Modeling subtropical tomato crop production

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ABSTRACT
Crop models are a versatile tool in the integrated management of vegetable crop production. The ability to accurately forecast the time that a tomato crop will be ready for harvest and the yield of fruit from the crop is valuable both for managing the harvest scheduling and informing marketing decisions. Currently available tomato crop models have been developed for greenhouses production in temperate climate US and European production conditions, but have limited application to subtropical and tropical climate field production systems. This project has identified field factors that need to be incorporated into tomato crop models to simulate field production under subtropical conditions. Assessments of crop flowering and fruit development phenology demonstrate significant soil type and site effects. Treatment of seedling transplants, including age at transplanting, affect flowering time and yield. Significant soil type effects on flowering and harvest date have been demonstrated and may be related to variations in soil moisture availability under standard irrigation management practices. Flowering date accounts for approximately 50% of the variation in initial harvest date but other factors such as branching pattern also appear to influence timing of harvest in semi-determinant type tomatoes under field conditions. Development of a model that incorporates these variables will be a useful tool in implementing good agricultural practices in field tomato production in subtropical and tropical climates.

Keywords
Tomato, phenology, crop scheduling

INTRODUCTION

The State of Queensland produces and supplies most of Australia's field grown fresh tomatoes. Queensland production accounts for 56% of the total production in Australia (ABS 2008). The Bundaberg and Bowen regions, located in sub-tropical and tropical climatic zones respectively, are the main production regions for field grown fresh tomato in Queensland, producing more than 80% of the state's tomatoes. The capacity to produce crops year round in Queensland provides an advantage for tomato production compared to other regions of Australia.

As is the case in many countries, an increasing percentage of sales of fresh fruit and vegetables in Australia occur through supermarket chains. The market for field grown fresh tomato is dominated by two supermarket chains, Woolworths, and Coles. These supermarkets contract growers directly to supply agreed quantities of produce within quality specifications, and tend to contract growers able to supply product all year round.

The ability to manage the production of the required quantity of fruit to fulfill the demand of the supermarkets in all seasons is a great challenge for the big producers. The growers need to manage their resources to optimize production otherwise they cannot compete successfully in the market. The capacity to accurately forecast production is critical to efficient crop scheduling and to the management of marketing activities with customers.

Crop modeling has become an important tool in many agricultural industries to assist in crop scheduling, and a wide range of models have been developed covering all significant crops and incorporating a broad range of crop specific inputs (Monteith 1996). Predicting the timing of harvest and the crop yield are the two most important model outputs for decision making in the crop production systems. These outputs help the growers to organize their planting schedules so that there is a regular supply of product to the market. The success of a crop yield forecasting system strongly depends on the crop simulation models ability to quantify the influence of the weather and other parameters over a range of spatial scales (Hansen et al. 2000). Harvest date and yield models vary from relatively simple heat unit models based solely on temperature inputs, for example models developed for pepper (Perry et al. 1993) and cucumber crops (Perry et al. 1986), to complex mechanistic models such as the model described by Marcellis et al. (1998) for cucumber incorporating a range of inputs for a series of components parts covering different processes in the crop. Prediction of the harvest date and yield in the major agricultural crops can be made using several different models, so selection of models is generally made on the basis of the required accuracy of output predictions within the production system in which the model will be used.

Many tomato crop models have been developed over the years to describe crop growth and development, dry matter production, and to predict harvesting date and crop yield. The harvest date and crop yield models range from simple thermal time models (e.g. Perry et al. 1997; Warnok and Isaak 1969) to black box harvest date prediction (e.g. Hoshi et al. 2000) and complex explanatory models include SUKAM (Heuvelink 1994); HORTISIM (Gijzen et al, 1998); TOMGROW (Dayan et al, 1993); TOMSIM (Heuvelink 1996); TOMPOUSE (Abreu et al. 2002); SIMULTOM (Sauviller et al. 2002) and CROPGROW (Scholberg et al. 1999). Other models have focused on specific aspect of crop development such as dry matter partitioning (e.g. Heuvelink 1996) and postharvest aspects such as fruit firmness (e.g. Schouten et al. 2010), fruit quality (e.g. Schouten et al. 2007) and pack house operations (Miller et al. 1997). The complex explanatory models provide the most relevant information for identification of knowledge gaps in the development of a crop model for field grown tomatoes in a sub-tropical climate.

