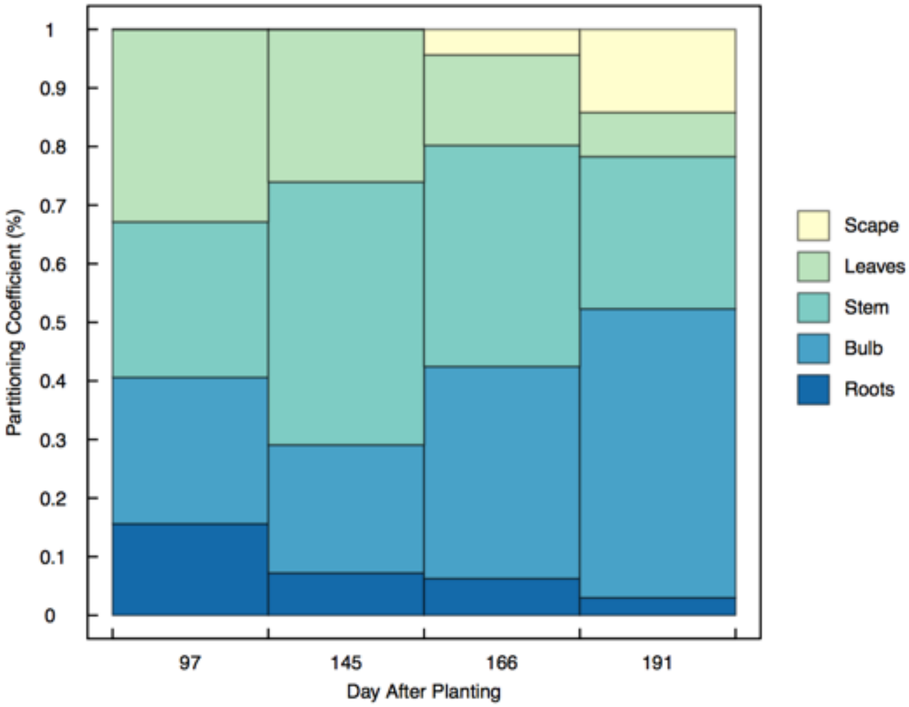


Figure 2.34. Carbon partitioning coefficients for root, bulb, stem, leaves, and scape for SP2 throughout plant development.

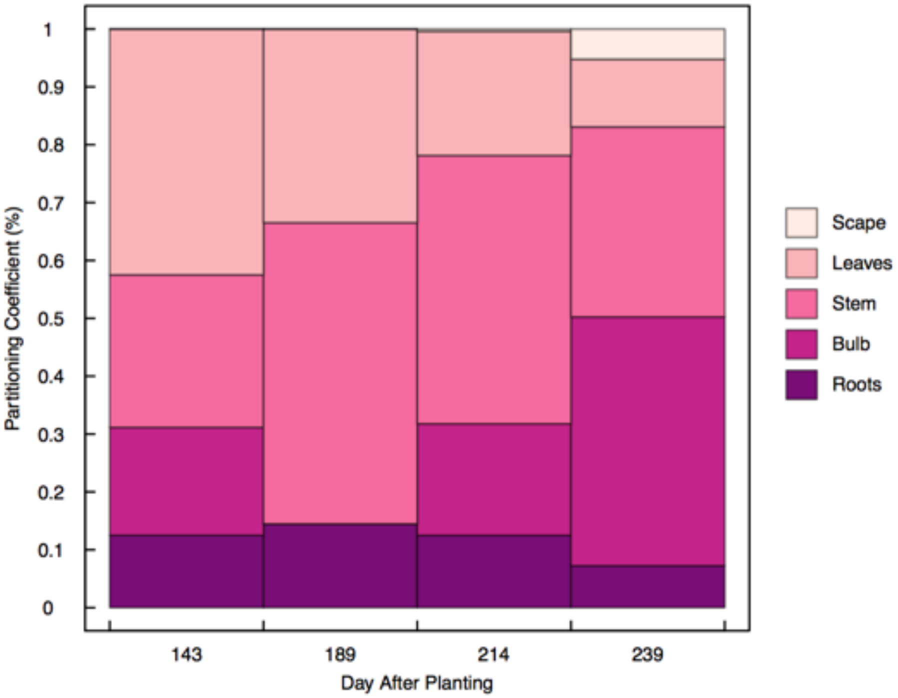


Figure 2.35. Carbon partitioning coefficients for root, bulb, stem, leaves, and scape for KM1 throughout plant development.

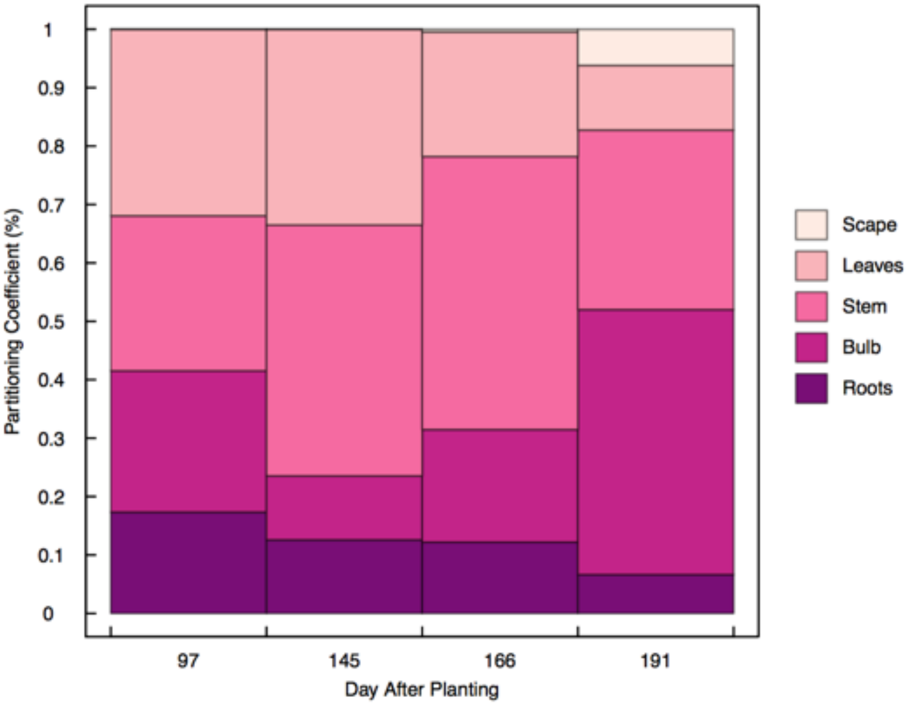


Figure 2.36. Carbon partitioning coefficients for root, bulb, stem, leaves, and scape for KM2 throughout plant development.