Of the explanatory models, the most widely reported and adopted models are TOMGROW (Dayan et al, 1993), TOMSIM (Heuvelink E 1995), CROPGROW (Scholberg et al. 1999) and TOMPOUSE (Abreu et al. 2002). These models are based on dynamic simulation of dry matter production in which the plant physiological processes and their interaction on environmental conditions are combined. Each of these models has been developed for indeterminate tomato plants grown in green house conditions, but the authors have indicated that the models can be calibrated and validated in different environment with different models input parameters. The applicability of the models to field grown, semi-determinant type tomatoes has not been tested.

Based on plant growth characteristics; tomato cultivars can be classified as determinate, semi-determinate and indeterminate. The growing period of determinate and semi- determinate type tomatoes is short and ranges from 90 to 150 days, whereas the life time of indeterminate type tomatoes is long and normally they can survive up to one year (Scholborg 1996). The growth and development of all types of tomato is sympodial (Child 1979). The shoot branching determines the plants overall architecture and affects many aspects of crop management. The determinate type stops growing when fruit is set at the apical meristem, producing a compact plant with few fruit, and the compact size means that normally they require limited amount of staking for support. This characteristic also makes determinate cultivars suitable for container planting. They are the preferred cultivars for the processing industry as all the fruit can be harvested at the same time, facilitating mechanised harvesting of crops with low production costs as trellising is not required. The semi-determinate and indeterminate type cultivars grow larger and require substantial support. The flowering, fruit ripening and harvesting is continuous in these varieties, therefore all the fruit cannot be harvested at the same time. Production in Queensland is based on semi-determinant type tomatoes, while most greenhouse production systems utilise indeterminate type cultivars.

The vegetative and reproductive growth and development processes in semi-determinate and indeterminate tomato cultivars are continuous. There is a juvenile growth period prior to initiation of the first flower truss during which only vegetative growth occurs, but at the end of this period vegetative, floral and fruit development may also be occurring on the plant. Vegetative shoot growth can be divided into production of individual nodal sections. The shoot apical meristem forms an elongated internode, a leaf and an axillary bud in the leaf axil. The juvenile phase involves formation of 7 to 11 nodes (Lozano et al. 2009). The primary shoot apical meristem is transformed into an inflorescence at floral initiation and develops the 1st inflorescence on the plant. The axillary bud of the node at which the inflorescence initiates develops as a vegetative shoot. Normally after formation of a further three nodes, the apical meristem of this sympodial shoot then initiates an inflorescence. The main axis is again continued by the sympodial shoot in the axil of the youngest leaf primordium. Sympodial shoot growth above the inflorescence is generally vigorous and its leaves cover the inflorescence (Sawhney et al. 1984).

In the tomato plant, axillary buds are formed early in development in all axils of leaf primordial (Tucker, 1979). Growth of lateral shoots from leaf axils below the first inflorescence and between subsequent inflorescences produces a bushy plant structure. Greenhouse production using indeterminate cultivars requires removal of side shoots restricting growth and fruit production to the main stem. Modeling of crop growth is therefore focused on rate of production of main stem nodal segments, and number of nodal segments between inflorescences. Removal of some but not all side shoots is practiced in field production of semi-determinate cultivars, resulting in a more complex pattern of production of nodal segments and inflorescences. Factors regulating branching pattern therefore need to be considered in a field crop model.

The juvenile period of the tomato plant varies with environmental conditions, primarily light intensity and temperature. These factors also influence the flowering time of the inflorescences. In controlled environment studies, light intensity and temperature have been shown to affect days to flowering and number of leaves preceding the first inflorescence to develop in tomato (Uzun 2006). Leaf number below the first fruit cluster declined linearly with decreasing temperature in the range 7.4 to 24.2° C, but the effect was modified by light intensity with little temperature effect at high light intensity. Similarly, it was found that the number of leaves formed before initiation of the first inflorescence was decreased with increased light intensity (Kinet 1977). Time to flower is also considered to be controlled by intra plant competition for assimilates (Dieleman and Heuvelink 1992). It has been concluded that all environmental factors may impact on flowering and no single factor can be regarded as critical for flower induction (Heuvelink 1995).

Most of the research examining different aspects of tomato plant growth and development were conducted under controlled environmental condition in greenhouse. It is easy for grower to adjust conditions in greenhouse production to provide the suitable environments for optimum production of tomato fruits. In contrast, under field condition in the Bundaberg region where crops are grown year round, the environmental factors such as light and temperature that influence crop growth and development may fluctuate significantly within short time period as well as from season to season in a year. Therefore, to develop a model to predict harvesting and crop yield for field production in the Bundaberg region climate, characteristics such as the pattern of truss formation, rate of fruit sets, rate of fruit growth and ripening of the fruit in the plant that have been modeled under greenhouse conditions must be examined under field conditions to determine if additional factors need to be incorporated into the model.

MATERIALS AND METHODS

Investigation of the timing of crop developmental events and variability within and between crops was undertaken to identify plant growth stages and production conditions that have a significant impact on harvest timing and yield. In addition, commercial crop records, including detailed assessments of rates of fruit development and harvest yields, were analysed to assessed if the identified key growth stages and production conditions from the first experimental area are consistent with commercial crop data.

Crop development

Six crops were selected for the trial, with three Roma and Gourmet fruit type crops. The crops were chosen to cover three planting times and three production locations. At each of the three locations, adjacent blocks of the Roma and Gourmet cultivars, planted on the same day or within 7 days of each other, were selected. Planting date varied between the three locations and covered the main crop production times for the Bundaberg region

The crops used in the study were selected one week after planting. The first Roma and Gourmet crops were planted on 23nd and 22rd of February 2011 respectively; the second crops were planted on 10th and 17th of March 2011 and the last two crops were planted on 26th and 28th of April 2011. The soil types at each site were a heavy red clay soil, sandy loam soil and medium clay soil respectively. All crops were managed according to standard commercial practice with trellising, drip irrigation under plastic mulch, fertilization at rates based on soil nutrient and plant sap test result, crop protectant chemical applications for pest and disease management as required.

Within each crop, monitoring and sampling were conducted on five plots, each containing four plants, in each crop. The total number of sample plants in each crop was 20; the four plants in each sampling plot were adjacent in a row and the five plots were distributed randomly within each crop.

The crop monitoring involved assessment of a range of parameters on each of the 20 plants in each crop, as the recorded parameters were:

- Flowering date of first truss (date that the first flower reached anthesis)
- Position (node on the main stem) of the first truss
- Number of leaves (counted at the flowering date of first truss)
- Side shoots and nodes (counted at the flowering date of first truss)
- Flower and fruit number on 1st, 2nd and 4th trusses
- Total number of trusses
- Fruit numbers and harvested fruit weight at each harvest date.

Sampling to measure fruit weight was timed to coincide with commercial harvest. As tomato crops are harvested multiple times, each crop was sampled just prior to or the day of commercial harvest and the number and total weight of harvested fruit from each plant at each harvest sampling date was recorded.

Commercial crop data analysis

Commercial crop data for 288 Roma and Gourmet crops grown between 2008 and 2011 were analysed. Data were collected by the industry partner, SP Exports, and consisted of detailed crop records on crop area, timing of management activities, yield and quality.

Specific parameters recorded in the database included planting time, flowering time, flower numbers, fruit set on each truss, harvest dates, yields and site information for each production block. Climatic information was collected from the Bureau of Meteorology weather records for stations closest to the tomato crop production block. Correlative analysis of climacteric, crop growth and yield data was undertaken.