2.5.3.2 Model Performance Post Phenology and Morphology Calibration

The accuracy of biomass accumulation largely builds on the accuracy of phenology and leaf area accumulation predictions. Model performance of biomass accumulation after the phenology module is calibrated and the leaf area simulation algorithm is modified is shown in Figure 2.35. Results show that the previous issue in overestimation is greatly improved. However, inaccuracy in carbon partitioning is still present for both cultivars (Figure 2.39).

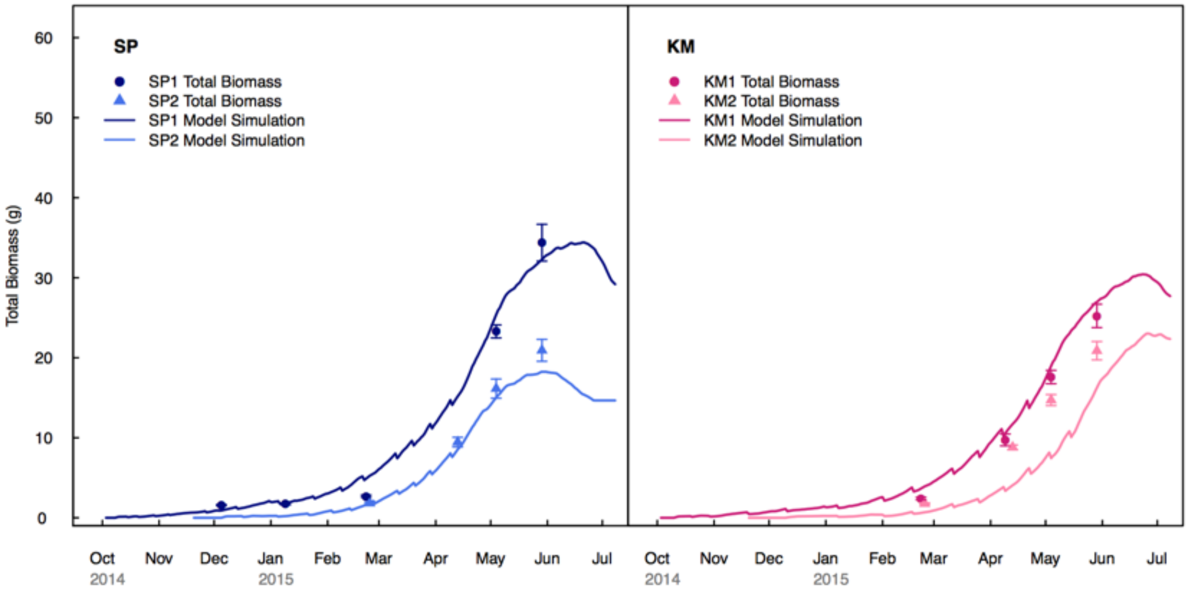


Figure 2.37. Total biomass accumulation for two planting dates and cultivar SP (blue) and KM (pink) after model calibration and modification. Solid points indicate field observations while lines indicate model simulations.

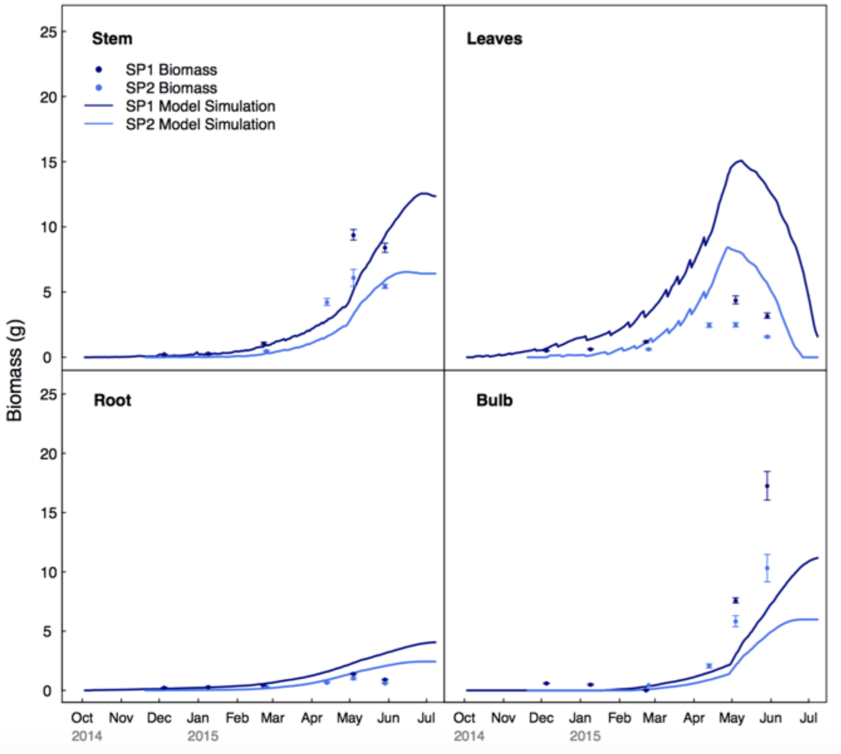


Figure 2.38. Biomass partitioning to stem, leaves, roots and bulb for cultivar SP after model calibration and modification. Solid points indicate field observations while lines indicate model simulations.

2.5.3.3 Model Validation

Total biomass gain and partitioning was also validated with an independent dataset from year 2013-2014. Comparison between field observations and model predictions for total biomass gain are shown in Figure 2.40. Model performance with calibrated parameter sets increased model performance for cultivar KM, but slightly decreased the model performance for the earlier planting date in SP, with values increasing from 5.09 to 6.15. Models also produced underestimated biomass values for both planting dates in cultivar SP, which could be linked with the underestimation previously seen in leaf area simulation.