RESULTS AND DISCUSSION

Variability within crops

Flowering and harvest dates for 5 blocks of 4 plants in each of six crops were measured and used to assess variability within and between crops. While large plant to plant differences were found, a similar level of variability was found in all crops. To demonstrate this variability, harvest date of the first truss varied by up to 19 days between individual plants in a single crop (Fig. 1). The Coefficient of Variation in flowering time was in the range 12-16% for all crops, and for first harvest date was in the range 5-7%. No significant differences between blocks within crops were found, suggesting uniformity within sites for each crop.

Yield patterns

The number of fruit harvested per plant at the times of commercial harvesting followed a cyclical pattern (Fig. 2). The cyclical pattern was concluded to be due to timing of ripening of successive trusses on the plants. Roma crops displayed a greater cyclical range than Gourmet crops. Large differences in the duration of the harvesting window and the total number of fruit harvested were recorded between crops, and this trend was evident even in crops planted only 2 to 3 weeks apart (Fig. 2).

Flowering date vs. harvest date

When individual plant data within crop were analysed, a relationship between flowering date and first harvest date was observed (Fig. 3). Plants that displayed delayed flowering also tended to be ready to harvest at a later date. Regression analysis revealed that flowering date only explained approximately 50% of harvest date variation.

Flowering characteristics

Significant differences in flowering date were demonstrated between crops (Table 1 and 2). These differences between crops were not related to differences in degree days accumulated, suggesting site related management factors may have influenced flowering time. Differences in node number at which the first truss was initiated shows that the variation in flowering time was due to differences in the time of initiation rather than simply plant growth rate.

Small differences between crops in the vegetative structures, expanded leaf number and axillary shoot number, at the time of flowering were noted. Differences in flower number in the first truss existed between crops, and these differences did not appear to be related to flowering time. As fruit number is determined primarily by flower number, identification of the factors causing this variation in flower number will be important in modeling crop development and yield.

The results highlight the importance of the early phase of crop development in determining flowering time, and hence timing of the first harvest, as well as flower number and hence initial harvest yields. Seedling transplant age, physiological status or transplant stress were considered potential factors influencing flowering time and number, and further examination of the effects of these variables on field tomato development are required.

Commercial crop analysis

Analysis of commercial crop records revealed characteristic seasonal trends in timing of first harvest, yield and duration of the harvest period. Two periods of higher yield were noted, corresponding to crop planting in the autumn and late winter/early spring (Fig. 4). Crops planted in later spring and summer (weeks 1 to 6 and 40 to 52) and in winter (weeks 15 to 22) tended to produce lower yields. These times corresponded to periods of fastest and slowest crop growth respectively, as is evident from the seasonal trend in time taken from planting to first harvest (Fig. 5).

The duration of the picking period also demonstrated the effect of seasonal climatic conditions on growth rate, with extended picking duration in crops harvested in the winter period (Fig. 6). Overall yield was not related to picking duration, with high yields recorded in crops planted at times of the year that produced both lengthy (week 11) and short (week 33) picking periods. This observation was consistent with the conclusion from the individual crop analysis that factors affecting early crop development play a significant role in the timing of crop development events and in crop yield. Thus, while climatic factors such as temperature and light are major input components in tomato crop models, refinements are required in models for field production under sub-tropical conditions to account for crop establishment and early crop development factors.

CONCLUSION

A consistent level of variability in key plant development parameters was found within crops. Flowering time and the node at which the first flowering truss was initiated varied between crops, and seedling transplanting was identified as a possible source of this impact on flowering. Flower number in the first truss was also found to vary between crops, and as initiation of the first truss occurs at a low node number, this event may be occurring prior to or shortly after transplanting. Examination of the timing of initiation and effects of transplanting practices on the number of flowers initiated in the first truss is needed to inform a field tomato crop model.

Flowering time explained approximately 50% of variability in initial harvest date, demonstrating the need to incorporate other environmental and resource partitioning processes affecting fruit ripening and hence harvest timing in a field crop model. Glasshouse tomato models incorporate temperature as a major input factor, and seasonal patterns noted in commercial crop data suggest that the temperature components of these models may be able to be extended to field models.