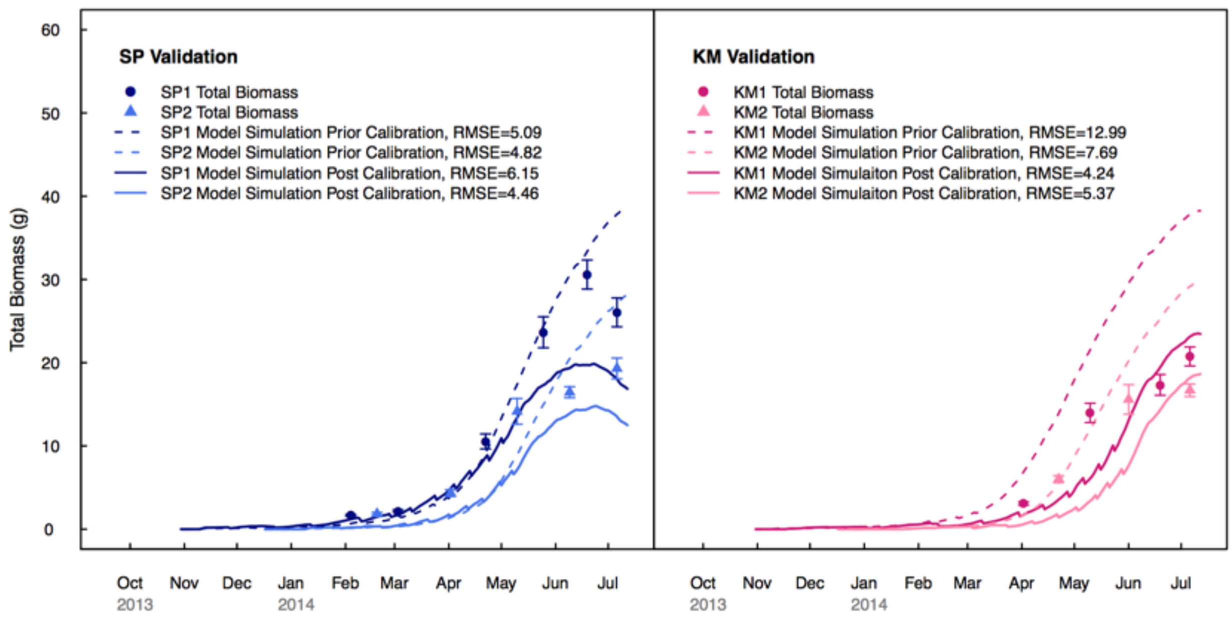
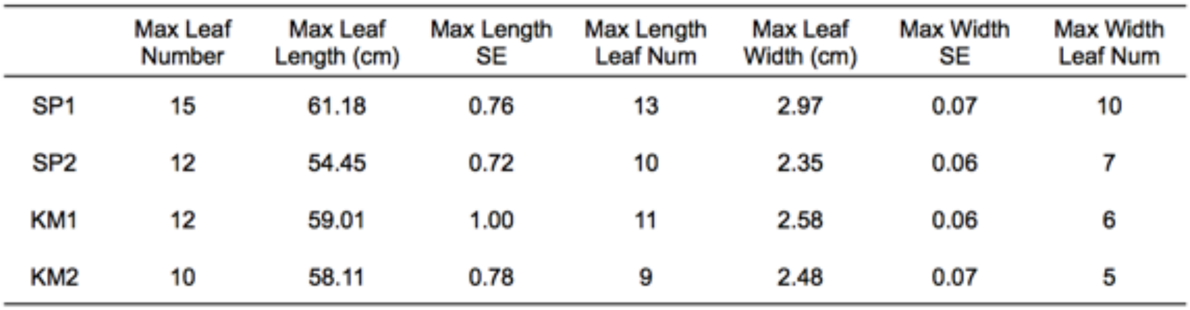


Figure 2.39. Validation results for total biomass simulations for both planting dates of cultivar SP (blue) and KM (pink). Solid points indicate field observations from the earlier planting date and solid triangles show observations from the later planting date. Dashed lines show model simulations with un-calibrated parameter sets, and solid lines indicate outputs from calibrated parameter sets along with a modified leaf area simulation algorithm. RMSE values are shown to evaluate model performance.

2.5.4 Maximal Leaf Number Simulator

Maximal leaf number is an important and required input for both phenology and morphology module. In the phenology module, maximal leaf number determines the endpoint of leaf development (Figure 2.12), and in the morphology module, it is required to normalize the leaf length and width data (Figure 2.24). However, field observations show that the final number of leaves a plant develops differs amongst cultivar and planting date (Table 2.2). Manual input of the final leaf number can be one option to deal with this situation, but would also increases the required inputs and effort in order to operate the model. Therefore, development of a simple algorithm to simulate final leaf number for each cultivar was attempted. Results showed that maximal leaf number for both cultivars were related to planting date, growth period from planting to scape appearance, and thermal units. Simple linear modeling approaches were applied to all three factors, and also to the combination of photoperiod and thermal units to come up with the most efficient and accurate method to simulate final leaf number.

Table 2.2. Maximal leaf number, maximal leaf length, and maximal leaf width for all cultivar and planting date combinations.



	Max Leaf Number	Max Leaf Length (cm)	Max Length SE	Max Length Leaf Num	Max Leaf Width (cm)	Max Width SE	Max Width Leaf Num
SP1	15	61.18	0.76	13	2.97	0.07	10
SP2	12	54.45	0.72	10	2.35	0.06	7
KM1	12	59.01	1.00	11	2.58	0.06	6
KM2	10	58.11	0.78	9	2.48	0.07	5

Maximal Leaf Number and Planting Date

The relation between maximal leaf number and planting date can be easily seen in Figure 2.41. The later the planting date, the lower the final leaf number is observed in both cultivars. The final leaf numbers amongst two cultivars are also slightly different, with SP showing an overall higher final leaf number, regardless of planting date. A simple linear model was developed separately for the relation between planting date represented in day of year and final leaf number. A second order polynomial linear model was developed for cultivar SP (Eqn. 2.10), and a simple linear model was developed for KM (Eqn. 2.11).

$\text{SPMaxLNum} = 103.3 - 0.533 * (\text{PDate}) + 0.00077 * (\text{PDate})^{2}$ ……………….…….... Eqn. 2.10

$\text{KMMaxLNum} = 21.88 - 0.037 * (\text{PDate})$ ……………………………………..…….. Eqn. 2.11

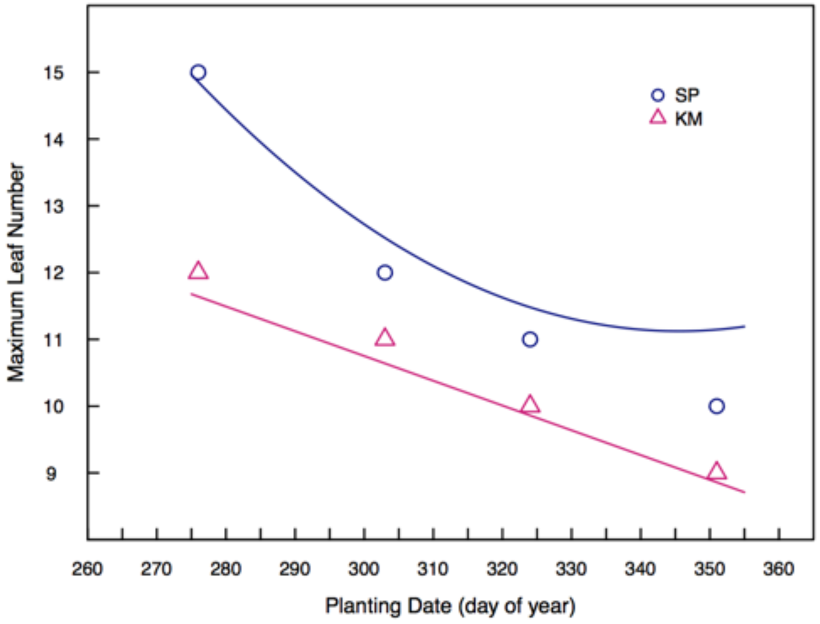


Figure 2.40. Relation between planting date (day of year) and maximal leaf number for the two cultivars SP (blue) and KM (pink). The points indicate actual observations and the lines indicate the linear model simulation.