Fruit yield followed a cyclic pattern as different trusses reached harvest maturity at different dates. Models able to simulate the timing and rate of fruit development at the individual truss level are required if this cyclic pattern is to be accurately predicted. At a crop level, plant to plant variability is sufficiently large to mask the cyclic pattern within individual plants.

Length of the harvest window and total yield varied between crops and followed seasonal trends. It was concluded that glasshouse tomato crop models, incorporating temperature and light as input components to predict the seasonal trends, combined with modeling of effects of crop establishment factors on flowering time and flower number, could provide a valuable tool for large scale field tomato producers.

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TABLES AND FIGURES

Table 1. Plant assessments at flowering time for Roma crops. DAP = days after flowering.

Crop	R wk08	R wk11	R wk17
Planting date	22-Feb	10-Mar	26-Apr
Flowering (DAP)	23.5	17.5	19.6
Flowering node	9	6.5	7.6
Leaf number	12.4	10.6	8.7
Shoot number	1.4	1.4	0.75
Flowers in truss 1	8.1	7.2	7.2

Table 2. Plant assessments at flowering time for Gourmet crops. DAP = days after flowering.

Crop	G wk08	G wk10	G wk17
Planting date	22-Feb	10-Mar	28-Apr
Flowering (DAP)	24.5	17.7	30.8
Flowering node	7.6	6.6	7.2
Leaf number	11.7	10.8	14
Shoot number	1.3	1.2	3.4
Flowers in truss 1	5.4	6.6	6.3

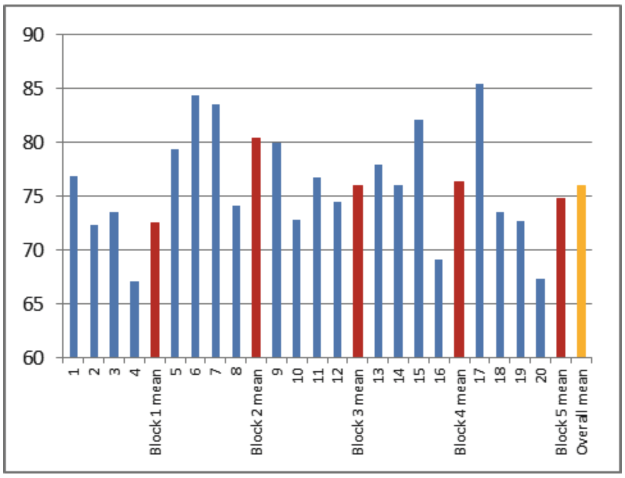

Figure 1. First harvest date (days after planting) for 20 individual plants in 5 blocks within the Roma week 8 planted crop.

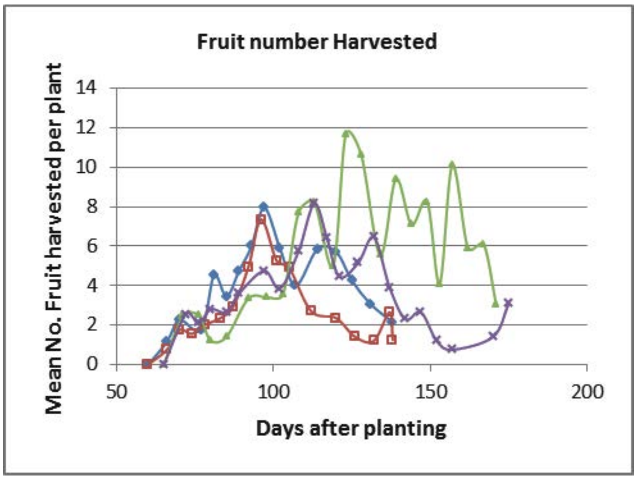

Figure 2. Number of fruit harvested in Roma tomato crops planted in weeks 8 (♦) and 11 (Δ), and Gourmet crops weeks 8(□) and 10(X) respectively.