Maximal Leaf Number and Growth Period Until Scape Appearance

The relation between maximal leaf number and the growth period until scape appearance (days) is a modified concept from the maximal leaf number relationship. Scape appears after the final leaf is developed, therefore has a close relation with the final leaf number. This relation leads to a generalized assumption that the more time the plants has before scape appears, the more leaves it is able to develop. The beginning of this time growth period is determined by planting date, which is determined by the planter. However, the end point of this growth period, which is the time of scape appearance, still needs to be determined.

Many factors can affect the timing of scape appearance, including storage conditions, temperature, and photoperiod. Photoperiod is known to be one of the main factors influencing scape appearance (Takagi, 1990), and therefore was chosen as the indicator to model the timing for scape appearance. The correlation between scape appearance time and photoperiod can be seen in Figure 2.42, which showed that regardless of cultivar and planting date, scape appearance for all plants happened mid to late April when the photoperiod was within the range of 14-14.5 hours. This photoperiod is determined as critical photoperiod for scape appearance, and the date that photoperiod approached this range was chosen as the end point for the leaf development period.

Once the growth period until scape appearance is determined, the relation between this time period and the final developed leaf number can be generated, which is shown in Figure 2.43. Results show that for the two cultivars and planting dates chosen for this experiment, the longer the time period between planting date and scape appearance, the more leaves the plants developed. This relation was modeled by separate simple linear regression for the two cultivars respectively. The equation for SP is shown in Eqn. 2.12, and the equation for KM is shown in Eqn. 2.13.

$$\text{SPMaxLNum} = 24.253 - 0.201 * (\text{GrowthLen}) + 0.0007 * \text{Len}\ (\text{GrowthLen})^2 \quad \ldots\ldots\ldots\ \text{Eqn. 2.12}$$

$$\text{KMMaxLNum} = 4.223 + 0.037 * (\text{GrowthLen}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \text{Eqn. 2.13}$$

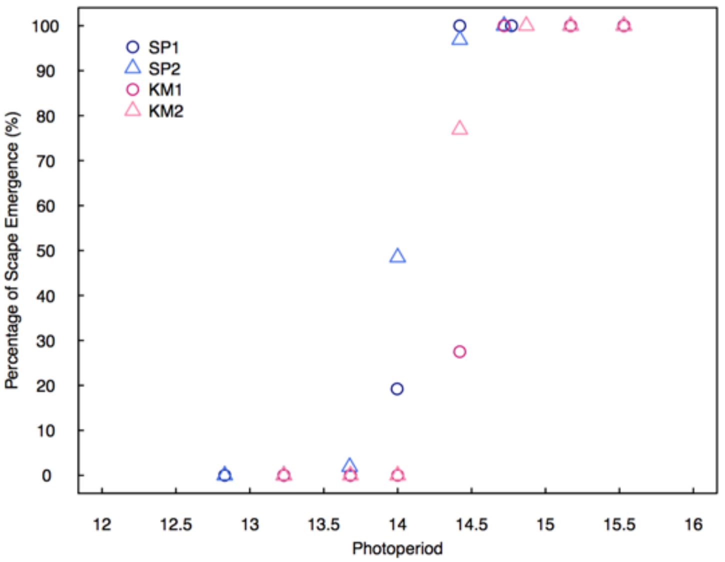


Figure 2.41. Relation between photoperiod and percentage of scape emergence for all cultivar and planting date combinations. Results show that regardless of cultivar or planting date, the timing of scape emergence is fairly similar, and falls within the range of photoperiod from 14 - 14.5. Blue colors indicate cultivar SP, and pink indicates cultivar KM. Open circles show the earlier planting date (10.03.2014) and the open triangles show the later planting date (11.20.2014).

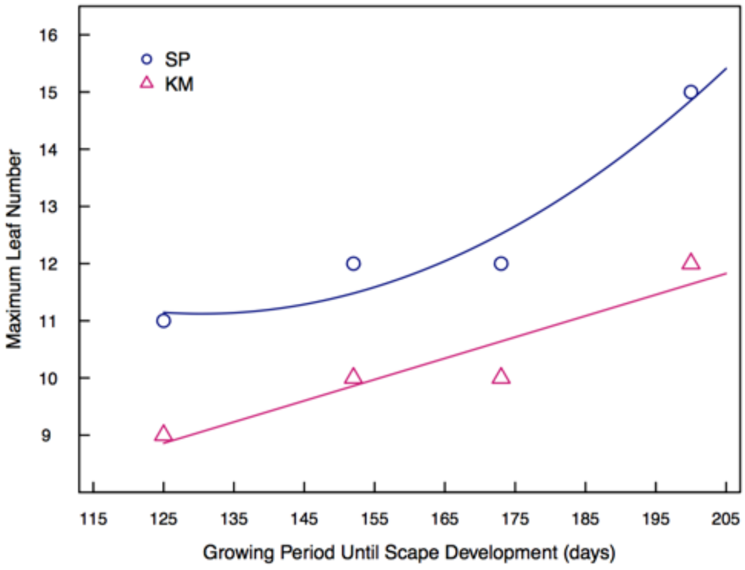


Figure 2.42. Relation between growth period until scape development (days) and maximal leaf number for the two cultivars SP (blue) and KM (pink). The points indicate actual observations and the lines indicate the linear model simulation.

2.6 Discussion

2.6.1 Phenology

Field Observations

Field observations of leaf development phenology showed phenological differences between cultivars and amongst planting dates (Figure 2.7 and 2.8). These differences were mainly caused by the difference in final leaf number, and the environmental conditions the plants were exposed to during various developmental stages.

The greater final leaf number observed in the earlier planting date in both cultivars may be due to the extended amount of time the plants were given for development. Once scape development has initiated, no longer can the garlic plants develop leaves, and therefore final leaf number is determined. The strong relation between scape initiation and photoperiod has been observed in previous studies (Kamenetsky et al., 2004; Pooler and Simon, 1993; Takagi, 1990). A similar photoperiod trigger for scape appearance was observed amongst both cultivars and planting dates, leading to a similar timing for scape appearance regardless of cultivar and planting date. Therefore, the earlier the plants were planted, the longer time period the plants have to grow and develop leaves, leading to a greater leaf number.

Different temperature conditions amongst the two planting dates also contributed to differences shown in leaf development. The average daily temperature for October was 15˚C while the average for November was 7.5˚C. Warmer late autumn weathers the plants were able to experience when planted earlier facilitated leaf development during early developmental stages. Less time was required for the emergence for lower leaf numbers, leading to an advanced leaf development phenology caused not only by the earlier planting, but also by the warmer temperatures. This temperature relation concept is also the foundation of the beta function used to describe leaf development phenology, making it possible for the model to capture the temperature effects on leaf development.

Cultivar difference may have also contributed to difference in leaf development and final leaf number. Garlic cultivars have been categorized into several different groups based on morphological as well as physiological and ecological characteristics. Morphological characteristics include traits such as bolting type, number and size of cloves, bulb weight, color of bulb protective skin, width and length of foliage leaves and plant height while physiological and ecological characteristics include the timing of bulbing and maturity, chilling and photoperiod requirements for bulb formation, cold hardiness and bulb dormancy (Takagi, 1990). Classification of different cultivation groups can be seen in Figure 1.5, and the two cultivars chosen for this study fall into two different categories, with Shantung Purple categorized within the Turban group and Korean Mountain as part of the Asiatic group.

The two groups differ in several morphological, physiological and ecological traits described above. Cultivars within the Turban group generally have a shorter low-temperature requirement, allowing them to release dormancy earlier, leading to an earlier leaf development phenology compared to other cultivars. These characteristics make them the earliest varieties to mature and ready for harvest. Cultivars within the Asiatic group, on the other hand, have a wider range for temperature adaptation, making them suitable for both warm and cold climate. The higher chilling requirement, however, require these cultivars to go through a longer period of cold temperature before the bulb dormancy can be broken, giving them distinctly different phenological traits compared with the Turbans.

Regardless of planting dates, Shantung Purples showed a sooner leaf emergence compared to Korean Mountain, and when planted earlier, the sooner the leaves emerged. This suggested a lower chilling requirement for this specific cultivar, and the brief storage period prior to planting was sufficient to break the bulb dormancy. Dormancy has already been released at the timing of planting; therefore the timing required for sprouting was only temperature dependent. The warmer the temperature, the faster the cloves sprouted out, and vice versa, which further contributed to the phenological difference between the two planting dates. As for Korean Mountain, emergence time for the first leaf for the two planting dates were not too far apart, likely suggesting that a certain amount of shilling would needs to be fulfilled before the release of bulb dormancy.

Bulb Dormancy and Leaf Development Phenology

The active growth and development of cloves slow down and eventually cease, leading to a complete dormancy as the mother plant ages and the foliage leaves begin to senesce. Internal physiological controls of the plants influence the dormancy of the cloves, and certain environmental conditions would need to be fulfilled in order to break dormancy and to resume rooting and sprouting activities within the clove. Dormancy, which can be measured by the time period required from planting to sprouting, is at its deepest state immediately after harvest, and gradually diminishes during storage (Takagi, 1990). Several factors can influence the release of dormancy, including storage temperature, storage period, maturity of the bulb when harvest, and cultivar.

Storage temperatures can be categorized into cold temperature (5-10˚C), warm temperature (30-35˚C), or room temperature (20-25˚C) storage conditions. Different temperature conditions combined with the length of storage have great influence on the dormancy level of the bulb, leading to changes in the number of days required between planting and sprouting. Both cold and warm temperature storage have been shown to facilitate the time required between planting and sprouting, with warm temperatures showing a greater effect on weakening dormancy within bulbs that only experienced a short storage period and are still in deep dormancy, but may end up causing necrosis in newly developed roots when the storage period is prolonged, and bulb dormancy has partially decreased. Cold storage, on the other hand, is optimal for longer storage periods, in cases where bulbs dormancy have gradually started to release. The longer the cold storage period led to a shorter time length between planting and sprouting. These results indicate a decrease in or overcome of bulb dormancy.

Storage temperature can be manually controlled, whereas storage period is determined based on the choice for planting date. The later the planting date, the longer the storage period, which generally leads to a decrease in or release of bulb dormancy, meaning less time required between planting and sprouting. However, under natural field conditions, the later the planting, the colder the field temperatures usually get, which slows down the growth and development process as a whole. The combination of storage temperature, storage period, planting date, field temperature, and also cultivar differences can eventually all influence the timing of root development and the sprouting for the cloves, and also the following leaf development phenology, which complicates the task of trying to model leaf development phenology completely based on a temperature-based beta distribution function which only takes into account the effect field temperature has on plant development, and neglects the influences storage temperature and period has on leaf development phenology.

Calibration

Leaf development phenology simulations showed an overall improvement after calibration, with the model capturing timing and overall pattern for individual leaf development. However, this overall improvement resulted from a greater increased model performance for early planting date simulations, while slightly decreasing model performance for later planting dates. This result is seen in both cultivars. Overall model performance after calibration for leaf development phenology simulations are also shown to be higher for cultivar SP compared to KM, a higher model performance is also seen in the earlier planting dates compared to the later planting dates for both cultivars. Storage and dormancy may be the two reasons that led to inaccuracy in leaf development phenology predictions.

How the model predicts leaf development phenology is based completely on a beta distribution function that describes the relation between leaf developmental rate and temperature through a bell-shaped curve. However, even though temperature is one of the most important components determining leaf development, other factors such as storage temperature, storage period and bulb dormancy are also known to affect the timing of sprouting, eventually influencing leaf development as discussed earlier (Takagi, 1990). Errors may occur due to the incompleteness of incorporating the underlying processes that determine leaf development phenology.

The inaccuracy in phenology predictions is seen in both cultivars for the later planting date, and a lower model performance was also seen for cultivar KM compared to cultivar SP. The later the planting date, the longer the bulbs were under storage conditions, and the colder the environmental temperature during planting. Field observations showed that the later the bulbs were planted, the more time it required for the plants to sprout out, resulting in an additional delay in leaf development phenology on top of the original delay caused by the later planting. After calibration, the model performance for earlier planting dates in both cultivars showed great improvement, but at the same time model performances for the later planting date decreased slightly. Possible reasons may be related to bulb storage and dormancy aspects that are currently not incorporated within the model. The later the planting date, the longer the storage period, which generally leads to an earlier sprout out due exposure to additional chilling conditions and satisfying the requirements to break dormancy. However, since storage related mechanisms are not incorporated in the current model, the model is incapable of capturing this effect, and the discrepancy between field observations and model simulations can be seen in Figure 2.14 for the later planting date for both cultivars, where actual phenology observations were earlier compared to the model outputs.