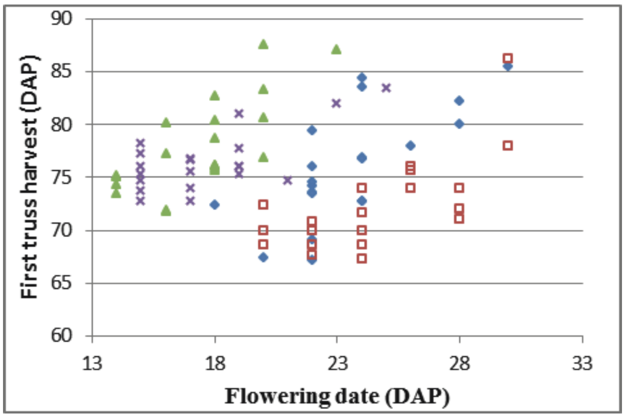

Figure 3. Relationship between flowering date (Days After Planting) and harvest date in Roma tomato crops planted in weeks 8 (♦) and 11 (Δ), and Gourmet crops weeks 8(□) and 10(X) respectively.

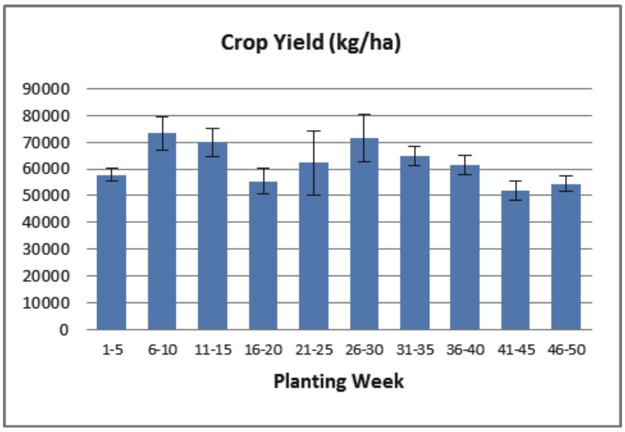

Figure 4. Mean (±SE) crop yield for commercial Gourmet tomato crops.

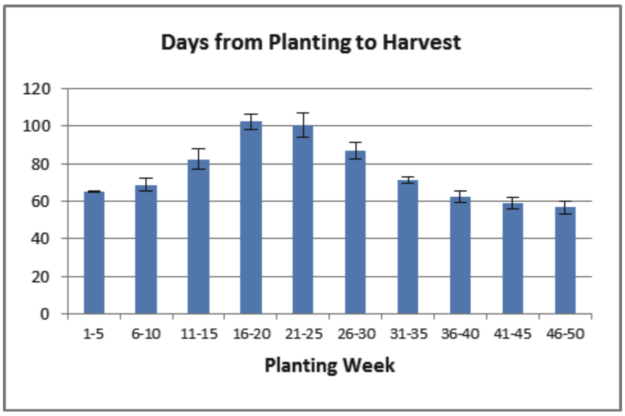

Figure 5. Mean (±SE) time from planting to first harvest for commercial Gourmet tomato crops.

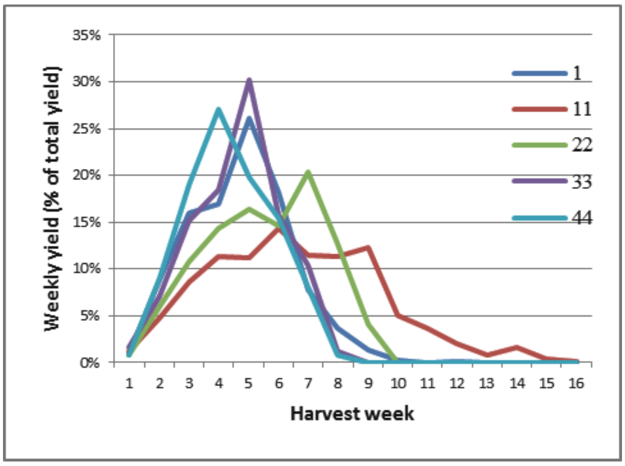

Figure 6. Mean weekly yield, expressed as percentage of total yield, for commercial crops planted in weeks 1, 11, 22, 33 and 44.