Differences amongst cultivars also contribute to the ability for the model to accurately capture the phenology development. Through actual field observations, differences between the sprouting times for the two cultivars can be seen. Shantung purple, which belongs to the Turban cultivation group, require a shorter cold storage period to break dormancy, along with possibly a lower optimal growth temperature. These characteristics make it easier for the bulbs to meet the environmental conditions to break dormancy, leaving the timing for sprouting only to be limited by a having a suitable temperature. Bulbs were under cold storage for 33 days before the earlier planting date on October 3rd. Cloves sprouted out fairly quickly for Shantung Purple after planting, with the tips of the first leaf emerging less than a week. This indicated that a 33-day storage period under 4˚C is sufficient for breaking the bulb dormancy, and the corresponding average temperatures in early October were also suitable for leaf development. For the latter planting date of November 20th, it took a longer period of three weeks instead for the cloves to sprout and for the first leaf to emerge. This longer time period for leaf emergence delay in phenology can be associated with the lower temperature during mid to late November.

Korean Mountain, on the other hand, is categorized within the Asiatic cultivation group. Field observations show a much later leaf development phenology in comparison with Shantung purple. For the October 3rd planting date, cloves required up to a month until the emergence of the first leaf, while up to a month and a half was required for the November 20th planting date. After the 33 days of cold storage for the earlier planting date, cloves still required up to a month to sprout, which could indicate that the environmental requirement for breaking dormancy has not yet been satisfied after this length of storage period and temperature conditions, causing the delay in leaf emergence. A higher optimal growth temperature compared with Shantung Purple may also be a contributing factor leading to a slower developmental rate under the same temperature conditions, resulting in a delayed leaf development phenology.

This difference amongst cultivars is not surprising, since different origins and ecological characteristics may result in variations in phenological timing. The model has flexibility to account for the possible difference in optimal growth temperature amongst cultivars, but lacks the ability to track storage and chilling requirement differences between cultivars, and to reflect those differences on the phenology output. Using only the temperature-based beta distribution function to describe leaf development phenology builds on an assumption that dormancy of cloves have ceased by the time of planting, and therefore development solely depends on temperature. This assumption, however, is not always held true based on the storage conditions and phenological differences amongst cultivars described earlier. For the cultivar Korean Mountain, discrepancy is seen in the prediction for sprouting date, which determines the start point for leaf development. Model predictions for sprouting date were several weeks earlier than field observations for both planting dates due to the model's inability to account for dormancy, leading to a greater prediction error observed in cultivar Korean Mountain. Parameters within the beta distribution function such as optimal growth temperature (T_{opt}) and maximum developmental rate (R_{max}) can be calibrated to lower simulation errors, but this still is unable to lead to an accurate prediction for sprouting date, which inevitably leads to further error in following leaf development phenology.

Original parameters were default values determined through greenhouse and field experiments conducted in the process of building the model, and the same values were applied for both cultivars. Key parameters of T_{opt} and R_{max} for the temperature-based beta distribution function were adjusted after calibrating the model with cultivar and planting date specific field data. T_{opt} and R_{max} were treated as cultivar based parameters, meaning that these parameters would remain as same values within the same cultivars. Parameters that resulted in a lowest RMSE were chosen, with the results shown in Table 2.1. Results showed that major changes in the calibration process were in T_{opt}. The T_{opt} value resulted in a lower 27˚C for cultivar Shantung Purple, and a higher 32˚C for Korean Mountain. The higher T_{opt} value for cultivar Korean Mountain is the result of the beta distribution function attempting to adjust for the delayed leaf development phenology.

Phenology predictions have improved after calibration, with higher model performance in the earlier planting dates for the two cultivars, and for the cultivar Shantung Purple when comparisons were made between cultivars. The model has the ability to capture the temperature responses of leaf development, but creates error when factors other than temperature, primarily dormancy, need to be considered. The influence dormancy has on leaf development phenology depends both on the ecological and physiological characteristics of the cultivar, the storage temperature, and also the planting date related storage period. The more these factors influence phenology, the less accurate the model predictions, and the current flexibility within the model structure can only partially account for this issue.

Validation

Model performance determined through validation results were greater for the earlier planting date of Shantung Purple, while showing a slight delay in phenology timing prediction in the later planting date. Phenology predictions for Korean Mountain were less than ideal, with both planting dates showing error, with an earlier prediction of sprouting date that gradually turned into a delayed prediction in further on leaf development. Underlying problems with using the current beta function to describe leaf development phenology were seen and have been described earlier, with problems mainly related with storage, bulb dormancy, and cultivar characteristics, therefore it is not surprising to see the same problems showing in the validation results.

Due to cultivar characteristics, Shantung Purple that belongs to the Turban cultivar group, requires a shorter storage period for breaking bulb dormancy, and therefore has a faster response to temperature, leading to earlier sprouting and further leaf developments. This characteristic is more similar to the structure of how the temperature-based beta function is used for phenology simulation, since as long as environmental temperatures are above the base temperature set within the function, in this case 0˚C, the model will start responding to the surrounding temperature input and begin the process of leaf emergence. This underlying mechanism seems to be capturing the phenological development of a wide range of planting dates. However, for late planting dates after mid December, the long cold storage periods may have had further effects on the bulb physiology, commonly leading to a facilitation of the sprouting process and resulting in a delayed simulation for model predictions.

Korean Mountain, on the other hand, has a longer storage requirement, leading to a delay in sprouting date and leaf emergence phenology compared to Shantung Purple. The current model structure of beta function, however, cannot depict this characteristic since there is no additional equation to describe phenology delays due to storage and dormancy causes, which led to greater error, especially for later planting dates. Having an additional parameter input of germination date may be an alternative solution to account for the discrepancy seen between modeled and actual sprouting date. Recalibration would be necessary.

2.6.2 Morphology

Field Observations

Morphological differences in leaf length and leaf width for individual leaf numbers, along with final leaf number were observed both between cultivars and amongst planting dates. This difference influenced leaf area for individual leaf numbers, and eventually led to differences in total leaf area per plant within different developmental stages.

Cultivar difference were not only seen in the phenological timeline but also in the final leaf number developed. Shantung Purple generally had a greater final leaf number compared to Korea Mountain, with the total leaf number gradually decreasing with a later planting date. The difference in total leaf number had a significant influence on total leaf area, since the more leaves, the greater leaf area present. However, final leaf number was not the only factor leading to differences in total leaf area seen in both cultivars and planting dates. The leaf length and width profile were also different amongst cultivars, and were affected by planting date as well, with differences between planting date more distinct with Shantung Purple. As the final leaf number decreases, so did maximal leaf length and maximal leaf width, which resulted in a shift in the leaf length and width profile (Figure 2.17 and 2.18).

Factors influencing final leaf number are likely linked with temperature and photoperiod, while causes of change in leaf length and width are less clear, but are likely to be related with cell division and temperature relations with cell expansion. The main control of leaf growth and final leaf size is determined through cell division and cell expansion. However, the underlying mechanism of these two processes is still far from clear and remains an active field of study due to the complexity within the interaction of the two processes. Current knowledge allows us to further divide the process of leaf development into five successive and overlapping phases: an initiation phase, a general cell division phase, a transition phase, a cell expansion phase, and a meristem division phase (Gonzalez et al., 2012).

The different timing in planting resulted in different environmental conditions for plant growth, especially for the early stages of development. Early planted groups were exposed to the warmth of mid to late autumn, while later planted groups had their early stages of development under colder winter conditions. Studies have shown that rates of expansion and of epidermal cell division are linearly related to temperature of a wide range (Tardieu et al., 1999) which could have been one of the underlying reasons of the change in leaf length and width according to the change in planting date.

Model Calibration

The difficulty of modeling leaf area based on leaf length and leaf area relationships increased due to the changes in leaf length according to cultivar and planting date. A single equation would not be sufficient to describe all scenarios without creating error, however, modifying and calibrating the equations for all scenarios would also be a tedious and unrealistic modeling approach. Detailed understanding of how cell division and expansion link with temperature, and how it eventually influences final leaf area are not yet available to construct a mechanistic approach, therefore an alternative approach to summarize the different morphological responses through normalization was used instead.

It was found that despite the different patterns seen in the relation between final leaf length and leaf number (Figure 2.17 and 2.18), the differences could be minimized after normalizing against final leaf number and maximal leaf length. This creates a great alternative to simplify the constantly changing leaf length and leaf area under different conditions. However, trade offs are also created when aiming for model simplicity. Additional information of the final leaf number and maximal leaf length would be required for the normalization process. Additional errors may also be generated through the translation between normalized scale and actual scale. However, results from calibration year 2014-2015 showed great improvement in model performance (Figure 2.29), which could imply that error caused through the normalization process was minimal.

Model Validation

The updated leaf area simulation algorithm along with the calibrated parameter LER was validated with field data from experiment year 2013-2014. Model performance was greater for Shantung Purple, but with a slight underestimation with the earlier planting date. Results for Korean Mountain are less than ideal, mostly resulted from an inaccuracy in timing of leaf area accumulation, which could partially be due to the inaccuracy in phenology module as for cultivar characteristics and bulb dormancy reasons discussed earlier. These results further emphasize the importance of the accuracy of the phenology module, and the current issues seen when only using the temperature-based beta distribution function to represent leaf emergence. Further adjustments would be necessary to overcome this limitation in the current model.

2.6.3 Relations Between Phenology and Morphology

Leaf growth, which is defined as the elongation and expansion of individual leaves leading gain in leaf area, is treated as a separate process than leaf development phenology, which is defined as the timing of emergence of individual leaves. However, when discussing the relationship leaf morphology holds with total leaf area during specific developmental stages, morphology and phenology aspects of the plant become inseparable.

The linkage between phenology and morphology can easily be seen when looking into total leaf area accumulation. The original simulation of total leaf area prior to phenology calibrations shown in Figure 2.20 is greatly overestimated. Phenology calibrations not only improved the predicting of leaf development timing, but also resulted in a more realistic simulation for total leaf area, shown in Figure 2.21. These results show the strong influence phenology has on total leaf area simulation, which further determines the accuracy in prediction total biomass gain and the partitioning of assimilates.

The appearance rate of individual leaves along with the rate of leaf growth are the two major factors that influence calculation of final leaf area. Leaf appearance is determined by leaf tip appearance rate (LTAR, leaf/day) within the phenology module, while leaf growth is determined by leaf elongation rate (LER, cm/day). Leaf appearance and leaf elongation are two separate processes. The rate of leaf development is determined through the setting of optimal temperature (T_{opt}) and maximal leaf tip appearance rate ($LTAR_{max}$) through the temperature based beta function. After the emergence of individual leaves, the leaves then start to elongate based on the elongation rate (LER_{max}), which is also determined through the beta distribution. The combination of the timing of leaf emergence along with the process of leaf growth leads to the final simulation of total leaf area. Therefore, an accurate prediction of total leaf area, not only an accurate morphology module would be needed, but a well calibrated and performing phenology module would be required as well.

2.6.4 Biomass Accumulation and Partitioning

Biomass accumulation and partitioning leads to the prediction of final yield, and may be one of the most important outputs one would wish to obtain from crop models. However, an accurate biomass gain simulations depends largely on phenology and total leaf area predictions. Biomass partitioning, on the other hand, can be considered as a further step after simulating total biomass gain. It not only requires an accurate prediction in total biomass to start out with, but also a well-developed relationship between phenological stages and carbon partitioning to separate plant parts. Biomass gain and partitioning was not the main focus of this study, but was rather used as an additional test for model performance. Results showed improvement in total biomass prediction after calibration in leaf development phenology and modification in leaf area simulation, but improvements did not extend to the predictions for biomass partitioning, indicating the necessity for a further improvement in biomass partitioning.

The current method used for biomass partitioning is by assigning partitioning coefficients to individual plant parts. These specific values change according to the developmental stages the plants are in. This method is relatively straightforward, but is also criticized for its lack of mechanistic descriptions of the underlying processes governing biomass partitioning. The difficulty that exists within modeling biomass partition is a common issue faced by crop modelers. The lack of full understanding of the underlying processes that govern biomass partitioning makes it the weakest part of the model in many cases.

Alternative attempts for modeling biomass partition such as the sink strength method (Marcelis, 1996)have been made in attempt to capture this portion of the model more realistically and mechanistically. Organs that have the ability for carbon assimilation is seen as a carbon source, while other organs that require the import of carbon are considered as sinks. The main concept of this method is built upon the assumption that dry matter partitioning among plant sinks is primarily regulated by the sinks themselves, and the ability of the sinks to attract and import assimilates is determined as ‘sink strength’ (Marcelis, 1996). Sink strength may differ amongst organs, and may also alter according to developmental stages. Overall, the concept of the sink strength method is similar to assigning partitioning coefficients to organs, and altering them based on developmental stages, but through a more mechanistic way. Partition of dry mass is determined by the sink strength of the organ, which can be determined through the potential growth rate, which can also be seen as the potential capacity of an organ to accumulate assimilates. Potential growth rate of an organ can be described as a function of both age and temperature, making it possible to model the process with a mechanistic approach.

In order to further improve the model’s capability of capturing the distribution of dry matter amongst plant organs, calibration is the first and necessary step. However, restructuring the partitioning algorithm to incorporate the sink strength concept may ultimately need to be the direction for further improvements.

2.6.5 Final Leaf Number Simulation

Final leaf number simulation was an additional module added to the current model in hope to bypass the need for the input of final leaf number through actual field observations or information through literature, but giving the model the ability to simulate it instead. Being able to know the final leaf number is critical in the model structure, since it is required for two major outputs: phenology and total leaf area accumulation.

The input of final leaf number allows the phenology module to know when the leaf development should stop, which is an important aspect in terms of leaf area accumulation, as well as predicting the timing of transition from vegetative stage into reproductive stage. The input of final leaf number is also required for the modified morphology module for leaf area predictions, since it is a required parameter to normalize the leaf number and leaf length relationship. The importance the phenology and morphology module hold in the whole model structure has been emphasized several times, which makes the final leaf number an important parameter. It is no doubt the best to be able to obtain the actual value of final leaf number through field observations in order to avoid error. However, it is understood that this value is different amongst cultivar groups, and may also be cultivar specific. Even within cultivar the value is not set, and may vary depending on the time of planting. This information, or the practice to acquire such information may not always be available, and an alternative method to simulate the value instead was proposed.

The structure of this module is relatively simple, which is based on the tight linkage seen between planting date and final leaf number, together with the influence photoperiod has on scape emergence, which is the most straightforward signal of the end of leaf emergence. By determining the starting and ending point given for leaf development, the module builds on a simple assumption that the longer time period in between the more leaves the plant would be able to develop. Field results show that this assumption is mostly true under the range of planting dates tested, and the two cultivars chosen (Figure 2.43), making it possible for the development of simple linear relations to predict final leaf number. However, it can also be seen that the linear relationship amongst the two cultivars are quite different, which led to a need for cultivar specific equations. This may be an inevitable process due to the many differences seen amongst the two cultivars, ranging from phenology, morphology, and potentially physiology and ecological properties. This modeling approach may not be as well established as other modules within the current structure, but can be treated as an alternative add-on function when information on final leaf number is lacking and needs to be estimated instead.

2.7 Model Implications and Suggestions for Future Study

The current model developed for hardneck garlic is still in its development. This study is attempting to calibrate the current model and to test the model performance under the choice of two cultivars from different cultivation groups and a under a range of planting date, in the hope to understand the maturity of the current stage of model development for actual implications of yield prediction, agricultural decision supporting, and climate change impact on crop production assessments.

Current model performances have shown to be satisfactory for phenology outputs after necessary calibrations were made for cultivar Shantung Purple, while results were less ideal for cultivar Korean Mountain. The importance of phenology is emphasized throughout this study, therefore modifying the current beta function for phenology predictions to incorporate bulb dormancies is an important first step for improvement in model performance, especially for cold climate varieties that tend to have a longer dormant period and later phenology. Morphology simulations were also improved after calibration of the phenology module, along with the modification of the underlying algorithm. The change in leaf area resulting from changes seen in leaf length and leaf width were able to be represented through a single equation after the process of normalization, but how far can this equation be generalized, and whether it applies to other cultivars or other environmental conditions or farming practices would still require further testing.

Calibration or modifications were not carried out on the biomass accumulation and partitioning portion of the model, but was used instead as a validation tool to evaluate the calibration and modifications made in the phenology and morphology modules. Results showed that improvement in the two modules have led to improvements in prediction of total biomass gain, indicating first that the adjustments made in the two modules were helpful in terms of improving the accuracy in model prediction, and second that the underlying algorithm for biomass gain is well structured to capture the gain of biomass once the corresponding phenology and leaf area accumulation is well simulated. Predictions of the partitioning of the gain carbon, however, is less than ideal, regardless of the calibration and modification practices, and can be seen as currently the least accurate portion within the whole model. Further calibration is still required in order to improve the partitioning module, which is essential for a reasonable and reliable prediction for crop yield, which is one of the most important and valuable information for further applications of the model.

The current model is formed by the basic modules that simulate potential growth and yield, assuming that conditions other than temperature and irradiation that cannot be manually controlled under a field agricultural setting are all optimal for plant growth. This assumption, however, is usually not the case for field settings. Water availability would depend on local climate of each planting region, soil type, along with the chosen irrigation method and nutrient availability would depend on the fertilization rate, timing, soil type, and precipitation or irrigation patterns that could potentially lead to runoff and influence fertilization efficiency. Herbivory, pests and weed may also cause damage and competition, which are individual systems that have complicated interactions with the growth and final yield of the crop. The actual cropping system is complex and consists of many other factors that are not yet incorporating into the model structure at the current stage of development, other than calibration, validation and modification of the current model structure, factors discussed above could all be potential directions for model improvement.

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APPENDIX A. List of Parameters and Variables

Table A1. Equations of the phenology and morphology model

Equation	Description	Cultivar	Value Prior Calibration	Value Post Calibration	Unit
Phenology model					
$r = R_{max}\left(\frac{T_{max}-T}{T_{max}-T_{opt}}\right)\left(\frac{T}{T_{opt}}\right)^{\frac{T_{opt}}{T_{max}-T_{opt}}}$					
r	Relative rate of leaf tip appearance, value between 0 and 1				
R_{max}	Maximal leaf tip appearance rate (LTAR)	SP	0.23	0.22	leaves/day
		KM		0.23	leaves/day
T	Temperature				˚C
T_{max}	Maximal temperature, temperature that R_{max} is reached		43		˚C
T_{opt}	Optimal temperature, temperature where R_{max} is reached	SP	25	27	˚C
		KM		31	˚C
Morphology model – Leaf Length					
$Length = Len_{max}\left(\frac{LNum_{max}-LNum}{LNum_{max}-LNum_{opt}}\right)\left(\frac{LNum}{LNum_{opt}}\right)^{\frac{LNum_{opt}}{LNum_{max}-LNum_{opt}}}$					
Length	Final leaf length for individual leaf numbers				cm
Len_{max}	Maximal leaf length amongst all leaves	SP1	61.18		cm
		SP2	54.45		cm
		KM1	59.01		cm
		KM2	58.11		cm
LNum	Leaf number				
$Lnum_{max}$	Maximal leaf number	SP1	15		
		SP2	12		
		KM1	12		
		KM2	10		
$Lnum_{opt}$	Optimal leaf number that has the longest leaf length	SP1	13		
		SP2	10		
		KM1	11		
		KM2	9		
Equation	Description	Cultivar	Value Prior	Value Post	Unit

		Calibration	Calibration	
Morphology model – Leaf Elongation				
$r = R_{max}\left(\frac{T_{max} - T}{T_{max} - T_{opt}}\right)\left(\frac{T}{T_{opt}}\right)^{\frac{T_{opt}}{T_{max} - T_{opt}}}$				
r	Relative rate of leaf elongation, value between 0 and 1			
R_{max}	Maximal leaf elongation rate (LER)	1.25	6	cm/day
T	Temperature			˚C
T_{max}	Maximal temperature which	43		˚C
T_{opt}	Optimal development temperature, temperature when R_{max} is reached	25		˚C